CHAPTER VII

COGENERATION OF FIBRE SYNTHESIS PLANT

7.1 Background of The Factory

<u>Location</u> Changwad Pathumthani, Thailand.

Area about 297,000 m^2

<u>Main Line of Business</u>

Manufacturing and sales of polyester fibres.

<u>Etablished</u> 1967

<u>Commencement of Operation</u>

Staple fiber, 1970

Filament yarn, 1971

<u>Capital</u> Registered capital 550,000,000 Baht.

As paid up capital 320,000,000 Baht.

<u>Production Capacity</u>

Polyester staple fiber 3,800 tons/month

Polyester filament yarn 1,200 tons/month

<u>Number of Employees</u>

Male 800, Female 300,

(Head Office = 40)

7.2 Polyester Synthesis Plant

Polyester is a kind of synthetic fibre as shown in Fig 7.1

As shown in Fig 7.2 this plant produced polyester using ethylene glycol, terephthalic acid and methanol as raw materials.

Terephthalic acid was reacted with methanol at 150^{o}C in the presence of sulphuric acid to yield dimethyl terephthalate. The dimethyl terephthalate is purified by distillation and then subjected to alcoholysis with ethylene glycol to yield the ethylene terephthalate monomer. The polymerization is carried out at 260 to 300^{o}C under vaccum. The polymerization releases glycol. The polymer melt is spun and stretched to become polyester fibre. More details of the process has been described by Shreve [22].

The important reactions involved are listed in Table 7.1

7.3 Utility Plant

Referring to Fig.7.3 the utility system of the present factory can be described as follows.

Steam at 500^{o}C, pressure 100 kg/cm^2 was generated in a water-tube oil-fired boiler.

The high pressure steam was first sent to a turbogenerator to produce electricity. Extracted steam from the turbine which had a medium pressure of about 17 kg/cm^2 was sent to the process, while a part of the medium-pressure steam was returned to the boiler for atomizing the fuel oil before combustion and another part was sent to the high pressure heater to preheat the boiler feed water.

Exhaust steam at a low pressure of about 3 kg/cm^2 was also sent to the process while a part of it was supplied to the deaeration tank. Another part of the low pressure steam was used to preheat the fuel oil.

Since low pressure steam and medium pressure steam came out in tandem from the turbogenerator and since medium pressure steam could also have its pressure reduced before use, the general strategy was to make sure that enough MP steam is always produced. In case there was an excess in the LP steam, the surplus was released to the atmosphere. The amount of exhaust and extracted steam also determined the amount of electricity produced.

The generated electricity was sent to the feeder lines named A-BUS and B-BUS. If the generated electric was not sufficient to meet the electricity demand of the plant, make-up electricity would be purchased from the Provincial Electric Authority the purchased electricity would flow to directly to the A-BUS or flow through bustie to the B-BUS.

In case the turbogenerator was taken out of operation for maintainance, the plants' steam requirement would be met by stand-by boilers B_1, B_2, B_3, B_4, B_5 and electricity would be generated by diesel generators AG_1, AG_2. This special situation, however, is not within the scope of the present study.

7.4 Formulation of Optimization Problem

7.4.1 Description of System Variables and Parameters

The definitions of system variables and parameter in the present model are as follows:

Definitions of Variables

x(1)	Boiler Load (T/h at $500^{o}C$ and 100 kg/cm^{2})
x(2)	Electricity produced by turbo-generator (kW)
x(3)	3 K Blow Steam (T/h)
x(4)	Purchased Electricity (kW)
x(5)	A-BUS Electricity supply (kW)
x(6)	Fuel oil consumption by main boiler (l/h)
x(7)	make-up water (T/h)
x(8)	Desuperheating water (h/h)
x(9)	17K steam sent to process plus steam for sale (T/h)
x(10)	3K steam sent to process (T/h)
x(11)	17K Steam supplied to feed water preheater (T/h)
x(12)	Mixing temperature of condensate and make-up water. (^{o}C)
x(13)	Temperature of condensate water from condensate tank at ambient pressure (^{o}C)

Definitions of Parameters (Constants)

CF	Fuel cost (Baht/litre)
CE	Electricity purchase price (Baht/KWH)
AB	Total requirement of electricity by process (kW)
PTOTAL	Total requirement of process steam plus steam for sale (T/h)
P17Kmin	Minimum process requirement of 17K steam plus steam for sale (T/h)
CON	Condensate water recovered (T/h)
FS	Steam for sale (T/h)
CB	Cost of 3K blow steam (Baht/T)
CS	Sale price of 17K steam (Baht/T)
CW	Cost of make-up water (Baht/T)

7.4.2 Mathematical Formulation

The mathmetical formulation is as follows:

Minimize :

$$\text{Objective function } Q = CW * X(7) + CF * X(6) + CE * X(4) - CS * FS + CB * X(3) \qquad ....(7.1)$$

Subject to:

Inequality constraints

$$g(1) = -x(4) + x(5) \le 0 \qquad ....(7.2)$$

$$g(2) = x(8) + 0.5 - ((EN1-EN2)/(EN1-EN5) * (x(9) + RC * x(1)) - ((EN3-EN4)/(EN3-EN5) * (X(10) + RD * X(1) + 2.3 * RE) \le 0 \qquad ....(7.3)$$

$$g(3) = 0.96 * RC * x(1) - x(11) \le 0 \qquad ....(7.4)$$

$$g(4) = 0.01 + x(11) - RC * x(1) \le 0 \qquad ....(7.5)$$

$$g(5) = 140 - (((CON + x(7) + x(11) + TODT) * EN5 - ((CON + x(7)) * x(12) * 1000 + TODT * EN4))/x(11)) * 1.0\ E\text{-}3 \le 0 \qquad ....(7.6)$$

$$g(6) = -170 + (((CON + x(7) + x(11) + TODT) * EN5 - ((CON + x(7) * x(12) * 1000 + TODT * EN4))/x(11) * 1.0\ E - 3 \le 0 \qquad ....(7.7)$$

Equality constraints

$$h(1) = (x(2) * 860) * (1/(.1699 * (x(2) **.195))) * (1/(A2-EN3) - ((A2 - EN1)/(A2 - EN3)) * ((EN2 - EN5)/(EN1 - EN5)) * x(9) - ((EN4 - EN5)/(EN3 - EN5) * (x(10) + 2.3 * RE) - x(3) = 0 \qquad ....(7.8)$$

$$h(2) = x(2) + x(4) - AB = 0 \qquad ....(7.9)$$

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h(3)      = x(6) - (x(1) * 1000/(13.9198 + (x(11) - 45)
            * 5E - 03) = 0                                   ....(7.10)
h(4)      = x(9) + x(10) + x(3) + RC * x(1) + (RD * x(1) +
            2.3 * RE) - x(1) - x(8) = 0                      ....(7.11)
h(5)      = x(11) + (RD * x(1) + 2.3 *RE) + x(7) + CON  -
            1.01 * x(1) - x(8) - (CPOIL * (90 - 60) * x(6)
            * DENOIL)/(EN4 - 100,000) - CPAIR * (122-35) *
            13.19 * DENAIR * x(6) * DENOIL/EN4 = 0           ....(7.12)
h(6)      = CPAIR * (122 - 35) * 13.19 * DENAIR * x(6) *
            DENOIL/EN4 + (CPOIL * (90 - 60) * x(6)
            * DENOIL)/(EN4 - 100,000) + RC * x(1) - x(11)
            + 0.01 * x(1) + x(9) + x(10) + x(3) - x(7)
            - CON = 0                                        ....(7.13)
h(7)      = x(9) + x(10) - PTOTAL = 0                        ....(7.14)
h(8)      = (x(11) * EN2 + (RD * x(1) + 2.3 * RE) * EN4 -
            EN4 * (CPOIL * (90 - 60) * Z(6) * DENOIL)/(EN4
            - 100,000) - CPAIR * (122 - 35) * 13.19 * DENAIR
            * x(6) * DENOIL + (CON + x(7)) * x(12) * 1000
            - 1.01 * x(1) * .19 E6 - x(8) * EN5)
            * 1.0E - 07 = 0                                  ....(7.15)
h(9)      = (CON * x(13) * 1000 + x(7) * 0.03E6 - (CON +
            x(7) * x(12) * 1000) * 1.0E - 07 = 0             ....(7.16)
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Here $g(i) \leq 0$, i = i,..., 6

h(i) = 0, i = i,..., 9

Upper ans lower bounds

50.0	$\leq$	x(1)	$\leq$	80.0
6500.0	$\leq$	x(2)	$\leq$	9000.0
0.0	$\leq$	x(3)	$\leq$	20.0
2010.0	$\leq$	x(4)	$\leq$	12000.0
0.0	$\leq$	x(5)	$\leq$	12000.0
3580.0	$\leq$	x(6)	$\leq$	5675.0
2.40	$\leq$	x(7)	$\leq$	75.0
0.01	$\leq$	x(8)	$\leq$	3.45
x(9)min	$\leq$	x(9)	$\leq$	43.0
15.0	$\leq$	x(10)	$\leq$	40.0
5.24	$\leq$	x(11)	$\leq$	7.36
55	$\leq$	x(12)	$\leq$	90
60	$\leq$	x(13)	$\leq$	100

In short, the model of the unility system consists of 13 variables, 6 inquality constraints and 9 equality constraints.

The details of the the model is explained in Appendix A.

The upper and lower bounds of each variable and their explanation is given in Appendix B.

The optimization problem has been coded in the Fortran IV, languque for implementation on the IBM 3043 of the Computer Center of Chulalongkorn University. The listing of the necessary subroutines is given in Appendix C. The generalized reduced gradient method (GRG) was used to find the optimal solution. To assure the validity of the optimization results, mass and heat balances were carried out to check the answers, as shown in Appendix D.

7.5 List of Optimization Case Studies

Table 7.2 shows the objective function used in each type of case study.

Table 7.3 shows the list of optimization case studies.

Table 7.4 summarizes the optimization results obtained under various types of case study. A brief description of each type of case study now follows:

<u>Type 1</u> The purpose of this case study was to investigate the effect of fuel cost on the optimum operating condition. For simplicity, the cost of 3K blow steam (CB), sale price of 17K steam (CS) and cost of make-up water (CW) were ignored.

<u>Type 2</u> The purpose of this case study was to investigate the effect of fuel cost on the optimal operating conditions. It is different from type 1 in that the cost of 3K blow steam (CB), sale price of 17K steam (CS) and cost of make-up water (CW) were considered. The cost of make-up water (CW) was fixed at 10 Baht/T in every optimization but the cost of 3K blow steam (CB) and sale price of 17K steam (CS) were estimates from the fuel cost.

<u>Type 3</u> The purpose of this case study was to investigate the effect of condensate recovery on the optimal operating conditions. This condensate recovery was 35 T/h for the standard case. It was changed to 30, 47.5 and 58.5, respectively, while all the other parametes were kept constant.

<u>Type 4</u> The purpose of this case study was to investigate the effect of sale price of 17K steam. In the standard case, in which the fuel cost was 2.620 Baht/litre, the sale price of 17K Steam was 122.9 Baht/ton. It was changed to at 50 and 110 Baht/T, respectively.

Type 5 The purpose of this case study was to investigate the individual effect of the fuel cost and electricity cost. First the fuel cost was increased 30% (from 2.620 Baht/litre to 3.406 Baht/litre) while the electricity cost was fixed at 1.438 Baht/KWH. Next the fuel cost was fixed at 2.620 Baht/litre while the electricity cost of was increased 30% (from 1.438 Baht/KWH to 1.869 Baht/KWH).

Type 6 The purpose of this case study was to investigate the combined effect of the fuel cost and electricity cost. At first the fuel cost was increased 15% (from 2.620 Baht/litre to 3.010 Baht (litre) while the electricity cost was decreased 15% (from 1.438 Baht/KWH to 1.222 Baht/KWH). Next the fuel cost was decreased 15% (from 2.620 Baht/litre to 2.230 BAht/litre) while the electricity cost was increased 15% (from 1.438 Baht/KWH to 1.654 Baht/KWH).

Type 7 The purpose of this case study was to investigate what happens when the amount of sale steam was varied. In fact, if the amount of steam for sale was changed, it would mean that the total process requirement of 17K steam would change accordingly. The standard case had 6 T/h of steam for sale while minimum process requirement of 17K plus steam for sale (P17Kmin) was 20 T/h. Here the steam for sale was changed to 3 T/h and 10 T/h, respectively, which made P17Kmin become 17 T/h and 24 T/h respectively.

Type 8 In this type the effect of process requirements was investigated. At first, the total steam requirement was fixed at 43 T/h and electricity requirement was changed from 11,000 KW to 10,000 KW, and 12,000 KW, repectively. Next the electricity requirement was fixed at 11,000 KW and total steam requirement was changed from 43 T/h, to 53.75 T/h, 60.2 T/h and 62.0 T/h, respectively.

To further investigate the effect of the total steam requirement, another set of optimization experiments were carried out. Here the electricity requirement was fixed at 10,000 KW, whereas the total steam requirement was changed from 43 T/h to 53.75 T/h and 60.2 T/h, respectively.

Next it is supposed that the production capacity of the plant would be enlarged, and more utility would be required. Here the total requirement of electricity was increased from 11,000 KW to 12,000 KW and the total requirement of steam was simultaneously increased around 40% from 43 T/h to 60.2 T/h.

7.6 Results of Optimization Studies

The results of all the optimization studies are summarized in Table 7.4

7.7 Discussion of Results

The results of optimization will be discussed case by case with respect to the type of case study.

Type 1 Effect of fuel cost

Table 7.5 and Fig 7.4 reveal that when the fuel cost was 2.62 Baht/litre and the CB, CS, CW were ignored, 75.93 T/h of superheated steam was produced under the optimal operating conditions, 16.88 T/h 3K steam was blown off and 8,990 KW of electricity was generated.

However, when the fuel cost was increased to 5.00 Baht/litre, the new optimal conditions called for the superheated steam production to decrease to 60.238 T/h while 3K blow steam was reduced to 4.36 T/h. Electricity was generated at 6500 KW which was the minimum safe capacity of the turbogenerator. The remaining 4,500 KW of electricity requirement was pruchased. It is obvious that when the fuel oil was more expensive, it was cheaper to buy more and to generate less electricity.

Immediately after the fuel cost was increased to 5.00 Baht/litre, the objective function value was found to be 29,548.2 Baht/h at the starting point (i.e.the provious optimum point before the increase in fuel cost). It then decreased to 27,992.2 Baht/h at the new optimum point. The resulting savings of 1,556 Baht/h was achieved by lowering the plant steam production from 75.93 T/h to 60.24 T/h. The benefit was equivalent to 37,344 Baht/day, 1,120,320 Baht/month, or 12,323,520 Baht/year (with 330 working days).

Type 2 Effect of fuel cost with consideration for the costs of blow steam and of make-up water.

As seen from table 7.6 and Fig 7.5, when the fuel cost rose to 5.00 Baht/litre, the optimum operating conditions called for a sizable reduction in steam generation to 60.238 T/h due to the high fuel cost. Even when the fuel cost was kept at 2.62 Baht/litre, i.e. the same as that of case study type 1, the optimum steam production would still be 60.238 T/h less, if the costs of feed water and 3K blow steam were considered, thus making steam generation more expensive.

Next another theoretical case in which the fuel cost was 1.50 Baht/litre was optimized. The result showed that when the fuel cost was very cheap, steam generation as well as electricity generation should be maximized, and the purchased electricity should be at the mimimum contracted quantity.

Type 3 Effect of Condensate Recovery

So far all of the optimization experiments had been carried out with an assumption of 35 T/h condensate recovery. Here the rate of condensate recovery was varied as 30 T/h, 47.5 T/h and 58.5 T/h, respectively. The optimization results in table 7.7 and Fig 7.6 show that when condensate recovery was reduced from 35 T/h to 30 T/h, make-up water to the boiler simply increased from 15.21 T/h to 20.21 T/h. In other words, when less condensate was recovered, the make-up water increased by the same amount.

Similarly, when 12.5 T/h more condensate was recovered, the make-up water was reduced by the same amount to 2.71 T/h.

The boiler feed water consisted of recovered process condensate, make-up water, condensate from the high pressure heater and the low pressure steam sent to the deacrator.

When Condensate recovery were varied to 30 T/h and 47.5 T/h, make-up water to boiler became 20.21 T/h and 2.71 T/h respectively. One sees that the combined of process condensate and make-up water was either (30+20.21 T/h) or (47.5+2.71 T/h), each equaling 50.21 T/h. Meanwhile condensate from the high pressure heater and the low pressure deacration steam were kept constant at 50.21 T/h as the boiler load remained constant at 60.238 T/h.

Next we consider the case in which 58.5 T/h of condensate was to be recovered. If we were to keep the combined condensate and make-up water at 50.21 T/h, the make-up water would become -8.29 T/h, which has no physical meaning. So the utility plant needed to be run at an abnormally high boiler load of 75.928 T/h to increase the condensate from the high pressure heater and the low pressure deacration steam.

In other words, the unrealistically high condensate recovery of 58.5 T/h could only be accomplished by generating an abnormal amount of steam.

Type 4 Effect of Sale Price of Steam

The pressure of sale steam was 17 kg/cm^2 and its sale price should be linked directly to the fuel cost. The sale price of 17K steam was calculated to be 122.9 Baht/T, the actual production cost, for the standard case. However, the sale price of steam was in reality subjected to negotiation with the customer firm. Here the sale price was theoretically changed to 50 Baht/T and 110 Baht/T, respectively. As seen in Table 7.8 and Fig 7.7, the optimum operating conditions of the whole plant were not changed even steam had to be sold at a loss. It only affected the value of the objective function.

Type 5 and Type 6 Effect of Fuel Cost and Purchase Price of Electricity.

As seen from Table 7.9 and Fig 7.9, when only the fuel cost was increased 30% from 2.620 Baht/litre to 3.406 Baht/litre, the optimum operating conditions were not changed from the standard case. This is because in the standard case steam was already expensive and electricity relatively cheap. Thus just enough steam was generated to satisfy the overall process steam requirement and the generated electricity was correspondingly at a minimum.

When the fuel cost was fixed at 2.620 Baht/litre and the purchase price of electricity was theoretically increased 30% from 1,438 Baht/KWH to 1.869 Baht/KWH, the plant was found to optimally produce more steam in order to generate more electricity while reducing electricity purchase because the cost of generated electricity wad cheaper than the purchase price of electricity. The cost of generated electricity was found to be 0.944 Baht/KWH, which was very cheap compared to 1.869 Baht/KWH of purchased electricity.

Similarly, Table 7.10 shows that when the fuel cost was increased 15% from 2.620 Baht/litre to 3.010 Baht/litre while the price of electricity was decreased 15% from 1.438 Baht/KWH to 1.222 Baht/KWH, the optimum operation conditions were not changed from the standard case. However when the fuel cost was decreased 15% from 2.620 Baht/litre to 2.230 Baht/litre and the electricity price was increased 15% from 1.438 Baht/KWH to 1.654 Baht/KWH, the plant was found to optimally produce more steam in order to generate more electricity while purchasing as little electricity as possible. The cost of the produced electtricity in the case was 0.80 Baht/KWH.

Type 7 Effect of Sale Quantity of Steam

The cost of steam production may be defined in two different ways. One was the "real" cost, and the other, "apparent" cost.

The real cost here consisted of the fuel oil cost and make-up water cost in producing steam. The apparent cost was defined as the real cost minus profit from steam sale. In the present case study we will direct our attention to the effect of sale quantity of steam on the apparent cost.

Here the amount of sale steam was varied from 3 T/h to 6 T/h and 10 T/h, respectively. This was done by increasing the value of

P17Kmin (minimum process requirement of 17K steam plus steam for sale) from 17 T/h to 20 T/h and 24 T/h. Similarly PTOTAL (total requirement of process steam plus steam for sale) was increased from 40 T/h to 43 T/h and 47 T/h. Table 7.11 and Fig 7.9 show that the total apparent cost of producing steam and electricity was increased when more steam could be more. This means that it was not worthwhile to try to increase the amount of sale steam because at 122.9 Baht/T it is being sold at a loss. This is partly because in the standard case the fuel cost was relatively high and the plant was already trying to generate just enough superheated steam to satisfy the process steam requirement. So there was no merit at all in trying to produce more superheated steam in order to sell more 17K steam while the purchase electricity was relatively cheap and there was no increase in the total electricity requirement.

On the other hand, we want to show here that the apparent utility cost per unit enegy produced actually decreased as PTOTAL increased. Table 7.12 shows the apparent cost of utility per unit energy produced. Energy content of P17Kmin steam and P3K steam (low pressure steams sent to process) in kcal/T was converted to exergy in KW and added with the total electric requirement by the process. Then the optimal objective function value was divided by the total exergy to yield the apparent cost of utility per unit energy produced. It can be concluded that the cost of utility per unit energy produced was reduced as PTOTAL increased. This happened because at high loads all the thermal equipment such as boiler and turbogenerator had more thermal efficiency.

Type 8 Effect of Higher Utility Requirement by Process

When the total steam requirement was fixed at 43 T/h and electricity requirement was increased from 10,000 KW to 11,000 KW and 12,000 KW, the value of the objective function cost increased in tandem due to the rise electricity requirement. In this case the fuel cost was relatively high and the plant was already to produce just enough steam to satisfy the process steam requirement. Therefore even though the total electricity requirement rose, the optimal conditions indicated that the extra electricity requirement should be purchased instead of being generated at a higher cost. Thus the amount of electricity generation remained constant.

Next the electricity requirement was fixed at 11,000 KW and the total steam requirement was changed from 43 T/h to 53.75 T/h and 60.2 T/h respectively. It was found that the value of the objective function was reduced from 17,512.37 B/h to 17,322.13 B/h and 17,265.34 B/h. This reduction was realized mainly because the increase in process steam requirement allowed more electricity to be generated, thus reducing the amount of perchased electricity. In addiiton, both the boiler and turbogenerator could be operated at a higher efficiency closer to that of full load. In conclusion, when the total process steam requirement increased while the electricity requirement remained constant, the objective function value instead decreased. This implies that under such a circumstance it was better to generate more electricity by producing more superheated steam than required by the process steam requirement and throwing away some of the surplus steam or better selling it at a very cheap price.

However when total steam requirement was further increased to 62.0 T/h, the objective function value became 17631.3 B/h. This was higher thant the objective function value at 60.2 T/h (17265.34 B/h). This means that when too much surplus steam had to be thrown away in order to generate were more electricity the situation would deteriorate. In other words, when the electricity requirement, was 11,000 KW, this plant would yield the lowest utility cost when the process steam requirement was well matched with the electricity requirement, which was around 60.2 T/h of steam.

When the electricity requirement was fixed at 10,000 KW and the total steam requirement was changed from 43 T/h to 53.75 T/h and 60.2 T/h, respectively, it was similarly found that the objective function value first decreased from 16074.41 B/h to 15884.12 B/h and then increased to 16396.0 B/h. It means that when the electricity requirement was 10,000 KW, this plant would achieve a global optimum if the total steam requirement could perfectly match the electricity requirement. In fact, this implies that it might be better to throw away some surplus in order to generate more electricity than to generate just the required amount of process steam.

In conclusion, the plant had a optimal ratio between the electricity and steam requirements. This information was very important. For example, if the present ratio of electricity to steam was higher than the optimal ratio, then more steam should be produced to achieve the optimal value. The surplus steam could either be thrown away or, if possible, be sold at a price, even if the price was lower than the actual steam production cost. The same information would also be very useful when one had to select a new piece of equipment. Suppose one had to choose between a steam turbine or an electric motor to run a large compressor. If the present ratio of electricity to steam was higher then the true optimum, then a steam turbine should be selected in order to bring the ratio closer to the optimum.

Next we consider the case in which a future plant expansion called for the total steam requirement to increase to 60.2 T/h and the total electricity requirement to simultaneously increase to 12,000 KW. It was found that optimally the plant should produce more steam while no steam was blown off to the atmosphere since the total demand for steam was very high. The total 17K steam sent to the process was 33.69 T/h, which was 5.69 T/h higher than the P17Kmin. (28 T/h) This means that part of the 17K steam sent to process had its pressure reduced to 3K to meet the demand for 3K steam.

The value of the objective function now became 19,180.10 Baht/h, which was naturally higher than the standard case. However, it must be noted that the total process demands of the two cases were different. For the sake of comparison, the process demands of the standard case were extrapolated to find the corresponding value of the objective function after the plant expansion, as shown in Table 7.14. Next Table 7.15 compares the two cases and it is agian found that when the process demands were higher, the utility cost per unit energy became lower.

Table 7.1 Importance Reaction in Polyester Synthesis

1. Raw material :

$$CH_3C_6H_4CN_3 \xrightarrow[\text{or air}]{HNO3} P\text{-}HOOC.C_6H_4.COOH$$

p-xylene — Terephthalic acid, impure

$$P\text{-}HOOC.C_6H_4.COOH \xrightarrow[\substack{150^{\circ}C \\ 0.01\ \% \\ H_2SO_4}]{CH_3OH} CH_3OOC.C_6H_4.COOCH_3+2H_2O$$

Dimethyl teraphthalate impure

2. Monomer :

The dimethyl terephthalate is purified by distillation and subjected to alcoholysis with ethylene glycol to yield the monomer

$$CH_3OOC.C_6H_4.COOCH_3+2CH_2OH\text{-}CH_2OH \xrightarrow{230^{\circ}C}$$

$$HOC_2H_4.\underset{\overset{\|}{O}}{OC}.C_6H_4.\underset{\overset{\|}{O}}{CO}.C_2H_4OH+2CH_3OH$$

3. Polymerization

$$\text{Monomer} \xrightarrow[\text{vacuum}]{260\text{-}300^{\circ}C} HO\left[C_2H_4OOC.C_6H_4.COO\right]_n C_2H_4OH$$

Polyethylene terephthalate

$$+\ n\ .\ \frac{1}{2}\ HOC_2H_4OH$$

Half of glycol distilled off

Table 7.2 Objective function for each type

Type	Equation of objective function	Remark
Type 1	Q = CF*x(6)+CE*x(4)	
Type 2, Type 3, Type 4, Type 5, Type 6, Type 7 and Type 8.	Q = CW*x(7)+CF*x(6)+CE*x(4)-CS*FS+CB*x(3)	

Table 7.3 List of Optimization Type Study

Type	Job name	value of parameter										Remark
		CF	CE	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW	
1	S002	2.62	1.438	11000	43	20	35	6	0	0	0	
	S001	5.00	1.438	11000	43	20	35	6	0	0	0	
2	S003	2.62	1.438	11000	43	20	35	6	79.96	122.9	10	
	S004	5.00	1.438	11000	43	20	35	6	152.6	234.5	10	
	S014	1.50	1.438	11000	43	20	35	6	45.78	70.35	10	
3	S005	2.62	1.438	11000	43	20	47.5	6	79.96	122.9	10	
	A011	2.62	1.438	11000	43	20	58.5	6	79.96	122.9	10	
	S017	2.62	1.438	11000	43	20	30	6	79.96	122.9	10	
4	S006	2.62	1.438	11000	43	20	35	6	79.96	50	10	
	S007	2.62	1.438	11000	43	20	35	6	79.96	110	10	
5	S008	3.406	1.438	11000	43	20	35	6	103.95	159.74	10	
	S009	2.62	1.869	11000	43	20	35	6	79.96	122.9	10	
6	S010	3.010	1.222	11000	43	20	35	6	91.86	141.17	10	
	S011	2.230	1.654	11000	43	20	35	6	68.06	104.59	10	
7	S012	2.62	1.438	11000	40	17	35	3	79.96	122.9	10	
	S013	2.62	1.438	11000	47	24	35	10	79.96	122.9	10	
8	A018	2.62	1.438	12000	60.2	28	35	6	79.96	122.9	10	

Table 7.4 The Optimization results.

Type		Variable													Obt. func. value		Remark
		x(1)	x(2)	x(3)	x(4)	x(5)	x(6)	x(7)	x(8)	x(9)	x(10)	x(11)	x(12)	x(13)	Initial	Optimum	
Upper bound		80.0	9000.0	20.00	12000.0	12000.0	5675.0	75.0	3.45	43.0	40.0	7.36	90.0	100.0	-	-	
Lower bound		50.0	6500.0	0.0	2010.0	0.0	3580.0	2.40	0.0	20.0	15.0	5.24	55.0	60.0	-	-	
Starting point		73.13	8536.0	14.38	2464.0	2463.0	5201.0	26.07	2.04	20.0	23.0	6.676	67.0	95.4	17169.85	-	
Type 1	S002	75.928	8990.0	16.88	2010.0	2009.99	5394.73	28.45	2.352	20.0	23.0	6.975	67.29	97.618	17169.25	10725.68	
	S001	60.238	6500.0	4.36	4500.0	2463.0	4303.99	15.21	2.198	20.0	23.0	5.53	62.21	76.22	29548.2	27992.2	
Type 2	S003	60.238	6500.0	4.36	4500.0	2463.0	4303.99	15.21	2.198	20.0	23.0	5.53	62.21	76.22	17843.14	17512.37	
	S004	60.238	6500.0	4.36	4500.0	2463.0	4303.99	15.21	2.198	20.0	23.0	5.53	62.21	76.22	30596.32	27402.46	
	S014	75.928	8990.0	16.88	2010.0	2009.99	5394.73	28.45	2.35	20.0	23.0	6.97	67.29	97.61	11841.64	11618.73	
Type3	S005	60.238	6500.0	4.36	4500.0	2463.0	4303.99	2.71	2.198	20.0	23.0	5.53	62.21	64.05	17843.14	17387.37	
	A011	72.60	8449.09	14.23	2550.9	2463.0	5164.44	2.40	2.319	20.0	23.0	6.412	69.04	70.65	17843.14	17623.57	
	S017	60.238	6500.0	4.36	4500.0	2463.0	4303.99	20.21	2.198	20.0	23.0	5.531	62.21	83.924	17843.14	17562.37	
Type 4	S006	60.238	6500.0	4.36	4500.0	2463.0	4303.99	15.21	2.198	20.0	23.0	5.53	62.21	76.22	18280.41	17948.76	
	S007	60.238	6500.0	4.36	4500.0	2463.0	4030.99	15.21	2.198	20.0	23.0	5.53	62.21	76.22	17920.41	17588.75	
Type 5	S008	60.238	6500.0	4.36	4500.0	2463.0	4303.99	15.21	2.198	20.0	23.0	5.53	62.21	76.22	22054.90	20779.0	
	S009	75.928	8990.0	16.88	2010.0	2009.99	5394.73	28.45	2.35	20.0	23.0	6.975	67.29	97.61	18905.12	18789.49	
Type 6	S010	60.238	6500.0	4.36	4500.0	2463.0	4303.99	15.21	2.198	20.0	23.0	5.53	62.21	76.22	19400.72	18161.15	
	S011	75.928	8990.0	16.88	2010.0	2009.99	5394.73	28.45	2.35	20.0	23.0	6.975	67.29	97.61	16285.55	16162.01	
Type 7	S012	59.186	6500.0	6.31	4500.0	2463.0	4230.35	14.11	1.976	17.0	23.0	5.43	61.43	74.10	18211.78	17831.92	
	S013	61.642	6500.0	1.77	4500.0	2463.0	4402.1	16.67	2.495	24.0	23.0	5.661	63.21	79.04	17351.63	17084.90	
Type 8	A018	74.992	8060.0	0.0	3939.1	2463.0	5330.0	28.72	3.406	33.69	26.51	6.889	68.30	99.748	17843.14	19180.10	

Table 7.5 Effect of Fuel Cost (Case Study Type 1)

Value of parameter	CF	CE	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW
	vary	1.438	11000	43.	20	35	6	0	0	0

Variable	Upper bound	Lower bound	Starting point	Optimum point		Remark
				CF=2.62	CF=5.00	
x(1)	80.0	50.0	73.13	75.93	60.24	
x(2)	9000.0	6500.0	8536.0	8990.0	6500.0	
x(3)	20.0	0.0	14.38	16.88	4.36	
x(4)	12000.0	2010.0	2464.0	2010.0	4500.0	
x(5)	12000.0	0.0	2463.0	2009.99	2463.0	
x(6)	5675.0	3580.0	5201.0	5394.73	4303.99	
x(7)	75.0	2.4	26.07	28.45	15.21	
x(8)	3.45	0.0	2.04	2.35	2.19	
x(9)	43.0	20.0	20.0	20.0	20.0	
x(10)	40.0	15.0	23.0	23.0	23.0	
x(11)	7.36	5.24	6.676	6.97	5.53	
x(12)	90.0	55.0	67.0	67.29	62.21	
x(13)	100.0	60.0	95.4	97.62	76.22	
Objective function (Baht/h)			17169.85	17025.68	(29548.2) 27992.2	

Table 7.6 Effect of Fuel Cost with consideration for costs of blow steam and of make-up water (case study type 2)

Value of parameter	CF	CE	AB	PTOTAL	F17Kmin	CON	FS	CB	CS	CW
	vary	1.438	11000	43	20	35	6	vary	vary	10

Variable	Upper bound	Lower bound	Starting point	Optimum Point CF=2.62	CF=5.00	CF=1.50	Remark
x(1)	80.0	50.0	73.13	60.238	60.238	75.928	
x(2)	9000.0	6500.0	8536.0	6500.0	6500.0	8990.0	
x(3)	20.0	0.0	14.38	4.36	4.36	16.88	
x(4)	12000.0	2010.0	2464.0	4500.0	4500.0	2010.0	
x(5)	12000.0	0.0	2463.0	2463.0	2463.0	2009.99	
x(6)	5675.0	3580.0	5201.0	4303.99	4303.99	5394.73	
x(7)	75.0	2.40	26.07	15.21	15.21	28.45	
x(8)	3.45	0.0	2.04	2.19	2.19	2.35	
x(9)	43.0	20.0	20.0	20.0	20.0	20.0	
x(10)	40.0	15.0	23.0	23.0	23.0	23.0	
x(11)	7.36	5.24	6.676	5.53	5.53	6.97	
x(12)	90.0	55.0	67.0	62.21	62.21	67.29	
x(13)	100.0	60.0	95.4	76.22	76.22	97.61	
Objective function (Baht/h)				(17843.14) 17512.37	(30596.32) 27402.46	(11841.64) 11618.73	

Table 7.7 Effect of Condensate Recovery

Value of parameter	CF	CE	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW
	2.62	1.438	11000	43	20	vary	6	79.96	122.9	10

variable	Upper bound	Lower bound	Starting value	Optimum Value CON=30	CON=35*	CON=47.5	CON=58.5	Remark
x(1)	80.0	50.0	73.13	60.24	60.24	60.24	72.60	
x(2)	9000.0	6500.0	8536.0	6500.0	6500.0	6500.0	8449.09	
x(3)	20.0	0.0	14.38	4.36	4.36	4.36	14.23	
x(4)	12000.0	2010.0	2464.0	4500.0	4500.0	4500.0	2550.9	
x(5)	12000.0	0.0	2463.0	2463.0	2463.0	2463.0	2463.0	
x(6)	5675.0	3550.0	5201.0	4303.99	4303.99	4303.99	5164.44	
x(7)	75.0.	2.40	26.07	20.21	15.21	2.71	2.40	
x(8)	3.45	0.0	2.04	2.19	2.19	2.19	2.32	
x(9)	43.0	20.0	20.0	20.0	20.0	20.0	20.0	
x(10)	40.0	15.0	23.0	23.0	23.0	23.0	23.0	
x(11)	7.36	5.24	6.676	5.53	5.53	5.53	6.41	
x(12)	90.0	55.0	67.0	62.21	62.61	62.21	69.04	
x(13)	100.0	60.0	95.4	83.92	76.22	64.05	70.65	
Objective function (Bath/h)				(17843.14) 17562.37	(17843.14) 17512.37	(17843.14) 17387.37	(17843.14) 17623.57	

* Standard Case

Table 7.8 Effect of Sale Price of Steam

Value of Parameter	CF	CF	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW
	2.62	1.438	11000	43	20	35	6	79.96	vary	10

variable	Upper bound	Lower bound	Starting Value	CS=122.9	CS=110	CS=50
x(1)	80.0	50.0	73,13	60.24	60.24	60.24
x(2)	9000.0	6500.0	8536.0	6500.0	6500.0	6500.0
x(3)	20.0	0.0	14.38	4.36	4.36	4.36
x(4)	12000.0	2010.0	2464.0	4500.0	4500.0	4500.00
x(5)	12000.0	0.0	2463.0	2463.0	2463.0	2463.0
x(6)	5675.0	3550.0	5201.0	4303.99	4303.99	4303.99
x(7)	75.0	2.40	26.07	15.21	15.21	15.21
x(8)	3.45	0.0	2.04	2.19	2.19	2.19
x(9)	43	20.0	20.0	20.0	20.0	20.0
x(11)	40.0	15.0	23.0	23.0	23.0	23.0
x(11)	7.36	5.24	6.767	5.53	5.53	5.53
x(12)	50.0	55.0	67.0	62.21	62.21	62.21
x(13)	100.0	60.0	95.4	76.22	76.22	76.22
objective function (Baht/h)				(17843.14) 17512.37	(17920.41) 17588.75	(18280.41) 17948.76

Table 7.9 Effect of Fuel Cost and Purchase Price Electricity (30 % Change in Either One)

Value of Parameter	CF	CF	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW
	vary	vary	11000	43	20	35	6	vary	vary	.10

Variable	Upper bound	Lower bound	Starting Value	Optimum Value		Remark
				CF=3.406 CE=1.438	CF=2.620 CE=1.869	
x(1)	80	50.0	73.13	60.24	75.93	
x(2)	9000.0	6500.0	8536.0	6500.0	8990.0	
x(3)	20.0	0.0	14.38	4.36	16.88	
x(4)	12000.0	2010.0	2464.0	4500.0	2010.0	
x(5)	12000.0	0.0	2463.0	2463.0	2009.99	
x(6)	5675.0	3580.0	5201.0	4303.99	5394.73	
x(7)	75.0	2.40	26.07	15.21	28.45	
x(8)	3.45	0.0	2.04	2.91	2.35	
x(9)	43.0	20.0	20.0	20.0	20.0	
x(10)	40.0	15.0	23.0	23.0	23.0	
x(11)	7.36	5.24	6.676	5.53	6.97	
x(12)	90.0	55.0	67.0	62.21	67.29	
x(13)	100.0	60.0	95.4	76.22	97.61	
objective function (Baht/h)				(22054.90) 20779.0	(18905.12) 18789.49	

Table 7.10 Effect of Fuel Cost and Purchase Price of Electricity

(± 15 % Change in Both)

Value of parameter	CF	CF	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW
	vary	vary	11000	43	20	35	6	vary	vary	10

variable	Upper bound	Lower bound	Starting value	Optimum Value CF=3.010 CE=1.222	Optimum Value CF=2.230 CE=1.654	Remark
x(1)	80.0	50.0	73.13	60.24	75.93	
x(2)	9000.0	6500.0	8536.0	6500.0	8990.0	
x(3)	20.0	0.0	14.38	4.36	16.88	
x(4)	12000.0	2010.0	2464.0	4500.0	2010.0	
x(5)	12000.0	0.0	2463.0	2463.0	2009.99	
x(6)	5675.0	3580.0	5201.0	4303.99	5394.73	
x(7)	75.0	2.40	26.07	15.21	28.45	
x(8)	3.45	0.0	2.04	2.19	2.35	
x(9)	43.0	20.0	20.0	20.0	20.0	
x(10)	40.0	15.0	23.0	23.0	23.0	
x(11)	7.36	5.24	6.676	5.53	6.97	
x(12)	90.0	55.0	57.0	62.21	67.29	
x(13)	100.0	60.0	95.4	76.22	97.61	
objective function (Baht/h)				(19400.72) 18161.15	(16285.55) 16162.01	

Table 7.11 Effect of Sale Quantity of Steam

Value of Parameter	CF	CE	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW
	2.620	1.438	11000	vary	20	35	vary	79.96	122.9	10

Variable	Upper bound	Lower bound	Starting Value	Optimum Value			Remark
				FS=3	FS=6	FS=10	
x(1)	80.0	50.0	73.13	59.19	60.24	61.64	
x(2)	9000.0	6500.0	8536.0	6500.0	6500.0	6500.0	
x(3)	20.0	0.0	14.38	6.31	4.36	1.77	
x(4)	12000.0	2010.0	2464.0	4500.0	4500.0	4500.0	
x(5)	12000.0	0.0	2463.0	2463.0	2463.0	2463.0	
x(6)	5675.0	3580.0	5201.0	4230.35	4303.99	4402.1	
x(7)	75.0	2.40	26.07	14.11	15.21	16.67	
x(8)	3.45	0.0	2.04	1.97	2.19	2.49	
x(9)	47.0	20.0	20.0	17.0	20.0	24.0	
x(10)	40.0	15.0	23.0	23.0	23.0	23.0	
x(11)	7.36	5.24	6.676	5.53	5.53	5.66	
x(12)	90.0	55.0	67.0	61.43	62.21	63.21	
x(13)	100.0	60.0	95.4	74.10	76.22	79.04	
objective function (Baht/h)				(18211.78) 17831.92	(17843.14) 17512.37	(17351.63) 17084.90	

Table 7.12 Comparison for Cost of Utility per Unit Energy Produced

Parameter				PHI	Energy	Cost
FS	PTOTAL	P17Kmin	P3X	(Bath/h)	KW	Baht/KW
3	40	17	23	17831.92	19171.36	0.930
6	43	20	23	17512.37	19938.22	0.878
10	47	24	23	17084,9	20960.7	0.815

Table 7.13 Effect of Higher Process Requirements

Value of Parameter	CF	CE	AB	PTOTAL	P17Kmin	CON	FS	CB	CS	CW
	2.620	1.438	12000	60.2	28	35	6	79.96	122.9	10

variable	Upper bound	Lower bound	Starting Value	Optimum Value AB=12000	Remark
x(1)	80.0	50.0	73.13	74.99	
x(2)	9000.0	6500.0	8536.0	8060.89	
x(3)	20.0	0.0	14.38	0.0	
x(4)	12000.0	2010.0	2464.0	3939.1	
x(5)	12000.0	0.0	2463.0	2463.0	
x(6)	5675.0	3580.0	5201.0	5330.0	
x(7)	75.0	2.40	26.07	28.72	
x(8)	3.45	0.0	2.04	3.406	
x(9)	60.2	20.0	20.0	33.69	
x(10)	40.0	15.0	23.0	26.51	
x(11)	7.36	5.24	6.676	6.88	
x(12)	90.0	55.0	67.0	68.30	
x(13)	100.0	60.0	95.4	99.75	
objective function (Baht/h)				(17843.14) 19180.10	

Table 7.14 Adjustment of the Standard Case (For Comparison)

Parameter	Old Value	New Value	Increment	Cost per unit	Cost (Baht/h)
P17Kmin	20	28	+8	122.9	983.2
P3K	23	32.2	+9.2.	79.96	735.63
AB	11000	12000	+1000	1.438	1438.0
			Total Cost Increased		3156.83
			Old Cost Value		17512.37
			Adjusted Cost Value		20669.2

Table 7.15 Comparative Energy Costs When Process Requirement Became Higher

Case	PTOTAL	P17Kmin	P3K	PHI (Baht/h)	Exergy KW	Cost Baht/KW
Adjusted Standard Case	60.2	28	32.2	20669.2	24513.51	0.843
Case 8	60.2	33.69	26.51	19180.1	25021.5	0.766

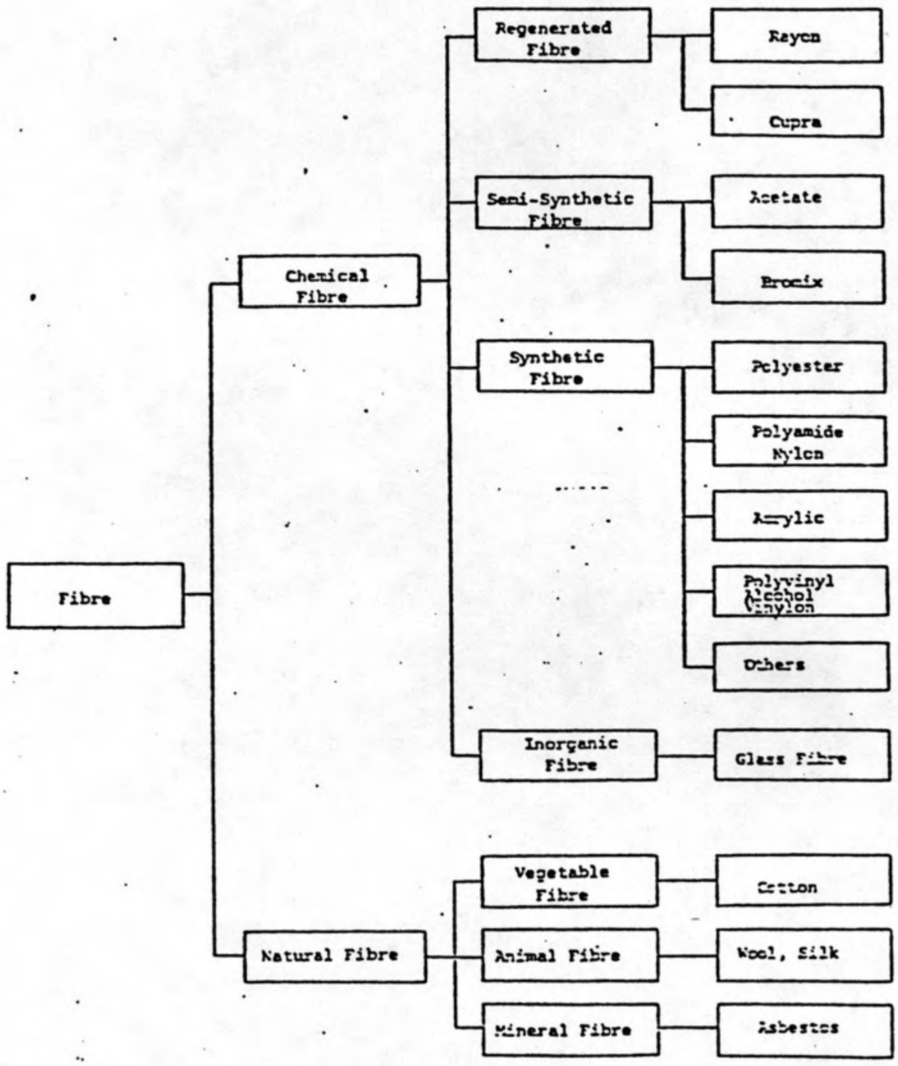

Fig 7.1 Classification of Fibre

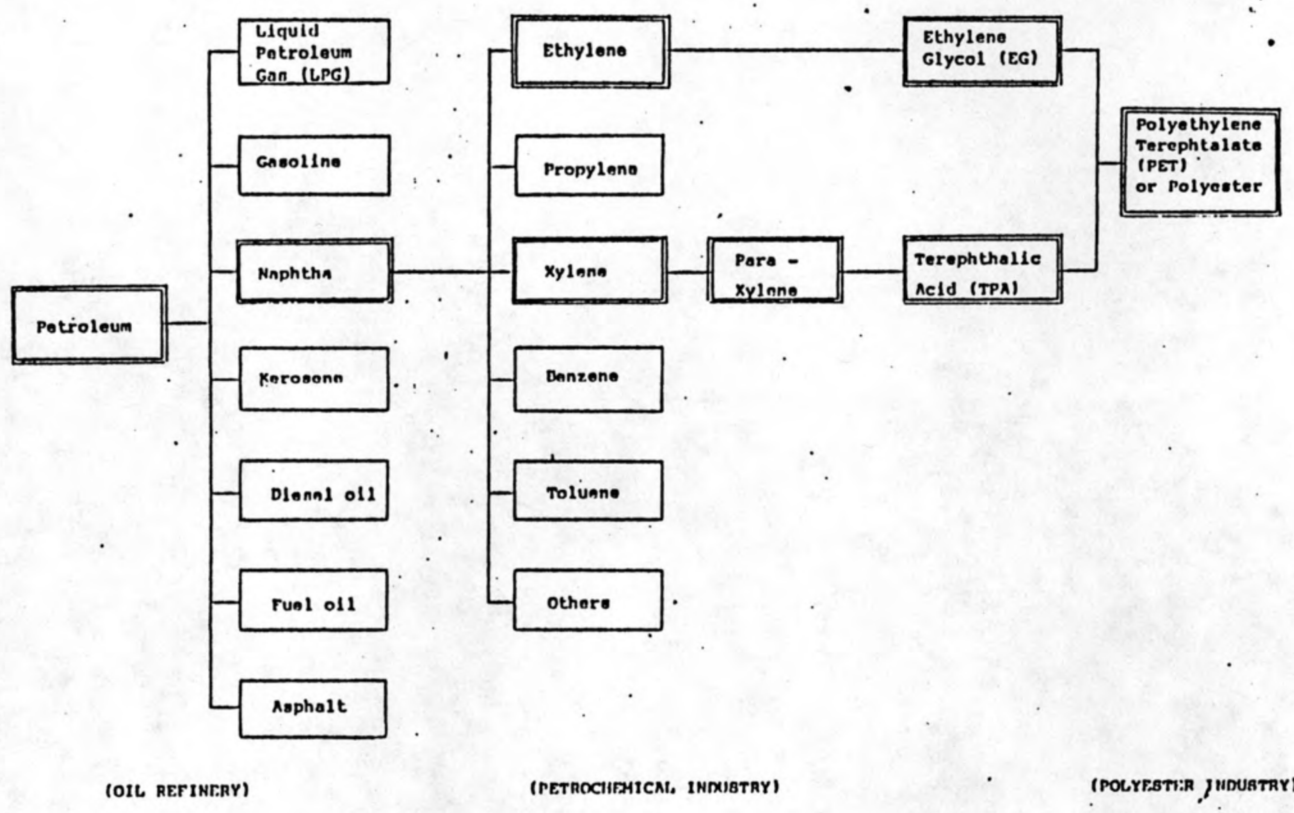

Fig 7.2 Flow chart of the raw material of Polyester

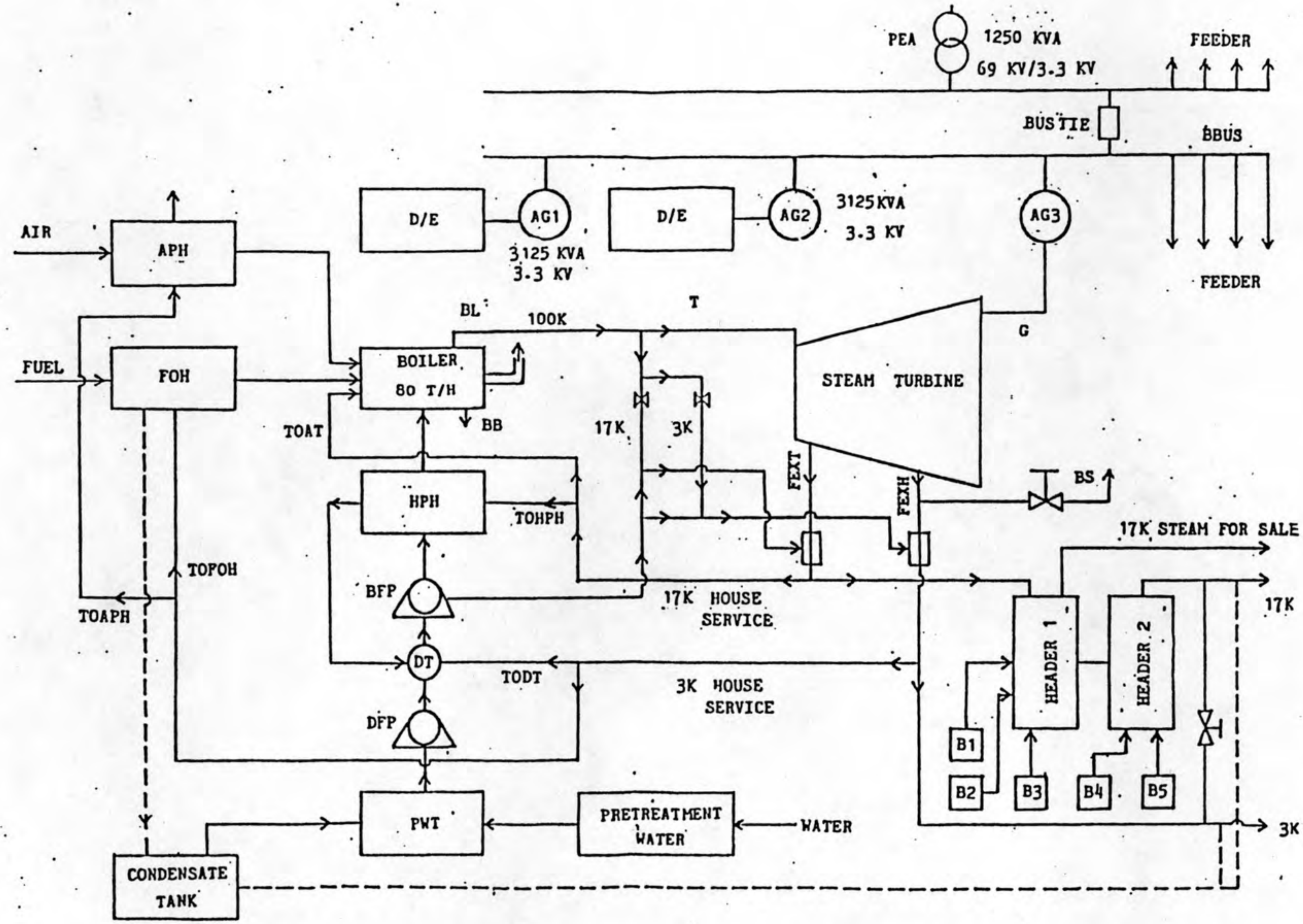

Fig 7.3 Block Flow Diagram of Steam Power System

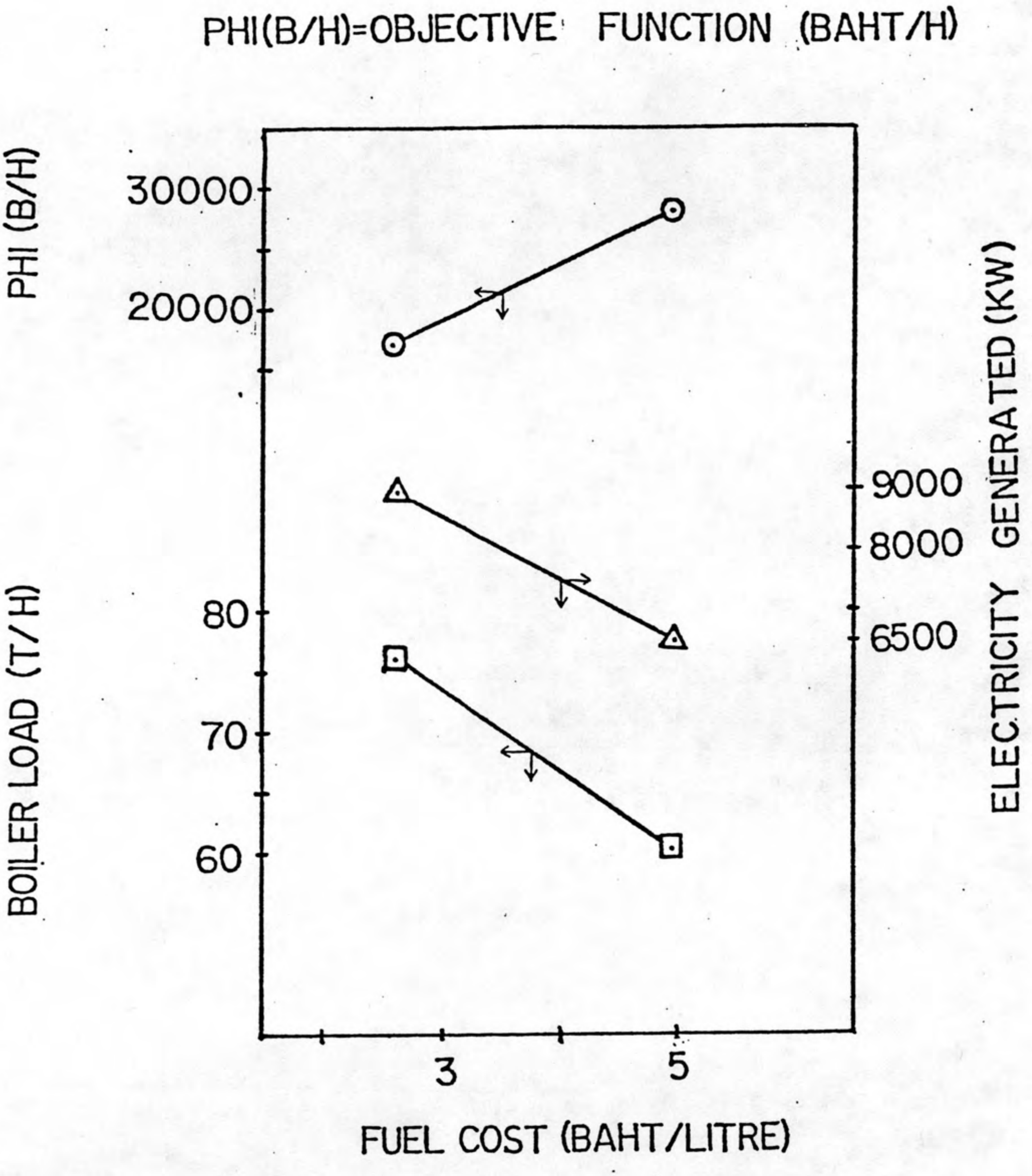

Fig 7.4 Effect of Fuel Cost

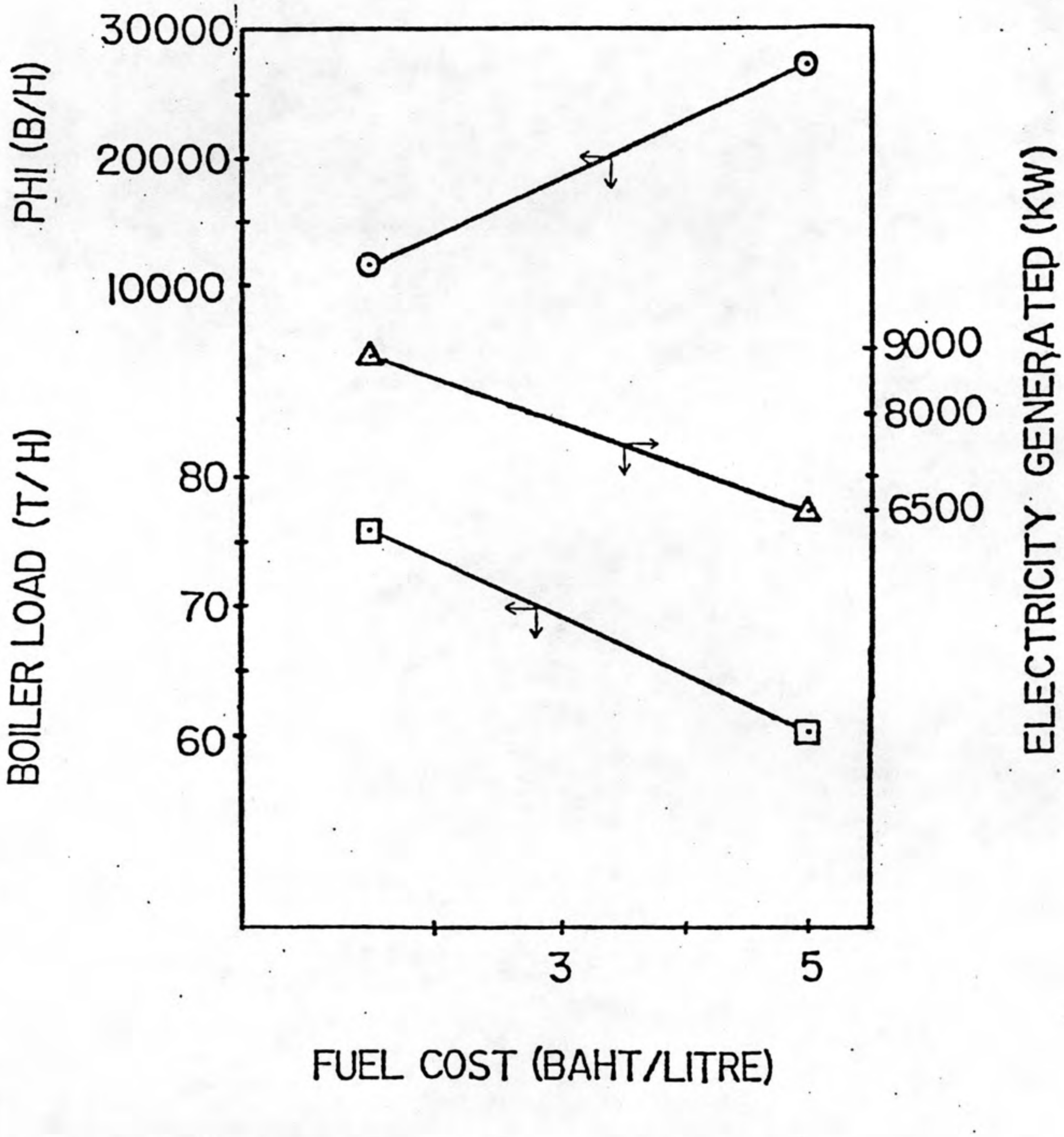

Fig 7.5. Effect of Fuel Cost with Consideration for the costs of blow steam and of make-up water

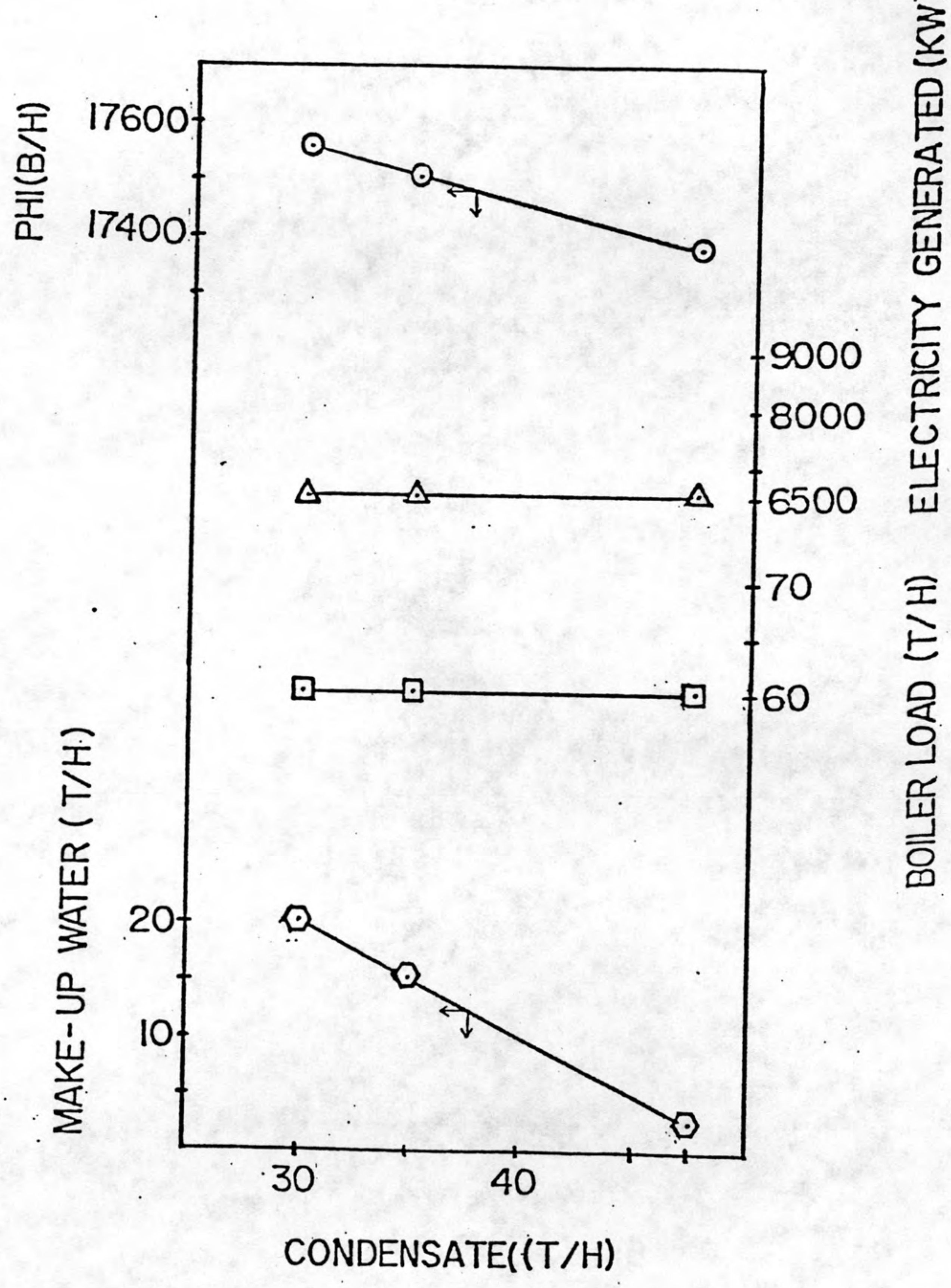

Fig 7.6 Effect of Recovery Condensate

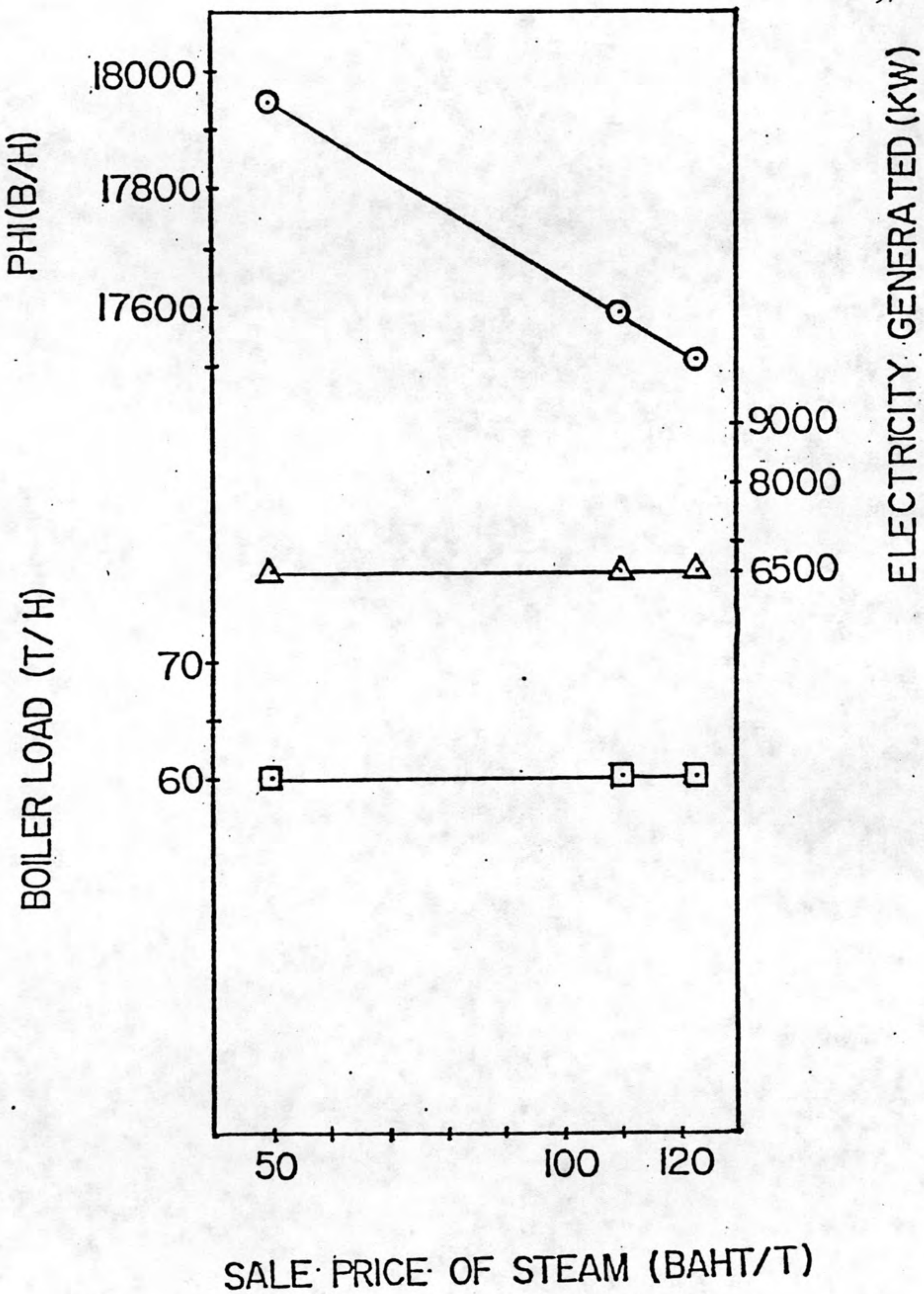

Fig 7.7 Effect of Sale Price of Steam

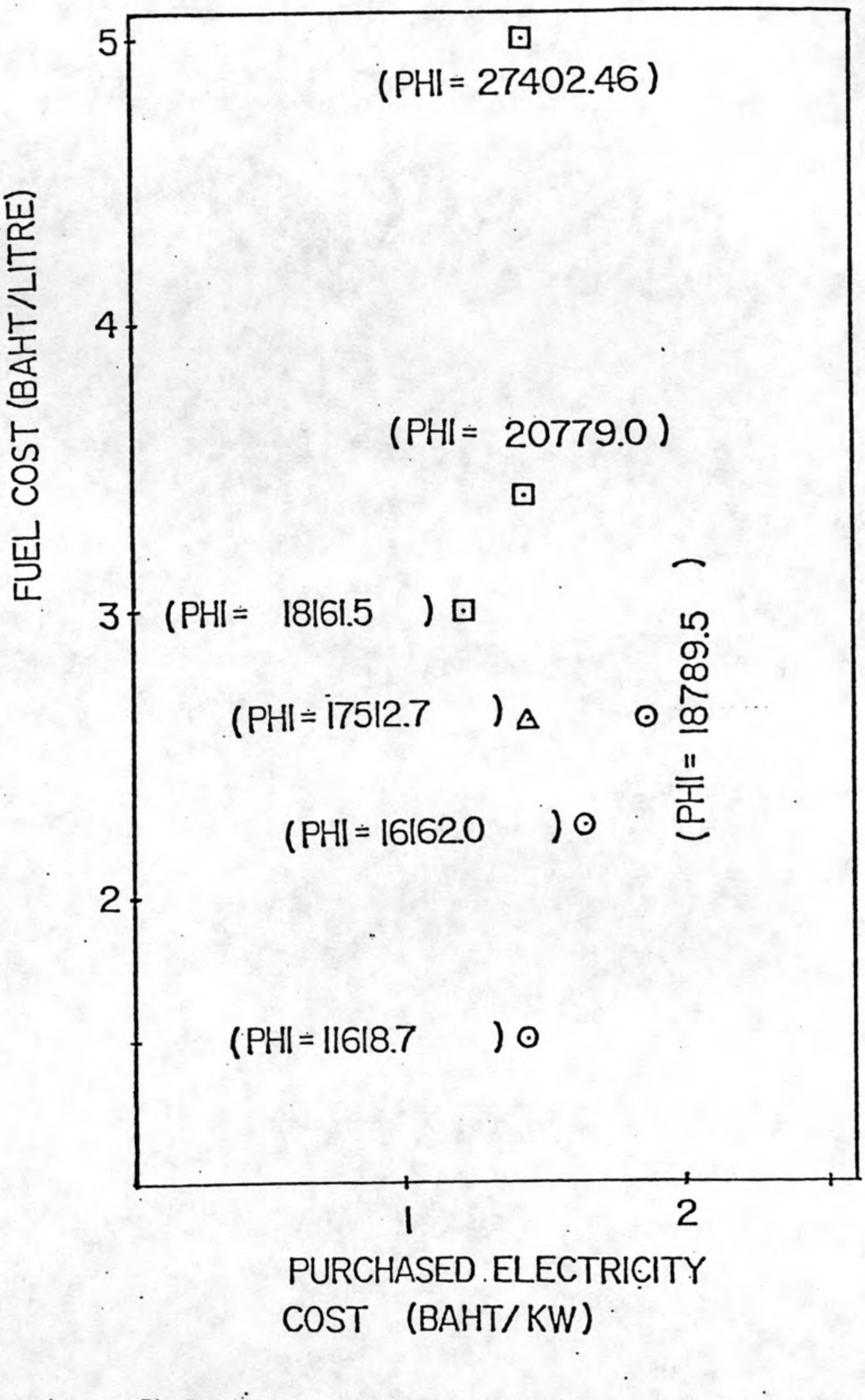

Fig 7.8 Effect of Fuel Cost and Purchase Price of Electricity

(△) Boiler load 60.23 T/h, Generated Electricity 6500 KW (Standard Case)

(○) Boiler load 75.93 T/h, Generated Electricity 8990 KW

(□) Boiler load 60.23 T/h, Generated Electricity 6500 KW

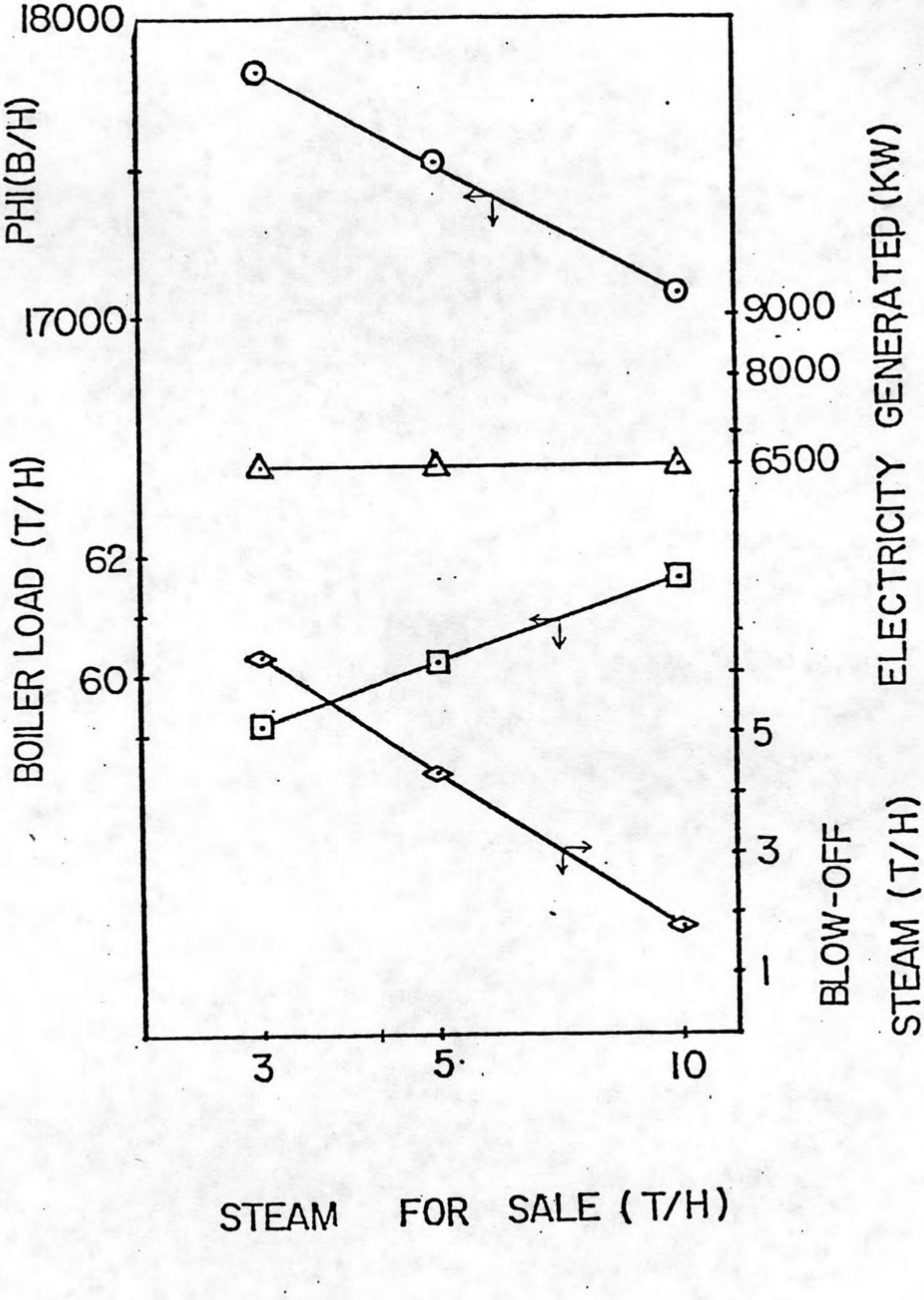

Fig 7.9 Effect of Sale Quantity of Steam

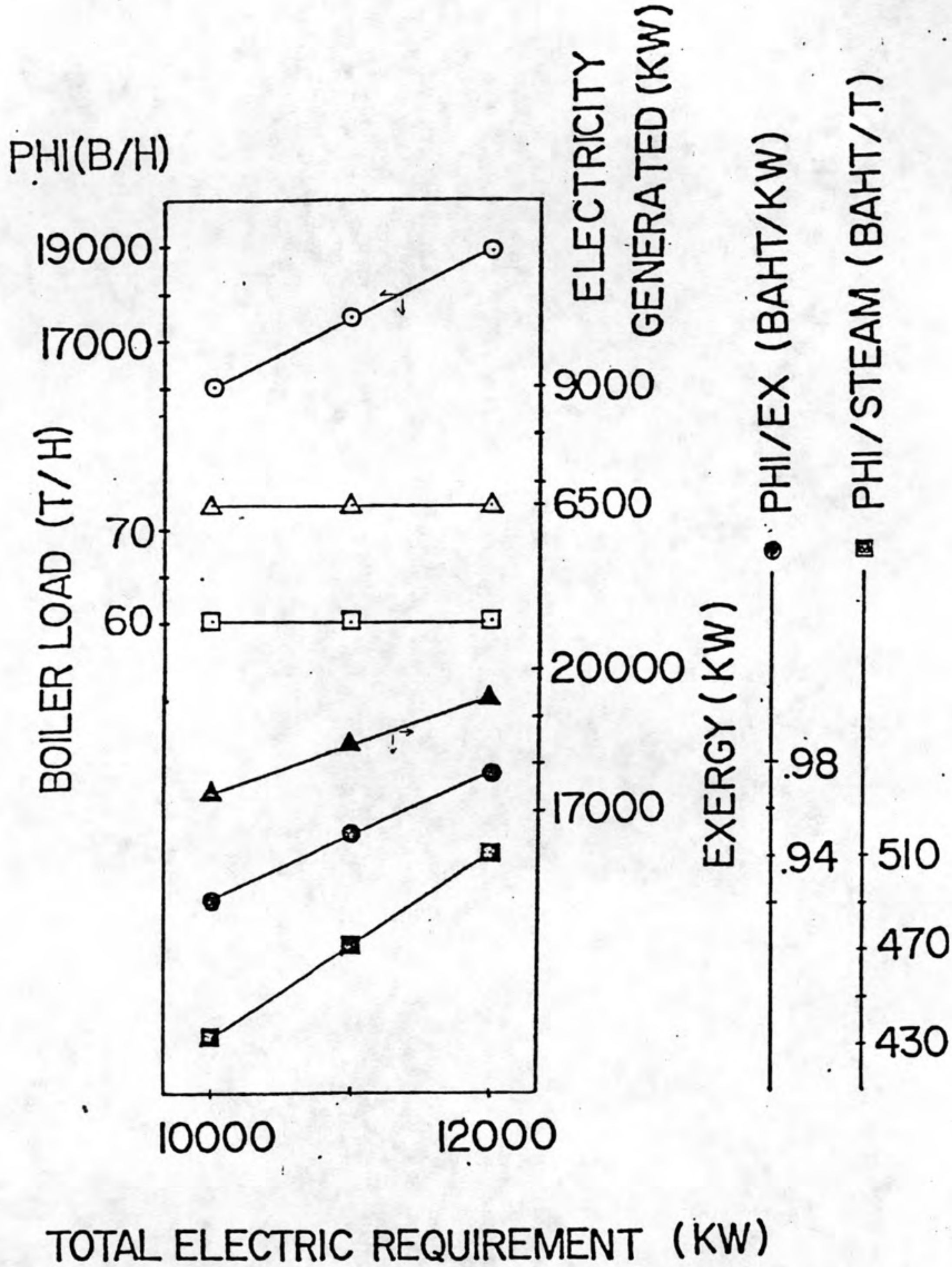

Fig 7.10 Effect of Higher Energy Requirement by Process

(when PTOTAL = 43 T/H)

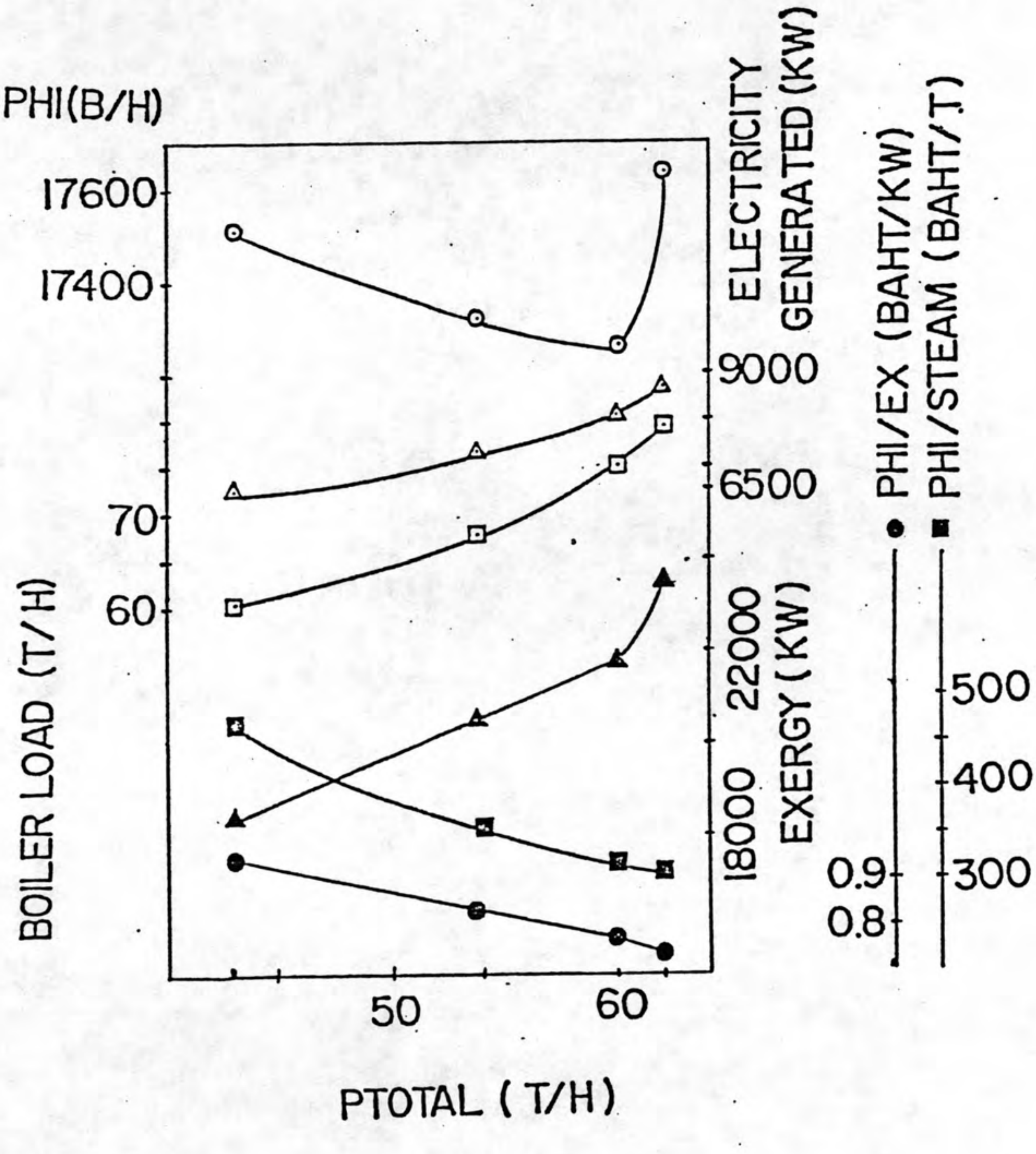

Fig 7.11 Effect of Higher Energy Requirement by Process

(when AB = 11000 KW)

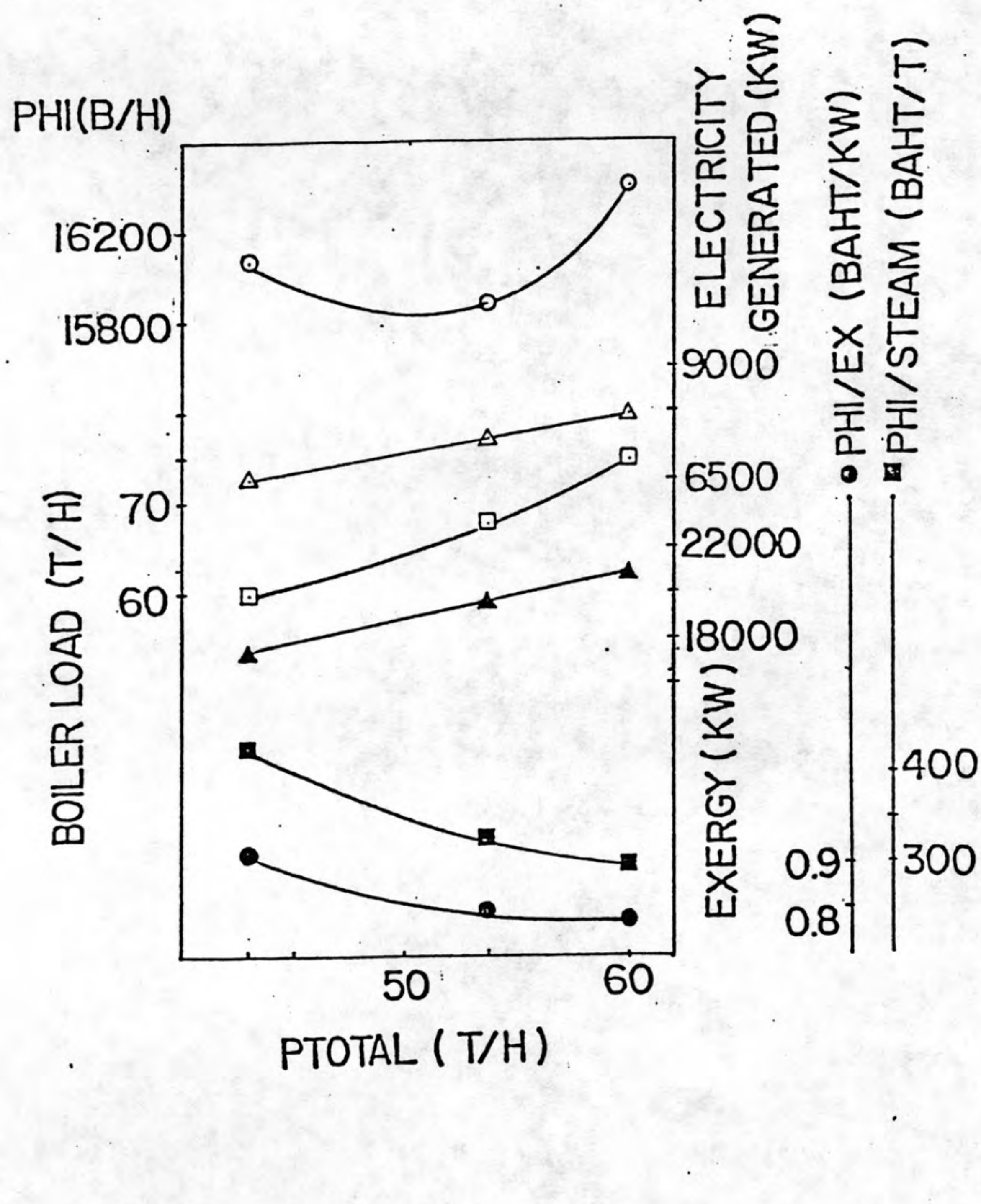

Fig 7.12 Effect of Higher Energy Requirement by Process

(when AB = 10000 KW)