



**DEPARTMENT OF CHEMICAL ENGINEERING**  
**UNIVERSITY OF CAPE TOWN**

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**ENERGY RETROFIT OF AN OIL REFINERY**  
**USING PINCH TECHNOLOGY**

by

Noel Gillespie

October 1989

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ENERGY RETROFIT OF AN OIL REFINERY

USING PINCH TECHNOLOGY

A thesis presented to the

UNIVERSITY OF CAPE TOWN

in fulfilment of the requirements for the degree of

MASTER OF SCIENCE

by

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October 1989

## ACKNOWLEDGEMENTS

I would like to thank the following people for their assistance throughout my project:

Mr K. Witts

Mr R. Eastes

Mr P. Fairlamb

Mr E. Randall

all Postgraduates in the Department of Chemical Engineering at UCT

A special word of thanks to my project supervisor, Dr. D.M. Fraser who was always willing to give assistance whenever asked and for his invaluable input to make the project a success.

## SYNOPSIS

The project completed for this thesis concerns energy conservation on an existing chemical plant. To identify badly placed exchangers in an existing heat exchanger network, pinch technology and tools were used. The development of a network is based upon a technique known as pinch technology. Pinch technology, in turn, is based upon a thermodynamic analysis of a process. At present, procedures begin by assuming a minimum approach temperature. In a retrofit, the optimum design is complicated by the availability of existing equipment.

A tool used to identify badly placed exchangers, is a relatively new concept known as Remaining Problem Analysis. This technique compares the placement of an actual exchanger to an ideal exchanger in that an area and energy efficiency is calculated. These efficiencies are based on the area and energy targets before and after a match has been placed.

A computer package (UCTNET) was written to perform both targeting calculations (using pinch technology) as well as network design. The network design section allows the user to perform a grass-roots design or a retrofit. In both cases, the user is guided by Remaining Problem Analysis.

In all, seven different plants were analysed. With the exception of plants 1 and 7 which are unpinched, the remaining plants all transfer energy across the pinch.

For all the plants, an optimum approach temperature was calculated using a costing analysis. Once the optimum  $\Delta T_{\min}$  had been set, the energy savings on each plant were calculated. In several plants, inter-unit streams were present (inter-unit streams transfer energy from one plant to another). For each plant, two sets of energy savings were calculated - these being:

- a) The savings after all inter-unit streams had been integrated.
- b) The savings before inter-unit streams had been considered.

These savings were calculated by subtracting the target utility requirement from the actual utility usage (the total utility corresponding to the hot and cold utility requirements). The savings associated with (b) represented the best that could be achieved if all plants could operate independently of each other. The value calculated in (a) represented the savings which could be achieved from present plant operation. By subtracting the two values, the integration already achieved was calculated. This represented the savings already achieved before this project was started with the savings calculated in (a) being those to aim for in this work.

The financial savings were arrived at by costing the above energy savings. In the case of hot utility, the financial savings were mostly calculated using fuel oil costs (since furnaces are the major source of heating) while the financial savings associated with the cold utility were mostly calculated using the costs to run fin fan motors (since fin fans are the major source of cooling). The financial savings provided the incentive to consider different modifications.

Once the potential savings for the individual plants had been calculated, it was decided to combine several plants into a single plant. Two such plants were considered on the basis that the individual plants combined already showed a large degree of integration and that they were located near to each other. The energy and financial savings were calculated in the same way as for the individual plants. When the savings for the combined plants were compared to the sum of the individual plant savings, it was found that the potential to save energy from the present position was approximately twice that considered for the individual plants.

The potential to raise steam before and after inter-unit stream integration was also calculated for each plant. With the exception of two plants, steam could be raised at different levels than those currently employed.

Once the potential savings had been calculated, modifications to each plant were considered. Since it would be very difficult to present all the modifications considered without a detailed discussion of each, only those modifications leading to energy savings will be presented below.

On plant 1 it was decided to change column pump-around target temperatures so that additional energy could be exchanged when these streams were matched against cold streams. This modification, together with a slightly revised order of stream matches (several hot streams were matched in series against a cold stream), would result in an energy saving of approximately \$72 700 per annum. The capital costs would be due to additional pipework and controllers.

On plant 2, the only unmatched hot streams were overhead streams. Due to physical constraints imposed on matches with these streams, no energy savings could be achieved. This was confirmed by removing the overhead streams from the stream data and re-calculating the energy targets. The potential to save hot utility was reduced to zero.

A modification involving the introduction of a feed stream to plant 1 (from plant 2) at a higher temperature was also investigated. By re-arranging the matches, it was hoped that better use of the available driving forces and area would be achieved. However, due to fixed duties in several pump-around streams, only one stream was able to exchange more heat than at present. The energy savings were calculated to be approximately \$63 000 per annum. The capital expenditure would be due to additional pipework and controllers.

No modifications on plant 3 were found to be feasible since a large amount of integration with a utility stream has already been achieved (if any changes to the process result in a reduced integration with this stream, then additional hot utility will be required elsewhere).

On plant 4 several modifications were considered - these being:

- 1) Installing additional area to reduce the duty in a furnace. The energy savings would be approximately \$172 000 per annum while the installed exchanger would cost approximately \$135 000.
- 2) A feed stream from plant 5 could be introduced at a higher temperature. This stream could then be mixed with a cold recycle stream. If the mixing point was changed, an energy saving of approximately \$30 000 per annum could be achieved. However, the drawback regarding this modification would be an increased fin fan duty of approximately 1500 kW. At present, the fin fan operation is marginal in summer and it was anticipated that problems may occur during these months.
- 3) A hot liquid stream could be matched against a cold liquid reboiler stream. This hot stream would replace the steam presently used in the reboiler. The energy savings would be approximately \$11 000 per annum.

On plant 5 additional area could be installed to reduce the furnace duty. An energy saving of approximately \$135 000 per annum could be achieved while the capital investment would be approximately \$200 000.

No modifications on plant 6 were found to be feasible.

On plant 7, the installation of additional area would reduce the energy transferred across the pinch. The energy saving would be approximately \$23 700 per annum while the cost of an installed, high pressure exchanger would be approximately \$132 000.

On combined plant B, 80% of the steam consumption in a reboiler may be eliminated by using a hot stream presently cooled in a fin fan. This would result in a financial saving of approximately \$62 400 per annum. The cost of installing an additional exchanger would be approximately \$75 000.

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**NOTATION**

$A$	heat transfer area ( $m^2$ )
$A_{\text{match}}$	area of heat exchanger required for a match ( $m^2$ )
$A_{\text{min}}$	minimum exchange target area ( $m^2$ )
$(A_{\text{min}})_{\text{original}}$	target area before stream modifications ( $m^2$ )
$(A_{\text{min}})_{\text{remaining}}$	target area after stream data modified ( $m^2$ )
$FCp$	heat capacity flowrate ( $W/K$ )
$h_i$	stream heat transfer coefficient ( $W/m^2.K$ )
$N_i$	number of hot or cold streams in an interval
$T_{ci}$	cold stream temperature (K)
$T_{hi}$	hot stream temperature (K)
$q_i$	duty associated with stream $i$ (W)
$Q$	duty associated with a heat exchanger (W)
$Q_{c_{\text{min}}}$	minimum cold utility requirement (W)
$Q_{h_{\text{min}}}$	minimum hot utility requirement (W)
$U$	overall heat transfer coefficient ( $W/m^2.K$ )
$\alpha$	area efficiency
$\Delta T_c$	approach temperature at cold end of a heat exchanger (K)
$\Delta T_i$	temperature difference, $ T_{hi} - T_{ci} $ (K)
$\Delta T_h$	approach temperature at hot end of a heat exchanger (K)
$\Delta T_{\text{lm}}$	log-mean temperature difference (K)
$\Delta T_{\text{min}}$	minimum approach temperature (K)

## 1 INTRODUCTION

On a chemical plant there are many process streams requiring heating and cooling. The hot and cold streams are matched using heat exchangers in order to recover as much process heat as is economically justified before external utility is used. This is achieved with a heat exchanger network (HEN). Since there are often many different ways of matching process streams, the objective in designing a network is to identify the cheapest design with respect to annualised costs expressed in terms of energy and capital, while ensuring plant operability and safety. When modifications are made to the initial network, a retrofit will have been performed. The project undertaken was to analyse a proposed retrofit to save energy on a local refinery.

A great deal of research has been directed towards the development of procedures for the design of efficient networks after the fuel crisis of 1973. Since the pioneering work of Hohmann (1971) and Linnhoff (1979), there has also been an increasing output of work in this area. The most recent summary of literature on the subject was by Gundersen and Naess (1987). The development of heat exchanger network synthesis (HENS) has been based upon the development of a technique known as pinch technology. Pinch technology, in turn, is based upon thermodynamic analysis of processes. It has resulted in improved design methodology as well as the ability to determine, prior to design, the energy requirement of the process, the capital cost associated with its heat recovery network and the optimum trade-off between these two.

At present, procedures begin by assuming a minimum approach temperature between streams, called  $\Delta T_{\min}$ . This value is obtained from previous experience of having performed network designs. Networks initially designed are evolved to optimise the energy against capital. This is complex, usually requiring several design evolutions and often adjusting the minimum approach temperature. Thus one of the most basic features of HEN design is to determine the energy-capital relationship. As the minimum approach temperature is increased, so the demand for external utilities increases, but the requirement for heat exchange area

decreases initially. At some stage, temperature driving forces can increase more slowly than the corresponding increase in heat exchanged (Ahmad, 1985). Thus at large values of the minimum approach temperature, the overall requirement for heat exchange area can increase. The tradeoff between energy and capital, however, implies that total annual network cost is minimised at some intermediate value of  $\Delta T_{\min}$ .

When establishing capital costs, the sizing of heat exchangers is first required. To have confidence in these cost predictions, the effect of the number of shells and the type of materials of construction should be included. Several such procedures exist to evaluate the overall heat exchange area target for a particular problem. These will be presented in Section 2.6 in Chapter 2.

Pinch technology has also been applied in retrofitting. The first retrofit study was performed by Linnhoff and Turner (1981). Subsequent work reported energy savings of 20-70% in retrofit applications which is significantly larger than the 10-15% possible through good housekeeping and the 5-8% possible through operations improvement (Boland, 1983, Linnhoff and Vredevelde, 1984, Boland and Hindmarsh, 1985 and Tjoe and Linnhoff, 1986). These figures are for modern chemical plants 10-20 years old, already incorporating a fair degree of energy recovery. The major study on energy retrofit has been the work of Tjoe (1985). The energy savings realised are a combination of increased energy recovery by better placement of heat exchangers, as well as additional savings due to process modifications.

In retrofit, the optimum design is complicated by the existence of existing equipment. At the outset, the designer has the knowledge of the existing plant and how it performs. He or she has a limited amount of capital investment which must yield an appropriate return. Thus application requires much improvisation. Anticipated constraints encountered with retrofitting projects would lie in the fact that exchanger costs, at present, have a more dominant influence on the overall annualised cost than do the relatively low-priced energy costs.

The tools which are available for energy retrofit studies are the fundamental energy analysis of a plant, together with network design techniques. The most appropriate network design techniques for these applications appear to be Remaining Problem Analysis (Ahmad, 1985) and RESHEX (a computer analysis and design program by Saboo, Morari and Colberg, 1986)

### 1.1 Aim of the Project

The aim of the project was to identify ways to save energy on an existing chemical plant, this plant being a local refinery, by performing a retrofit study. The refinery is divided into a number of smaller plants which will be termed units.

### 1.2 Scope of the Project

The project was divided into two sections, namely:

- 1) Establishing targets for the different units. The purpose of performing these analyses was to establish the potential energy savings and hence the potential financial savings (by costing the energy difference between the actual and target utility requirements). Also included in this section was an analysis to determine the potential to raise steam below the pinch.

The energy and financial savings were calculated for each individual unit as well as for combined units. Several units were combined into a single unit since inter-unit integration existed amongst the individual units. The inter-unit integration was in the form of hot and/or cold streams originating in one unit but affecting the heating and/or cooling requirement(s) in a different unit.

- 2) A retrofit study on each unit. Included in this analysis were the following:
  - a) Location of actual exchangers on a Driving Force Plot.

- b) Identification of cross-pinch exchangers.
- c) Process modifications.
- d) Plant modifications.

In this section, badly placed exchangers (as indicated on the Driving Force Plot) as well as cross-pinch exchangers were identified. Process modifications included pressure changes to columns and changed pump-around flowrates. Plant modifications included rerouting streams, changing stream mixing points and matching previously unmatched streams. The above analyses were performed for the combined units as well.

### 1.3 Layout of the Thesis

The thesis has been divided into seven chapters. The contents of each chapter may be summarised as follows:

- 1) Chapter 1 contains the introduction.
- 2) Chapter 2 contains a discussion of pinch technology theory as well as applications based on this technology. These techniques include an Energy-Area analysis, the possibility of raising steam below the pinch and moving columns relative to the pinch. A discussion of a grass-roots network design and retrofit is also included. All relevant work published in the literature is also included in the appropriate sections.
- 3) Chapter 3 contains a discussion on Remaining Problem Analysis pertaining to a grass-roots network design as well as a retrofit example.
- 4) Chapter 4 contains a discussion of the HENS package developed to implement the pinch technology theory and network design. This chapter will present a discussion of the software language chosen, the merits and demerits of this language and features of the package written.

- 5) Chapter 5 contains the actual pinch analyses of the plants investigated. These analyses include the location of the pinch temperature, the target hot and cold utility requirements, the actual hot and cold utility requirements, the associated costs of the target and actual utility requirements, an energy-area investigation and possible steam generation below the pinch. The calculation of the actual and target energy costs are used to establish the potential financial savings on each plant.
- 6) Chapter 6 contains a brief discussion of physical and financial constraints which must be considered when investigating modifications to the units. This is followed by a summary of all modifications considered on each individual and combined unit to save energy. The detailed discussion of these modifications are presented in an appendix. All modifications discussed have been analysed in terms of a financial energy saving and a capital cost. Where possible, a payback period has also been calculated. Also included in the chapter is a discussion on how and where steam may be generated in the individual units.
- 7) Chapter 7 contains all conclusions drawn and recommendations suggested from work performed for this project.

## 2 ANALYSIS OF HEAT EXCHANGER NETWORKS

### 2 Pinch Technology

#### 2.1 Minimum Approach Temperature

The minimum temperature difference allowed between the two streams in a heat exchanger, known as the minimum approach temperature,  $\Delta T_{\min}$ , is a basic parameter in the design of heat exchanger networks. For any particular problem, this is generally assigned a global value which has been found to be best in practice. This initial value is then optimised to give the lowest overall cost for the network, where the overall cost is the sum of the annual capital cost and the annual operating costs.

It is relatively straight forward to incorporate stream-dependent  $\Delta T_{\min}$  values in the formulation of the problem, in which case the minimum approach temperature allowed for any match will depend on the streams being matched (For purposes of this project, a global  $\Delta T_{\min}$  was used).

#### 2.2 Calculation of the Pinch Temperature and Targets

All hot and cold streams in a process can be presented on a temperature-enthalpy content graph once their supply and target temperatures and their flowrates and physical properties have been established (the term "enthalpy" used in this thesis generally refers to the enthalpy of a stream expressed as enthalpy/time). A hot stream is one requiring cooling whereas a cold stream is one requiring heating.

Using the individual streams, it is possible to construct one composite curve of all the hot streams in the process and another of all the cold streams, by simple addition of heat contents over the temperature ranges in the problem. This is illustrated in Figure 2.1. This method will be described in Section 2.3.

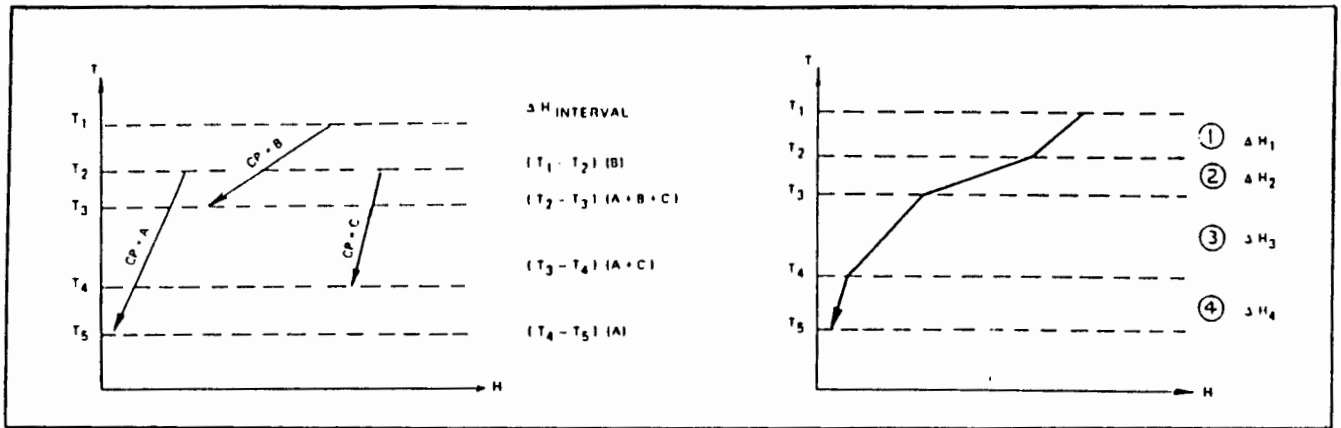


Figure 2.1 Construction of a Composite Curve by Addition of Stream Heat Contents

By plotting the hot and cold composite curves (as shown in Figure 2.2), the overlap between the composite curves represents the maximum amount of heat recovery possible within the process. The "over-shoot" of the hot composite represents the minimum amount of external cooling ( $Q_{c_{min}}$ ) and the "over-shoot" of the cold composite represents the minimum amount of external heating ( $Q_{h_{min}}$ ). Due to the shape of the curves, they approach most closely at one point, known as the pinch (Linnhoff et al, 1979). This point of minimum approach is equal to  $\Delta T_{min}$ .

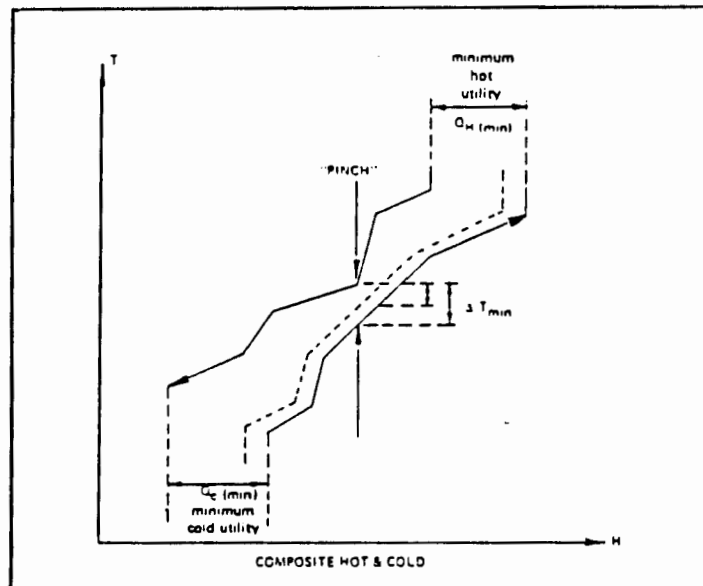


Figure 2.2 Hot and Cold Composite Curves

Thus the system may be separated at the pinch into two separate problems. Above the pinch, the hot composite gives all its heat to the cold composite with only residual heating required. The problem is therefore a heat sink. Conversely, below the pinch the system is a heat source.

If the cold composite is moved relative to the hot composite so that the minimum approach temperature,  $\Delta T_{\min}$ , increases, the overall effect is to increase the utility heating and cooling by equal amounts.

### 2.3 "Problem Table" Procedure to Determine Targets

The problem table formulation (as proposed by Linnhoff and Vredeveld, 1984), is based on the temperature interval method devised by Linnhoff and Flower (1978). The use of the problem table method to establish the pinch temperature and target utilities may be described as follows:

A series of temperature intervals is set up using stream supply and target temperatures. The heat available in each interval is given by the product of the absolute difference between the two boundary temperatures and the sum of the heat capacity flowrates (product of the stream heat capacity and the stream flowrate) of all streams present in that interval. Both hot and cold streams are included in the interval with the hot streams having a positive heat capacity flowrate contribution and the cold streams having a negative heat capacity flowrate contribution.

The only requirement in each interval is that the hot and cold streams are at least  $\Delta T_{\min}$  apart. This is ensured by decreasing all hot stream supply and target temperatures by  $\Delta T_{\min}/2$  and increasing all cold supply and target temperatures by the same amount. These adjusted values then form the boundaries for the temperature intervals. Each interval will either have a net deficit or net surplus of heat as dictated by the energy balance (or be in balance).

If one makes use of the fact that any heat surplus in a temperature interval is hot enough to supply any heat deficit in a lower temperature interval, then one can sum the heat availability for successive intervals by moving down the table. In this way, energy is "cascaded" down through successive intervals. The energy is transferred between intervals at the lower boundary temperature. Any overall heat deficit is thermodynamically infeasible since it represents a transfer of energy from a cold temperature interval to a higher temperature interval. This infeasibility is removed by adding the largest negative value to each interval. In this way, the interval originally having the largest negative value, will now have a zero duty associated with it. The temperature corresponding to this zero duty will be the bottom temperature of that interval.

This region is a bottleneck to heat recovery and corresponds to the pinch of the composite curves. The temperature at which this occurs is the pinch temperature for the system. The duty added to the hottest temperature interval (correcting for the largest negative value) will have to be supplied by hot utility and thus forms the hot utility requirement  $Q_{h_{min}}$ . The flow of energy from the lowest temperature interval represents the cold utility requirement  $Q_{c_{min}}$ . Thus using the problem table, the pinch temperature and utility targets have been established.

Not all heat exchanger network problems are pinched. Certain problems remain free of a pinch until the minimum allowed driving force,  $\Delta T_{min}$  is increased up to or beyond a threshold value,  $\Delta T_{thresh}$ . Such problems are known as threshold problems (Linnhoff and Hindmarsh, 1983).

## 2.4 Utility Pinches

It is not always necessary to supply hot utility at temperatures greater than the highest temperature in the process. Often it is profitable to make use of more economical heat sources such as low pressure steam instead of high pressure steam. Heat can be introduced at lower temperature levels above the pinch as long as the heat flow

between temperature intervals remains positive. By maximising the use of more moderate levels of hot utility, the heat flow between temperature intervals above and/or below the pinch may be reduced to zero so introducing additional pinches. These are known as utility pinches (Linnhoff and Hindmarsh, 1983).

Below the pinch, different levels of cold utility may be introduced. These levels may be due to cooling water or a refrigerant. The colder the utility used, the more expensive it becomes.

## 2.5 Grand Composite Curve

The grand composite curve is constructed using data from the energy cascade table. The heat flows from the cascade are plotted against their respective interval boundary temperatures. The result is a graph which characterises the regions above and below the pinch in temperature-enthalpy terms. This is illustrated in Figure 2.3. The point at which the duty is zero represents the pinch. In Figure 2.3, the shaded regions represent process to process heat exchange; i.e. the regions are in energy balance.

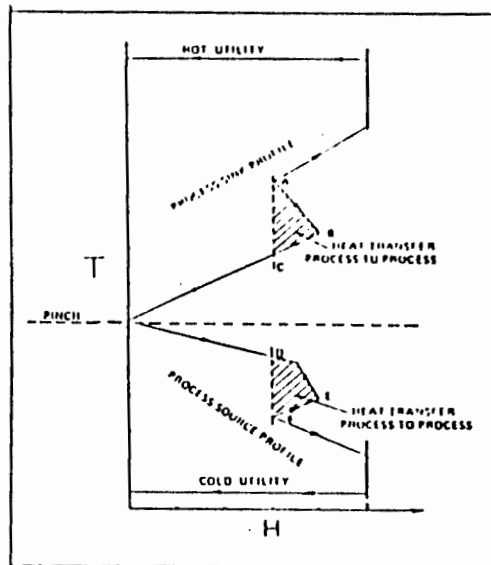


Figure 2.3 Grand Composite Curve

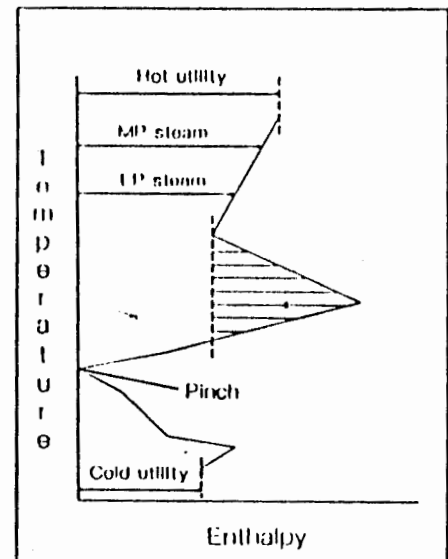


Figure 2.4 Utility Placement on the Grand Composite Curve

To maximise the use of the least expensive utilities, one uses the coldest hot utility and the hottest cold utility. Above the pinch, this would result in different levels of steam as indicated in Figure 2.4. It must be noted that one must not extend any horizontal line into the shaded regions since this region does not require any hot utility. If the pinch temperature is high enough, then one can raise different levels of steam below the pinch depending on the supply temperature of the boiler feed water and the shape of the steam-raising pre-heat/evaporation curve. This curve is moved until it just touches the source profile at some point. This will result in the largest generation of steam at that level (Linnhoff, 1982). Such a curve is shown below the pinch in Figure 2.4. The rest of the cold utility must be supplied at a lower temperature, this usually being cooling water.

## 2.6 Area Targets

The minimum area for a problem is obtained using the composite curves. The portions of the hot and cold composite curves lying opposite each other, as well as those regions representing the hot and cold utility requirements, satisfy an energy balance. The latter two regions exchange heat with the hot and cold utility respectively while the first region exchanges heat between the hot and cold process streams. This situation is illustrated in Figure 2.5.

The shaded region in Figure 2.5 can be divided into enthalpy intervals such that each interval has a "linear" portion of the composite curves forming its boundaries. These intervals are illustrated in Figure 2.6.

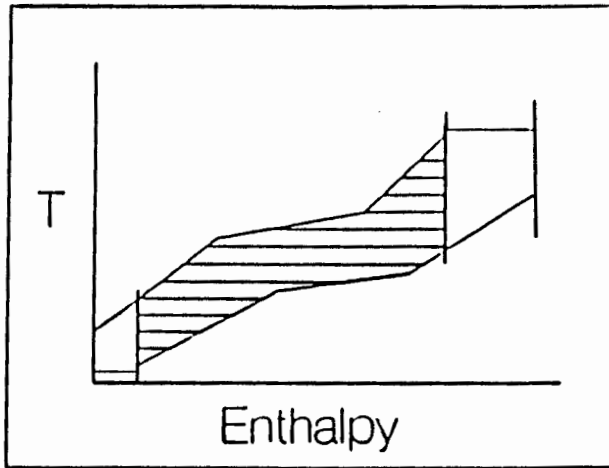


Figure 2.5 Minimum Area Target

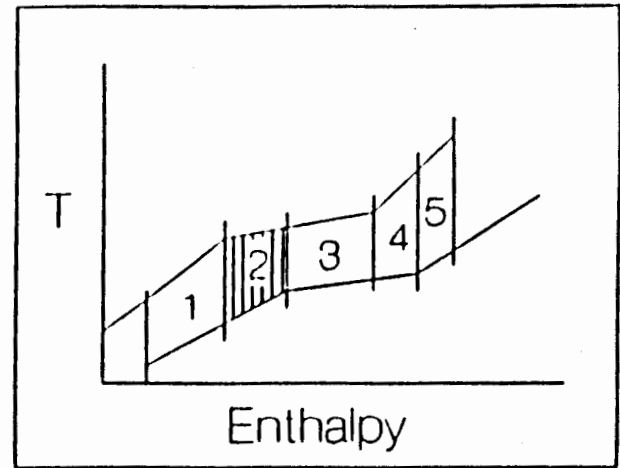


Figure 2.6 Enthalpy Intervals

In this figure, five such enthalpy intervals exist. If one assumes that all the matches are vertically aligned (as represented by the vertical lines in the second enthalpy interval in Figure 2.6), then pure countercurrent heat exchange occurs. Thus each interval may be assumed to represent an imaginary countercurrent heat exchanger. The area of this exchanger is given by the equation:

$$A = Q / (U \Delta T_{lm}) \quad (1)$$

Three equations will be presented for determining the area target. These equations range from a very simplistic model to a more complex model. The first equation for obtaining the overall surface area for a set of hot and cold streams is based on the assumption that all streams have the same heat transfer film coefficient resulting in the same overall heat transfer coefficient,  $U$ , in all the imaginary exchangers. This equation was proposed by Hohmann (1971). This is depicted in Figure 2.7 and Equation (2).

$$A_{min} = \frac{1}{U} \sum_j \frac{Q_j}{(\Delta T_{lm})_j} \quad (2)$$

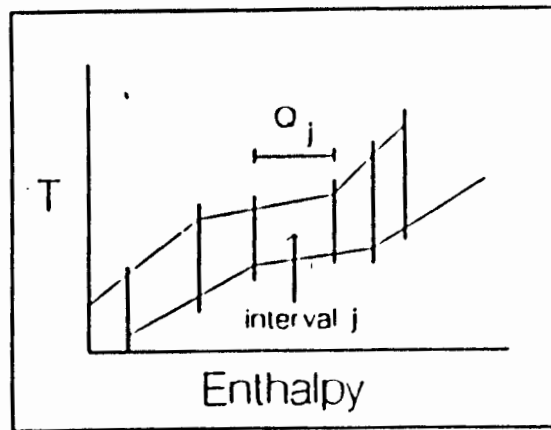


Figure 2.7 Intervals for Defining Minimum Area

The second equation for obtaining the area target assumes that streams have different film coefficients. The overall heat transfer coefficient in an exchanger may be expressed as:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{1}{h_2} \quad (3)$$

where  $h_1$  and  $h_2$  are the film coefficients of the two streams involved in the match. By applying a countercurrent heat exchanger model and using equation (3), the minimum area may be predicted using the "Bath" formula (Townsend and Linnhoff, 1984). This is depicted in Figure 2.8.

$$A_{\min} = \sum_j \frac{1}{(\Delta T_{lm})_j} \sum_i \frac{q_i}{h_i} \quad (4)$$

where  $q_i$  = enthalpy change of stream  $i$  in interval  $j$   
 $h_i$  = film coefficient of stream  $i$  in interval  $j$

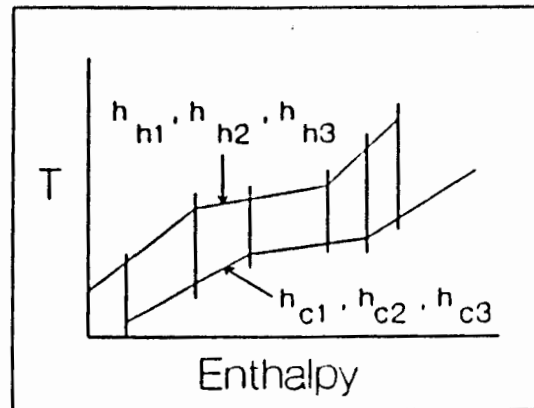


Figure 2.8 Area Based on Individual Stream Film Coefficients

Equation 4 however only holds true if all the hot streams in the interval have the same film coefficient (to ensure that the portion on the hot composite curve in that interval has the same film coefficient) and all the cold streams in the same interval have the same film coefficient (to ensure that the portion on the cold composite curve in that interval has the same film coefficient). The hot and cold stream film coefficients need not be the same. To account for streams in the same interval having different film coefficients, a third equation to obtain the area target was derived by Ahmad (1985). This equation has the form:

$$A_{\text{total}} = \sum_j \sum_{i=H} \sum_{k=C} \frac{1}{\Delta T_{LM\ i,k}} \frac{q_{ik}}{h_{ik}} \quad (5)$$

$$\text{where } q_{ik} = \sum q_i q_k / \Delta H$$

$$h_{ik} = h_i \text{ if } i=H \\ = h_k \text{ if } i=C$$

$$\Delta H = \sum_{i=H} q_i = \sum_{k=C} q_k$$

The ratio  $q_k/\Delta H$  represents the fraction of the enthalpy change  $q_i$  which goes towards heat exchange between streams  $i$  and  $k$ . This means that the duty of each hot stream in the interval is divided amongst all cold

streams in that interval corresponding to the ratio of the cold stream duties and that the duty of each cold stream in the interval is divided amongst all hot streams in that interval corresponding to the ratio of the hot stream duties.

## 2.7 Double Approach Temperature Model

The double approach temperature model (DTA) proposed by Colbert (1982) requires the selection of two approach temperatures, namely the heat recovery approach temperature (HRAT) and the exchanger minimum approach temperature (EMAT). The former is the minimum approach temperature between the composite curves while the latter is the minimum of the exchanger approach temperatures within the network of process exchangers. The threshold temperature is defined as that approach temperature which leads to the minimum utility requirement (i.e. decreasing the HRAT value below this temperature will not lead to a saving in utility). If  $\Delta T_{\min}$  is less than the threshold temperature then one solves the DTA method in which HRAT equals the threshold temperature and EMAT equals  $\Delta T_{\min}$ . If  $\Delta T_{\min}$  is greater than the threshold temperature, then one solves the DTA method with HRAT equal to EMAT.

In creating the initial network, the EMAT value is used to define the temperature intervals. The difference between the DTA method and the TI method is that HRAT and EMAT are treated as separate variables in the DTA method. Changing HRAT will vary the utility requirement with a decrease generally resulting in an increase in the total area of the process exchangers. The heat recovery will also be increased. Changing EMAT varies the network complexity with a decrease usually allowing networks to be solved in fewer units. Also, decreasing the EMAT will generally reduce the amount of stream splitting.

This method has been applied by Colbert et al (1981) in which computerized heat exchanger networks were derived. It was found that if the EMAT and HRAT values were equal, the network contained many exchangers and relatively few shells for each exchanger. As the EMAT

value was decreased below the HRAT value, the number of exchangers decreased but the number of shells for each exchanger increased. This in turn resulted in a minimum network cost. This method was however not applied to a retrofit study.

The DTA method was also used by Trevedi et al (1989). They however, combined the concepts of a fixed approach temperature and a DTA to give two subproblems which are in energy balance by defining a pseudo-pinch. The DTA method has a large number of associated subnetworks depending on the EMAT chosen (as opposed to the pinch design method). To calculate the pseudo-pinch, two sets of composite curves are generated using the HRAT and EMAT values. Both sets will have different energy consumptions. An energy difference  $\Delta$  was defined as follows:

$$\Delta = EC_{hrat} \text{ HRAT} - EC_{emat} \text{ EMAT}$$

where EC is the energy consumption. When designing a network, an amount of energy equal to  $\Delta$  traverses the EMAT pinch point providing additional flexibility when specifying stream matches. This method was, however, only used in an initial network design and not in a retrofit study.

## 2.8 Optimum Tradeoffs

Both energy and area targets are functions of the minimum approach temperature,  $\Delta T_{min}$ . Thus they are linked and can be optimized. The optimum point can be determined from a detailed evaluation of capital cost (dependent on heat exchange area, number of shells, materials, pressures, etc.) and of operating costs (utility consumption, utility prices, etc.). The cost of heat exchanger networks is usually expressed in terms of annualised capital and operating costs. The capital cost is obtained by costing the imaginary heat exchangers between the hot and cold composite curves. As discussed in Section 2.6, the imaginary exchangers include the cold utility exchangers, the process exchangers and the hot utility exchangers. Each interval between the composite curves corresponds to an ideal imaginary exchanger. The individual exchanger cost is based on the area calculated using either

equations 2, 4 or 5. The cost is related to the area by the following equation (Linnhoff, 1982):

$$\text{Cost}_{\text{exchanger}} = A \text{ area}^B \quad (6)$$

Equation 6 is a reduced form of the following cost equation (Ahmad, 1985):

$$\text{Cost}_{\text{exchanger}} = A \text{ area}^B + C$$

where C = constant

For the purpose of this project, each imaginary exchanger was costed using equation 6 and the total capital cost arrived at by summing these individual costs (Trevedi et al, 1989). The final annual capital cost was obtained by multiplying the summed exchanger costs by a capital factor (the annual rate of return). An alternative method of establishing the capital cost is to divide the total target area by the minimum number of units (see Section 2.9.3 for a discussion on the minimum number of units), cost the exchanger using equation (6) and multiply this value by the minimum number of units. This method is used by Ahmad (1985). The method used for this project will give an optimistic capital cost.

If the steam level is too low (the temperature of steam is less than that of the hottest cold stream), then a furnace is required. This is costed using the required duty by the equation (Douglas, 1988):

$$\text{Cost}_{\text{furnace}} = A \text{ duty}^B \quad (7)$$

This capital investment will then be used for the hot utility exchange instead of the imaginary exchangers.

The total utility cost is obtained by summing the hot and cold costs. These costs are calculated as follows:

$$\begin{aligned} \text{cost} &= \text{duty} * \text{operating time per annum} \\ &\quad * \text{enthalpy change/mass} \\ &\quad * \text{cost/mass} \end{aligned}$$

If a furnace is required, the hot utility cost corresponds to the cost of fuel oil required to fire the furnace. It will be assumed that the furnaces operate at an efficiency of 70%.

In the literature problems (4SP1, 6SP1, 10SP1, etc.) cited (Grimes et al, 1982), the dominant contribution to the total annual cost is usually the utility consumption. Thus the main priority in designing a network is to meet the minimum utility requirement. Once the minimum utility requirement has been satisfied, the minimum capital cost can be obtained by a combination of minimizing the area, distributing the area between exchangers (i.e. the number of shells) and the number of different units required. However, for several of the retrofit and grass-roots designs performed recently, the energy costs are less by a factor of three or even four (Trevedi et al, 1989 and Linnhoff and Kotjabasakis, 1989), resulting in the capital costs being the dominant cost.

## 2.9 Design of Heat Exchanger Networks

The various approaches to the design of heat exchanger networks have been classified by Gundersen and Naess (1987), as Mathematical Programming, Pinch Technology and Knowledge Based Systems. Of the three, Pinch Technology has been most widely applied in practice. The Driving Force Plot and Remaining Problem Analysis techniques used in this study fall within this class.

### 2.9.1 The Pinch Design Method

When designing grass-roots networks which achieve the minimum utility requirements, the following rules must be observed (Linnhoff, 1982):

- a) *No cold utility should be used above the pinch.* (as mentioned, the region above the pinch is a heat sink)
- b) *No hot utility should be used below the pinch.* (as mentioned, the region below the pinch is a heat source)
- c) *No process heat should be transferred across the pinch.* (any heat transferred across the pinch must be supplied by additional hot utility and will be rejected as additional cold utility)

The pinch design method incorporates two fundamental features. First it recognises that the pinch is the bottleneck to heat recovery. The design is started at the pinch and developed moving away. Second, it allows the designer to choose between options. In addition to the pinch principles presented above Linnhoff and Hindmarsh (1983) have developed the following rules when selecting matches starting or ending at the pinch. These indicate under what conditions streams need to be split at the pinch:

- a) Above the pinch, the heat capacity flowrate of the hot stream being matched must be less than or equal to the heat capacity flowrate of the cold stream being matched. If there is no cold stream with a high enough heat capacity flowrate, then the hot stream must be split.
- b) Below the pinch, the heat capacity flowrate of the hot stream being matched must be greater than or equal to the heat capacity flowrate of the cold stream being matched. If there is no hot stream with a high enough heat capacity flowrate, then the cold stream must be split.
- c) Above the pinch, the number of hot streams must be less than or equal to the number of cold streams. If this is not the case, cold stream splitting will be required.
- d) Below the pinch, the number of hot streams must be greater than or equal to the number of cold streams. If this is not the case, hot stream splitting will be required.

### 2.9.2 Design Method Summary

When designing a grass-roots network, the following procedure should be followed:

- a) The heat exchanger network is divided at the pinch into separate problems.
- b) The design for each section is started at the pinch and developed away. At the pinch essential matches, match options and stream

splitting requirements are identified by applying the rules presented in (a) to (d) above.

- c) When options exist at the pinch, the designer has the option to select a match.
- d) Away from the pinch, there is more freedom in selecting matches.

The latter two options ((c) and (d)) are based on the following rules (Tjoe, 1985):

- 1) The hottest hot stream must be matched against the hottest cold stream if possible (Ponton and Donaldson, 1979). This is to ensure that the approach temperature at each end of the exchanger does not become too large, which in turn prevents the match making use of excessive driving forces.
- 2) The streams with the largest duties must be matched first. This will ensure that the minimum number of units (exchangers) result.

An approach to be used in conjunction with the above two proposals, is to follow a "tick-off" heuristic (Linnhoff and Hindmarsh, 1983). This heuristic ensures that the minimum number of exchangers is achieved if every match brings one stream to its target temperature or exhausts a utility (hot or cold). In this case the match is said to "tick-off" the stream or utility. This heuristic can introduce the need for increased utility usage since driving force may be used up excessively in the pinch exchangers which have very large duties. The designer may then reduce the pinch exchanger duty or use another matching arrangement which does not use up as much driving force.

Grimes et al (1982) have designed networks where the above steps are followed in matching streams above and below the pinch. They have then, however, taken the arrangement one step further in that an evolutionary method was applied to improve the network. The evolutionary method creates and breaks loops in a network and is useful for modifying networks which already feature the minimum number of units and full heat recovery as well for those which do not. A loop may be identified by tracing a path starting and ending at the same unit by following

intervening streams. The existence of loops increases the number of matches compared to the minimum number for that network.

### 2.9.3 Minimum Number of Units and Heat Load Loops

Hohmann (1971) defined the "quasi-minimum" number of units for a system as:

$$N_{\min} = N_{\text{source}} + N_{\text{sink}} - 1 \quad (8)$$

where  $N_{\min}$  is the quasi minimum number of units

$N_{\text{source}}$  is the number of source streams

$N_{\text{sink}}$  is the number of sink streams

The source streams include hot streams and hot utility while sink streams include cold streams and coolant. When dealing with heat exchanger networks, equation (8) may be rewritten as

$$N_{\min} = N_{\text{source}} + N_{\text{sink}} - \text{number of independent heat load loops} \quad (9)$$

If the minimum unit solution that involves no split streams exists for a problem, then an appropriate set of matches can be placed. Such a network must be acyclic, i.e it will be impossible to trace a path that starts and ends at the same unit by following intervening streams. The opposite of an acyclic network is a cyclic network in which loops exist.

### 2.9.4 Loop level and Breaking

The definition of "level of loops" is proposed as:

The "nth level loops" are the loops that involve n source streams and n sink streams (Su and Motard, 1984). By this definition, the first level loops are those that involve one source stream and one sink stream.

Two important features about the loop level are:

- a) The existence of higher level loops does not depend on the existence of lower level loops.
- b) The redistribution of energy in a loop at a specific level always influences the loops of higher or lower levels.

In order to eliminate a loop, the smallest load in the loop must be taken up by the other members in the same loop. The energy transferred by the original units in the loop will be transferred by one less unit after the loop has been broken. Once the loop has been broken, the feasibility of the resulting structure must be checked i.e. the temperature differences between the hot stream and cold streams at either end of all the heat exchangers in this network must exceed the minimum approach temperature. Should the resulting network contain an infeasible match after loop breaking, the original structure must be used for further evolution or the loop altered to reduce the smallest load to a minimum, within the  $\Delta T_{\min}$  constraints.

#### 2.9.5 The Driving Force Plot

In obtaining the minimum area, a series of ideal heat exchangers was assumed (i.e. the temperature differences on the composite curves were met exactly). When designing a network the need arises to compare an actual match to the ideal. Such a tool is provided by the construction of a Driving Force Plot, which was first suggested by Linnhoff and Vredeveld (1984). This plot may take several different forms, these being:

- a) A plot of the approach temperature at each end of the ideal imaginary exchangers versus the cold stream temperatures at those values.
- b) A plot of the cold stream temperatures versus the hot stream temperatures.

All allow for precise placement of an actual heat exchanger relative to the ideal.

The driving force plot used in this project is constructed by plotting the temperature differences between the hot and cold composite curves against the cold temperatures of the cold composite curve as illustrated in Figure 2.9.

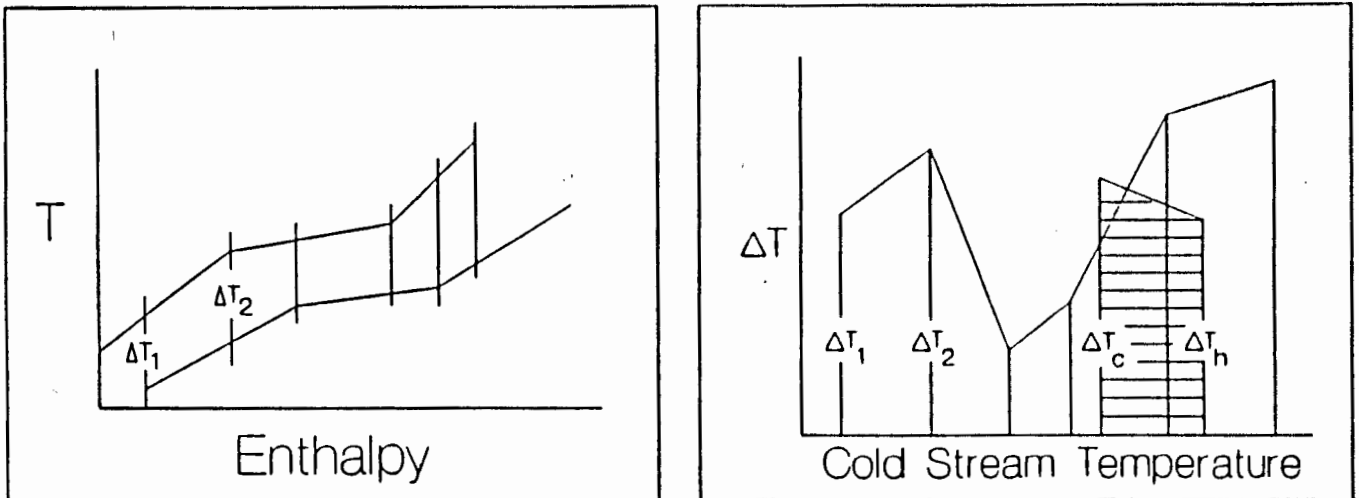


Figure 2.9 Construction of the Driving Force Plot

In order to see the placement of an actual exchanger, consider the case presented in Figure 2.10.

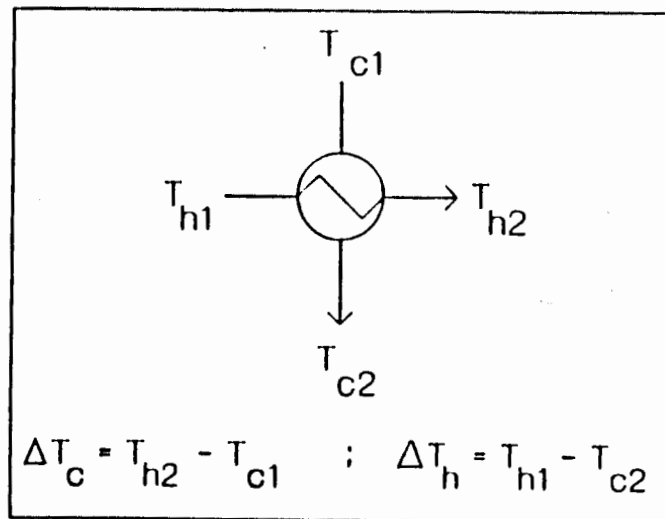


Figure 2.10 Actual Heat Exchanger

This match is represented by the shaded region in Figure 2.9. "Good" matches closely approximate the outline of the ideal driving force, whereas, "bad" matches are far away from it or are of opposite slope.

The use of too high a driving force at one point in a network will inevitably lead to too low a driving force elsewhere in the network and hence to increased exchanger costs (Ahmad, 1985).

Matches placed according to the heat capacity inequality (see the section on matching rules at the pinch in Section 2.9.1) at the pinch are in line with the slope of the Driving Force Plot. This is because the heat capacity inequality for individual plant matches (by considering the heat capacities of the actual hot and cold streams) is the same as the heat capacity inequality for the slopes of the composite curves at the pinch (after summing the heat capacity contributions from the hot and cold streams in that interval) (Ahmad, 1985).

#### 2.9.6 Remaining Problem Analysis

Visual inspection of a match placed on the Driving Force Plot may initially lead one to believe that the match was either well placed or that it should be disregarded. There is a need, however, to quantify the selection of a match more exactly than the Driving Force Plot allows, particularly as far as the implications of that match on the rest of the problem are concerned. This can be achieved via the Remaining Problem Analysis formulated by Ahmad (1985) and Tjoe (1985).

Remaining problem analysis provides a tool to study the effectiveness of a proposed match by investigating its effect on the stream data remaining after the match. It would ideally be required that the area of all exchangers in the network be as close to the area target obtained from the composite curves. The deviation from the ideal exchange is observed by performing Remaining Problem Analysis. This concept will be described in detail in Chapter 3.

## 2.10 Integration of Distillation Columns into the Network

Distillation columns tend to absorb a specified amount of heat,  $Q_{reb}$  at a given temperature,  $T_{reb}$  and then to reject another quantity of heat,  $Q_{cond}$  (which is usually roughly the same amount) at a lower temperature,  $T_{cond}$  (if the feed is at its boiling point). Thus they do not really run on heat but on temperature (Linnhoff et al, 1983). Integration across the pinch gives no benefit compared with the columns operating independently since heat is taken from the source and rejected to the sink which results in a transfer of heat across the pinch.

However integration above or below the pinch leads to the columns and the process requiring no more energy than the process would require on its own. The reason is that columns run on temperature not heat. Thus they simply make use of the spare temperature available from the process by absorbing and returning heat which is still usable and in so doing maintains the pinch as a region of zero heat flow.

The amount of heat borrowed from the process is limited in that sufficient heat flow must remain in the process at all temperatures spanned by the column. If a column crosses the pinch or requires more heat than is possible below or above the pinch, there are several ways in which it can be moved relative to the pinch (Linnhoff et al, 1983):

### a) *Pressure changes*

The pressure affects variables such as volatility and vapour density. However, the most important influence (as far as heat exchanger network synthesis is concerned) is the effect of volatility changes on the condenser and reboiler temperatures and hence the level of heating or cooling required. An increase in pressure raises the condenser and reboiler temperatures while a decrease in pressure results in the reboiler and condenser temperatures dropping.

### b) *Split column loads*

This means splitting the column feed and using two or more columns. The operating pressure in each column must be chosen such that the column operates entirely above or below the pinch.

c) *Thermal coupling*

The use of side-cut strippers and side-cut rectifiers will eliminate the use of at least one reboiler and/or condenser thus reducing the total heat load.

d) *Intermediate reboilers and condensers*

By using intermediate reboilers and condensers, heat can be added or removed at any plate via a pump around. Thus the reboiler and/or condenser duties can be reduced.

An alternative method consists of constructing hot and cold composite curves for the streams around the column. This method may be described as follows: (Hindmarsh, 1983)

The streams are either sink or source streams with the sink streams being the feed, the stream to be reboiled and the cooling medium while the source streams are the stream to be condensed, the top product stream, the bottom product stream and the heating medium. This is illustrated in Figure 2.11 below. If hot and cold composite curves are constructed from the sink and source streams and plotted on a T versus Q graph, the area between the curves represents the energy loss. This loss is due to the irreversible processes in distillation such as the heat lost from the exchangers and the column.

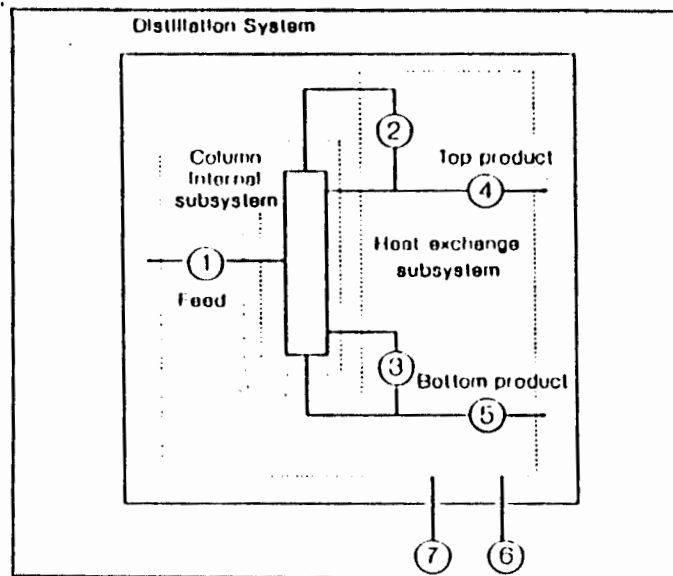


Figure 2.11 Sink and Source Streams in Distillation System

The area between the curves can be decreased by adjusting the operating parameters such as pressure and temperature.

The area between the curves can be decreased by adjusting the operating parameters such as pressure and temperature.

### 2.11 Heat Exchanger Network Retrofit

A retrofit involves modifying an existing heat exchanger network. The capital expenditure is governed by the payback period and the energy savings possible. Retrofit projects reported in literature include the following:

- a) Energy saving at a paper mill (Energy Efficiency Office, Project 16).
- b) Energy saving at a steel works (Energy Efficiency Office, Project 25).
- c) Energy saving in batch-processing (Energy Efficiency Office, Project 15).
- d) Energy saving at a whisky distillery (Energy Efficiency Office, Project 9)).
- e) Energy saving at a bulk chemicals plant (Energy Efficiency Office, Project 31).
- f) A retrofit approach for heat exchanger networks (Ciric and Floudas, 1989).
- g) A retrofit of a distillation system (Hindmarsh, 1983).
- h) A retrofit of a crude distillation train subject to pressure constraints (Ahmad et al, 1989).
- i) Cost reductions at a oil refinery (Energy Efficiency Office, Report No. RD/19/26).
- j) The Effect of Distillation Column Conditions on the Performance of Heat Exchanger Networks - A Case Study (Wood, 1988).

Retrofit projects are tackled via three different approaches (Tjoe and Linnhoff, 1986):

- a) Inspection. Examine the plant and choose a project intuitively.
- b) Computer search. Many different network designs are generated with a computer package and then compared to the actual network. A similar network may result in a viable retrofit project.

- c) Pinch technology. Pinch principles are applied and incorporated with process insight during the design.

Once a retrofit project has been decided on, plant modifications to be considered include the following:

- a) Installing additional area in the form of heat exchangers (Ahmad, 1985).
- b) Match different streams against each other i.e. change the matching order (Tjoe, 1985).
- c) Change pump-around flowrates. An increase in the flowrate has the effect of increasing the return temperature while a decrease lowers the return temperature since the total heat removed generally needs to remain constant (Wood, 1988).
- d) Change column operating parameters. These effects have been discussed in Section 2.10 above.
- e) Reuse any discarded exchangers (Tjoe and Linnhoff, 1986).

Two new modifications have been considered in this project - these being:

- f) Split streams (i.e. increase or decrease stream flowrates) to vary the duty in an exchanger.
- g) Change stream mixing points. This has the effect of changing the inlet temperature and hence the driving force in an exchanger.

The capital expenditure involved (particularly for modifications (a), (b) and (f)) must be traded off against the energy savings which would be saved by the modification(s).

The tools used to analyse existing networks include the following:

- a) Driving force plots.
- b) Remaining problem analysis.
- c) Energy-area analysis.

The above tools show badly-placed exchangers. The modifications discussed above must be applied to shift the exchanger so that it makes better use of the available area and driving forces and does not transfer energy across

the pinch. However, it is not always possible to improve the placement of the exchanger if the energy savings do not warrant the capital expenditure. The Driving Force Plot has been discussed in Section 2.9.5 above. The Energy-Area analysis will be discussed below, while RPA will be discussed in Chapter 3.

### 2.11.1 Energy-Area Analysis

This analysis is used to compare the actual plant operation (in terms of area and energy currently being used) to the ideal area and energy targets for the same problem (Tjoe, 1985). The targets are established by performing a pinch analysis where the approach temperature is varied from a minimum to a maximum value and the effect on the area and energy observed. A curve can be plotted using these calculated values and the actual point representing the plant can be located on this plot. This is shown in Figure 2.12 below.

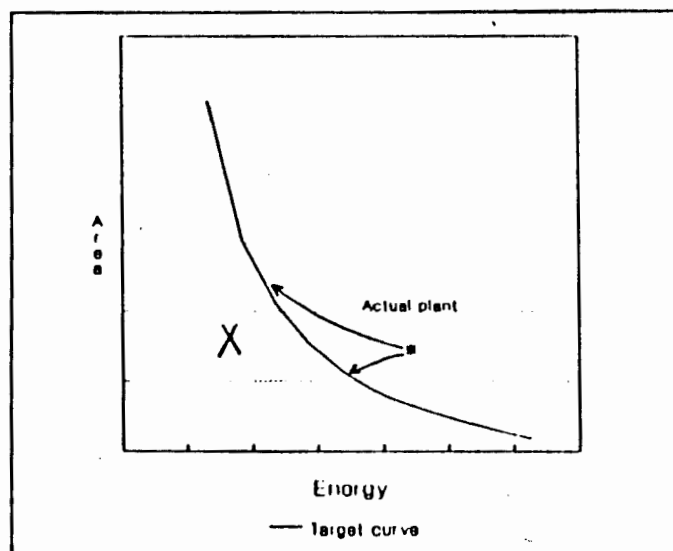


Figure 2.12 Energy-Area plot

The following features are noted:

- a) The plant uses more energy than the predicted target. To move towards the curve, this energy requirement must be reduced. However, to achieve this saving, additional area must be installed. This is represented by the curved line starting at the point

representing the actual plant. This line must slope upwards since additional area must be supplied to achieve the energy savings. However, if a new set of exchangers replaced the existing set, the area could conceivably decrease resulting in the line sloping downwards. A good retrofit using the existing exchangers will have a line close to horizontal.

- b) An infeasible region exists below the curve (marked with an X in the above figure) since no plant can operate using less energy than the predicted minimum.

This chapter has dealt with pinch technology theory as well as techniques based on this theory. The actual topics discussed were:

- a) Establishing a global approach temperature,  $\Delta T_{\min}$ .
- b) Calculating the hot and cold pinch temperatures as well as the target hot and cold utility requirements.
- c) Using a "Problem Table" procedure to calculate the utility targets.
- d) Identifying utility pinches.
- e) Constructing grand composite curves.
- f) Calculating area targets using three different equations.
- g) Using a double approach temperature model to determine the global  $\Delta T_{\min}$ .
- h) The tradeoff between annualised operating and capital expenses as the minimum approach temperature is varied between a minimum and a maximum value.
- i) Designing heat exchanger networks. Included in this section were discussions on matching rules and a procedure to design a grass-roots network.
- j) Calculating the minimum number of units.
- k) The construction of different Driving Force Plots.
- l) Remaining Problem Analysis.
- m) The integration of distillation columns into the process.
- n) Heat exchanger network retrofits.

The next chapter will discuss a tool used to analyse proposed matches, namely Remaining Problem Analysis.

### 3 REMAINING PROBLEM ANALYSIS

Remaining Problem Analysis (RPA) is used as a tool to analyse how effective a proposed match will be. The other tools used are Driving Force Plots and Energy-Area analyses.

#### 3.1 Concept of Remaining Problem Analysis

As mentioned, (RPA) provides a tool to study the effectiveness of a proposed match compared to an ideal imaginary exchanger. RPA is best illustrated by taking a set of dummy stream data, placing a match and investigating the effect of this match on the stream data remaining.

Consider the case of two hot and two cold streams as shown in Figure 3.1.

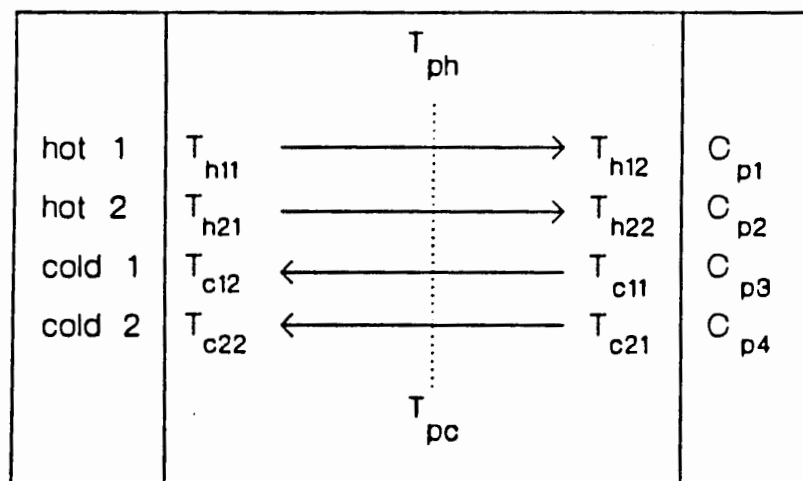


Figure 3.1 Dummy Stream Data

Using the problem table method, the pinch and minimum utility requirements for the problem (using a specified  $\Delta T_{min}$ ) can be obtained. The minimum area target can also be obtained from the composite curves. Since the pinch divides the problem into two independent sub-problems,

the placement of matches above and below the pinch may be considered separately. Considering the problem below the pinch, the stream data may be represented as shown in Figure 3.2. By applying the pinch analysis (using the problem table method) to this region, the same pinch temperature and cold utility requirement will be obtained as for the whole problem. However, the minimum target area will only be that required below the pinch. Let this area be denoted as  $A_{min}$ .

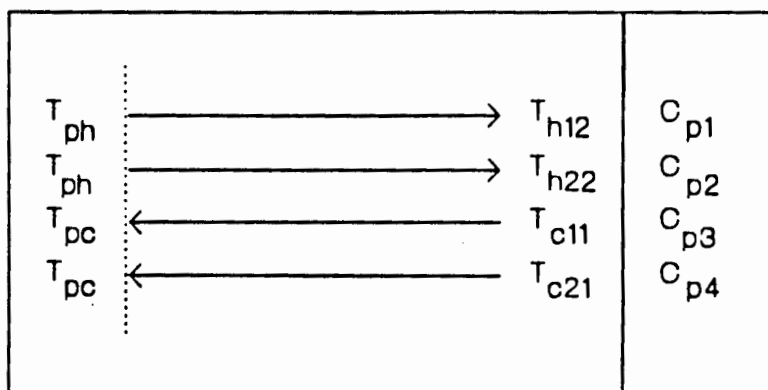


Figure 3.2 Stream Data Below the Pinch

If a match is placed between hot stream 1 and cold stream 1 such that the match is adjacent to the pinch (as in Figure 3.3), the stream conditions remaining after this match has been removed from the problem will be as indicated in Figure 3.4.

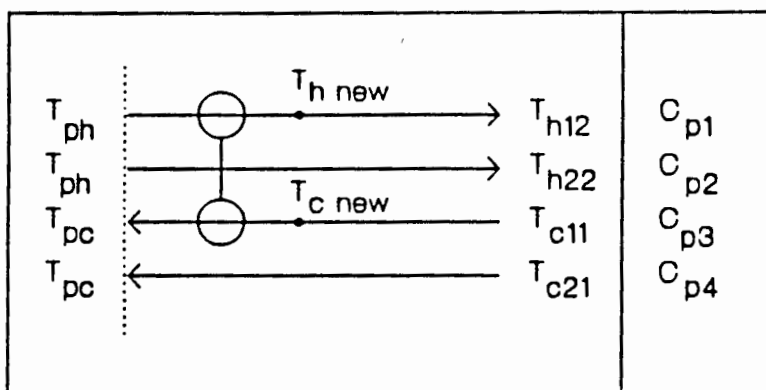


Figure 3.3 Placement of a Match Adjacent to the Pinch

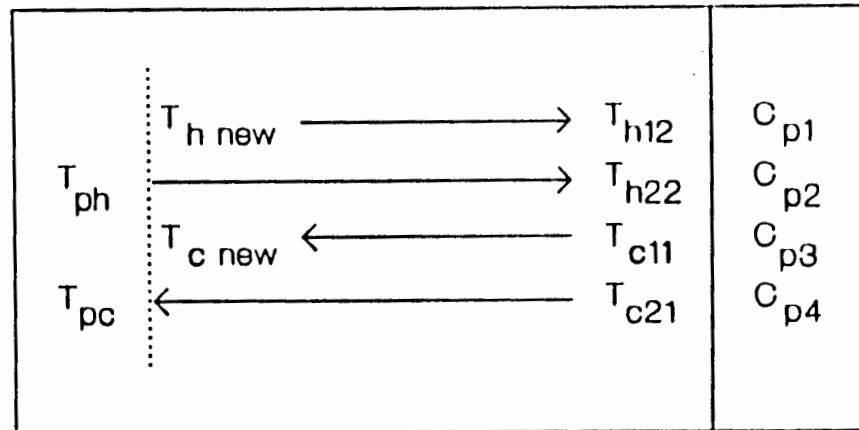


Figure 3.4 Stream Data after Removing the Match Data

If the stream data as represented by Figure 3.4 are once again analysed using the pinch analysis, the following differences from the original case may occur:

- The cold utility requirement may change.
- The minimum target area below the pinch may change.
- The pinch temperature may also change.

Most often the utility requirement remains constant with the target area changing. If the area of the actual match is added to the new target area and compared to the original target area,  $A_{min}$ , the "goodness" of the match can be assessed. The penalty in area in placing the match (additional area required over and above the target area due to the non-ideal match) may be calculated as follows:

$$\alpha = \frac{(A_{min})_{original}}{\sum_i (A_{match})_i + (A_{min})_{remaining}} \quad (1)$$

where  $\alpha$  = area efficiency

and  $i$  represents all matches made so far

Well-placed matches have an area efficiency close to unity while poorly placed matches, which lead to a large increase in area requirement, have low values. The area efficiency can thus be used to discriminate between alternative matches. Successive application of this technique covers the area aspect of remaining problem analysis.

The energy side of RPA is defined in a similar way. The new utility requirement is compared to the initial minimum utility with the penalty being the difference between the two values. This may be presented by the equation:

$$\text{energy penalty} = (\text{energy target})_{\text{remaining}} - (\text{energy target})_{\text{original}}$$

The energy efficiency may be expressed as a fraction by the equation:

$$\text{energy efficiency} = \frac{(\text{energy target})_{\text{remaining}}}{(\text{energy target})_{\text{original}}}$$

The area and energy remaining problems are illustrated in Figures 3.5 and 3.6 respectively:

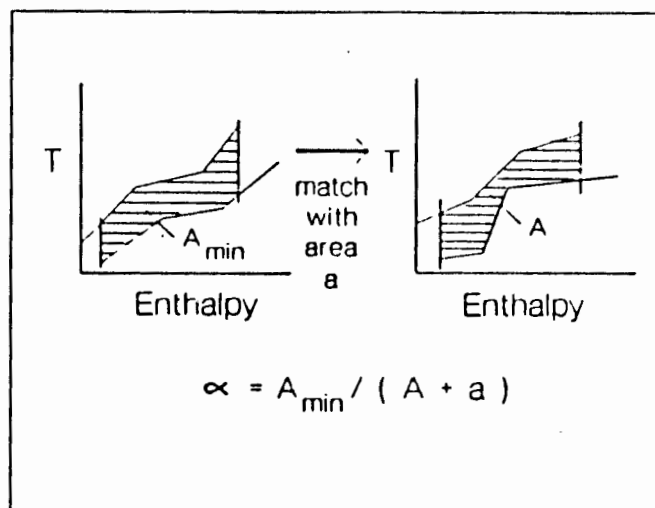


Figure 3.5 Remaining Area Analysis

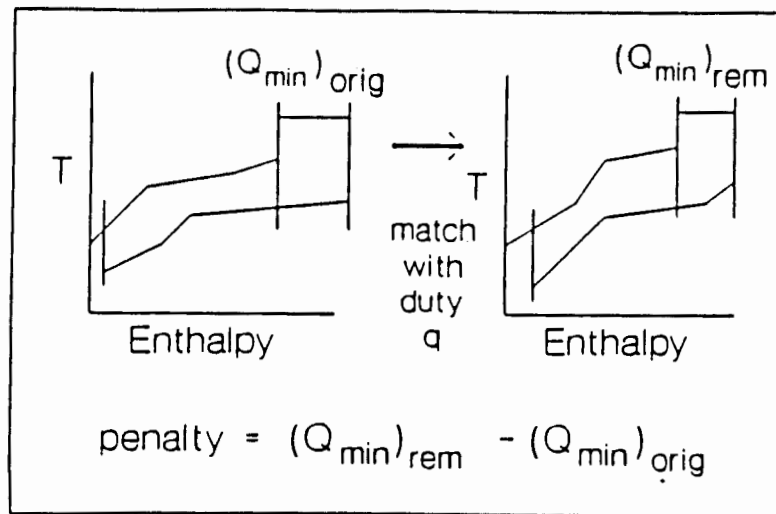


Figure 3.6 Remaining Energy Analysis

In a grass roots design (where the problem is divided into two separate regions - one above the pinch and one below the pinch), the area and energy efficiencies will always be less than or equal to unity. However, if a retrofit study is being performed, cross pinch exchangers usually exist. This complication requires the problem to be analysed without the pinch division which in turn may result in area and energy efficiencies larger than unity. This increase in efficiency may be due to the transfer of energy across the pinch with the result that the pinch temperature may change once the stream data for that match has been removed. This would indicate a new problem with different targets which would make it difficult to determine the effect of the match.

The RPA as discussed above, has only been applied in a grass-roots network design. In this chapter, RPA analysis has been investigated in a retrofit problem as well as in a grass-roots design where several matching options exist.

### 3.2 Grass-Roots Design with Matching Options

The stream data for the problem used to analyse matches with RPA is presented in Table 3.1 below. Analysing this data using pinch technology

showed that three hot streams ended at the pinch (design taking place above the pinch) and two cold streams started at the pinch. In designing a network where the feasibility criteria at the pinch (as presented in Section 2.9.1 in Chapter 2) are not met, stream splitting is necessary. In the case where different streams may be split, several matching options are available. Since all the hot stream heat capacities are less than the smallest cold stream heat capacity, either of the cold streams may be split. There will thus be 8 ( $2^3$ ) combinations of matches involving the three hot and three cold (two split and one unsplit) streams. The problem which arises would be which matching arrangement would result in a network with the lowest annual cost (process exchanger cost plus utility exchanger cost). This problem was investigated by completing all eight networks and comparing intermediate area efficiencies and total network costs. It must be noted that RPA does not tell the designer how to construct the network, but rather provides an indication of how good or bad his or her proposed matches are (Ahmad, 1985). Thus the work following should be used in conjunction with RPA when matching options exist at the pinch.

The networks were completed by first matching streams below the pinch and then above. The matching arrangement below the pinch required a single cold stream to have a double split (following the matching rules at the pinch as discussed in Section 2.9.1) and matched against three different hot streams. This matching arrangement was kept the same for each of the networks and hence the process and utility exchanger costs for this region were not included in the overall network capital cost.

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kW/°C.m <sup>2</sup> )	Heat Capacity Flowrate (kW/°C)	Duty (kW) *10 <sup>-4</sup>
Hot 1	166.0	90.0	0.0908	558	4.24
Hot 2	282.0	197.0	0.4917	1343	11.41
Hot 3	274.0	38.0	0.0764	226	5.33
Hot 4	164.0	27.0	0.6111	892	12.22
Hot 5	327.0	267.0	1.0972	1193	7.16
Hot 6	363.0	246.0	0.3264	661	7.73
Hot 7	327.0	165.0	0.6111	415	6.72
Cold 1	74.0	295.0	0.3056	1540	34.03
Cold 2	143.0	164.0	0.6111	3198	6.72
Cold 3	94.0	125.0	0.6111	3142	9.68

Table 3.1 Stream Data for the Grass-Roots Design Problem

Above the pinch, the matching arrangement for each of the networks was completed to the stage where all streams starting or ending at the pinch were matched. The area efficiency at this stage was recorded and the network then completed and costed. These intermediate efficiencies and process and utility exchanger costs are tabulated in Table 3.2 below.

From the table below it can be seen that the overall network cost increases as the area efficiency decreases. It is intuitively likely that the network with the highest area efficiency (i.e. closest to unity) after matching all streams starting and ending at the pinch, results in the lowest overall network cost.

Area efficiency	Process exchanger cost	Utility exchanger cost	Total exchanger cost
0.973	296400	10800	307200
0.969	296500	10800	307300
0.967	314000	6500	320500
0.795	338700	6700	345400
0.761	364500	10800	375300
0.737	392100	8700	400800
0.699	411500	9900	421400
0.658	440000	11100	451100

Table 3.2 Intermediate Area Efficiencies and Overall Network Costs for Eight Different Networks

It must be noted that although different stream film coefficients are recorded in Table 3.1, a constant film coefficient of 1 was used for all streams in the networks above. As mentioned in Section 2.6, the equation used to calculate the area target is the "Bath" formula. This equation, however, does not accurately calculate an area target if different film coefficients are used (can be a discrepancy of up to 10% in the calculated area). Thus when comparing area targets (as is the case when calculating the area efficiency), values larger than unity may result due to variations in the calculated area targets. This was in fact confirmed using the stream data with the differing film coefficients. Thus to demonstrate the method of selecting the best network, the uncertainty in the area calculation was eliminated using a constant film coefficient.

### 3.3 Area and Energy Efficiencies in a Retrofit Project

In a grass-roots network design, the area and energy efficiency give an indication as to how effectively the proposed match uses area and energy respectively. In a retrofit study, a means is also desired to determine the effectiveness of actual matches placed on the plant. The use of area and energy efficiencies was investigated by not dividing the problem into regions above and below the pinch. This was achieved by studying the effect of the match (in terms of area and energy penalty) on the total area target (corresponding to the area target above and below the pinch) and the total energy target (hot and cold utility) for the stream data involved. Thus the actual match was not considered relative to the pinch.

The same stream data presented in Table 3.1 was used for the investigation. An interesting observation was noted when placing a match (corresponding to a below pinch match in a grass-roots design) which did not transfer energy across the pinch. It was found that both the energy and area efficiency increased above unity (the area efficiency was 1.099 while the energy efficiency was 1.132). The increased energy requirement could not be explained in terms of cross-pinch exchange. The stream data remaining after the match was placed, was analysed using pinch technology. This analysis confirmed that the pinch had in fact shifted and that a new area and energy target had resulted. Thus the match had affected the stream causing the pinch which in turn resulted in a "new" problem with different targets.

A second match was placed which transferred energy across the pinch. The energy efficiency once again increased significantly above the previous value (1.531 as opposed to 1.132). This time the increased energy requirement could be explained in terms of the energy transferred across the pinch.

It was concluded that if an actual plant match was analysed using RPA (in a retrofit project), an increase in area and/or energy efficiency

above unity does not necessarily imply a cross-pinch exchanger. In analysing actual exchangers in a retrofit, the area efficiency has little meaning. The energy efficiency, on the other hand, may be used to detect cross pinch exchangers if any value greater than unity is noted for this type of exchanger. However, this detection may be achieved without the use of RPA.

#### 4 DEVELOPMENT OF A PACKAGE TO RATE OR DESIGN HEAT EXCHANGER NETWORKS

A computer package, UCTNET, was written to perform a pinch analysis (location of the pinch temperature and establishing area, energy and cost targets), construct the temperature-interval table, locate the optimum approach temperature (by investigating the change in overall cost as the approach temperature is varied), perform an energy-area analysis and finally to perform a grass-roots network design or a retrofit guided by RPA. UCTNET was developed to eliminate manual calculations and to quickly analyse or design networks. The tools available to perform a retrofit study (as is the case with this project) can be easily and quickly implemented using this package. A user manual, explaining how to use UCTNET, was also written.

##### 4.1 Need for the Development of a Package

- a) Heat exchanger networking packages available include the following: RESHEX (Saboo, 1987), SUPERTARGET (Ahmad, 1987), CHEMCALC-5 (marketed by Chempute Software, South Africa) and HEATNET (marketed by the National Energy Laboratory, United Kingdom). HEATNET and very recently RESHEX have been purchased by the Department of Chemical Engineering at the University of Cape Town (UCT). Two packages evaluated were HEATNET and CHEMCALC-5.

The two packages evaluated were found to be inadequate for the following reasons:

- 1) In studying threshold problems (i.e. unpinched problems), the packages still calculated a hot and a cold utility requirement. This was the result of forcing the specified approach temperature to occur at an intermediate temperature and not at the extremity of the temperature range.

- 2) A retrofit analysis could not be performed in that the tools used in analysing possible matches were not available. HEATNET was able to construct composite curves, a grand composite curve and an optimum approach temperature plot while CHEMCALC-5 could perform none of the above plots. CHEMCALC-5 has a simple grass-roots design procedure over which the user has no control. The required driving force plot, the Energy-Area plot and Remaining Problem Analysis were, however, not available. The two packages mentioned are thus better suited to a grass roots design than a retrofit analysis. CHEMCALC-5 does not allow any manual interaction when designing a grass-roots network. A totally automated network is generated on the basis of the matching rules presented in Section 2.9.2 in Chapter 2.

SUPERTARGET is suitable for retrofit but this package is not available to Universities (even at commercial rates). This package also offers the user the option of performing Remaining Problem Analysis. RESHEX is another package also suitable for retrofits in that the user can influence the automatic network synthesis by penalising matches, restricting stream splits and limiting the number of matches on a stream.

- b) When investigating the placement of actual exchangers, the tools used are Remaining Problem analysis (RPA) and Driving Force Plots. As explained in Chapter 3, the RPA method involves comparing the new targets to the original targets. Thus a pinch analysis is required after the placement of any match. The Driving Force Plot is also constructed using data obtained from the composite curves.
- c) Several of the problems investigated had more than ten streams (sum of the hot and cold streams) and thus establishing the targets (pinch temperature, utility consumption and area) manually would have been a very time consuming exercise.

- d) In determining the effect of varying the approach temperature on the targets (to calculate an optimum value for the approach temperature or to perform an energy-area analysis), it is necessary to perform a pinch analysis over a range of values of the approach temperature. As in (c), this would require extensive calculation time.

From the latter two points, it can be seen that for the purposes of this project, a pinch analysis and/or analyses were required for most of the investigations performed. The pinch analysis makes use of a problem table which can be very easily solved by writing a procedure and implementing it on a computer. A pinch analysis could easily be solved using one of the packages already purchased. However, to perform RPA without the use of a package designed specifically for this end, would be an impossible task. This was the major motivation behind writing UCTNET.

## 4.2 Program Specifications

To be generally useful, any package written would have to comply with the following requirements (Gillespie and Fraser, 1989):

- 1) It must be machine-independent i.e. it must be able to run on any IBM or IBM-compatible computer.
- 2) It must be a PC or AT computer based package.
- 3) It must be able to run without support i.e. without the use of libraries and other installation programs.
- 4) It must be able to perform a pinch analysis and establish targets.
- 5) It must be able to perform a network design using RPA.

### 4.3 Language Chosen

The high level language chosen to write UCTNET was Turbo Pascal version 4. UCTNET was later upgraded to run under Turbo Pascal version 5 (once this version had been released). This software was chosen for the following reasons:

- a) Turbo Pascal has very powerful editing features which makes it an ideal editor in which to enter the source code.
- b) One has the option of an integrated compiler or a stand alone compiler. The integrated compiler enables one to easily and quickly compile the source code from within the editor, thus avoiding the need to exit the programming environment to run a stand alone compiler. The stand alone compiler can also be easily invoked and lends itself to use in batch files since it can accept a large parameter list (list of directory paths and compiling options).
- c) Executable code can be produced which will run without the use of libraries. This code can be run on any IBM-compatible PC or AT computer.
- d) The limit on the size of any executable code written is governed by the following stack and heap sizes:  
    maximum stack size   64kb  
    maximum heap size    640kb

The above points support the fact that very large programs can be written (up to maximum size corresponding to the available RAM present in the machine after boot-up). Also available is the ability to execute child programs from within a parent program which makes it possible to write a package larger than the available RAM.

#### 4.4 Features of UCTNET

The software language chosen allowed the package to be written so that several features could be easily incorporated into UCTNET. These features included the following:

- a) Extensive use has been made of windows. This was to achieve user-friendliness and at the same time to give UCTNET a more "professional" touch.
- b) Four graphics drivers have been linked into the compiled code. These are:
  - 1) Hercules Graphics Card (HGC).
  - 2) Color Graphics Adaptor (CGA).
  - 3) Enhanced Graphics Adaptor (EGA).
  - 4) Virtual Graphics Adaptor (VGA).

The program automatically detects which driver is installed. If none of the above graphics cards are present, the graphics features will not be available to the program and UCTNET will probably crash when graphics mode is accessed.

- c) UCTNET consists of a suite of child programs (six in all), driven by a single parent program. All data needed to run each of the child programs is written to disk from the parent program.

#### 4.5 Hardware Requirements

As indicated above, UCTNET consists of six child programs driven by a single parent program. Each of these programs is very large (many of them are larger than 200kB). This, together with the fact that there is much data file manipulation while the program is running, makes the disk access time a important feature. The total executable code takes up more than 1MB of storage space. For these reasons UCTNET is best mounted on a hard drive.

Since UCTNET takes up so much storage space in memory, the minimum RAM requirement is 640KB. The machine best suited to run UCTNET is an IBM or IBM-compatible AT. This type of machine not only has the required hard disc drive and sufficient RAM, but it also has the added bonus that it can run at rates far higher than a PC (typically 10-12MHz, compared to approximately 7MHz for a PC).

UCTNET can be run on a dual floppy system, but as mentioned above this is a time consuming exercise due to the time taken in reading the child programs and reading and writing the data files.

#### **4.6 Functioning of UCTNET**

Before any calculations can be performed, data has to be inputted. The different kinds of data input will be discussed in the section below.

##### **4.6.1 Data input**

Data input to UCTNET is on two levels: those inputs needed to set up UCTNET to run correctly and those pertaining to the solution of the problem being presented to the program.

The first type of input includes the following:

- 1) The type of graphics printer available.
- 2) The directory paths on which different types of files reside.
- 3) Whether new stream data is to be entered or an existing data file is to be loaded from disk. If the latter option is selected, a list of all data files in the specified path is echoed and the user prompted to select the desired file.
- 4) The units (SI or British) in which the output values are to be presented.

The second type of input (which is accessed through a hierarchy of menus) defines the problem and includes the following:

- 1) Data file creation and manipulation. This section includes the ability to retrieve data previously entered, modify existing stream data (change target temperatures, or add or delete streams), delete existing data files, copy data files, rename data files or enter fresh stream data.
- 2) Changing the operating parameters. These include the exponent in the cost equation, the hot utility cost and the annual rate of return.

#### **4.7 Calculation of Targets using Pinch Technology**

##### **4.7.1 Pinch Temperature, Utility Requirements, Minimum Area and Cost Targets**

These targets are achieved by performing the conventional pinch technology tabular analysis (problem table) using all hot and cold streams specified for the problem. The calculations are based on a fixed value of the minimum approach temperature (see Section 2.1 in Chapter 2).

##### **4.7.2 Calculation of the Optimum Approach Temperature**

The approach temperature is varied from a user-specified minimum value to a user-specified maximum value with its effect being investigated on the total annual cost. The total cost is the sum of the annual capital cost and the annual operating costs. The variation of the total cost is plotted against the different approach temperatures to give the user a visual indication of where the optimum value occurs as well as the shape of the optimum (it often happens that the optimum value lies along a flat curve and can thus assume a range of values). The costs and approach temperatures are also tabulated.

#### 4.7.3 Variation of Energy and Area with varying Approach Temperature

As in the above section, the approach temperature is varied from a minimum value to a maximum value and the effect on the target area and total utility consumption (hot utility plus cold utility) is observed. To give the user a visual indication of the effects, three plots are constructed, namely:

- 1) Plot of the variation in area against the different approach temperatures.
- 2) Plot of the variation in utility consumption against the different approach temperatures.
- 3) Plot of the variation in area against the variation in utility consumption.

The area, utility consumption and approach temperatures are also tabulated.

#### 4.7.4 Composite Curves, Grand Composite Curve and Driving Force Plots

The composite curves are plotted to give the user an indication of the pinch point location, the utility consumption relative to the process exchange and the "tightness" of the curves (i.e. how closely they approach each other).

The grand composite curve gives the user an indication of the pinch point, whether there is the possibility to raise steam below the pinch and if different levels of utility can be introduced above and/or below the pinch.

The Driving Force plots give the user an indication of the ideal driving forces for a heat exchanger, since the coordinates for the plots are obtained from the points of inflection on the composite curves (which represent an ideal matching arrangement). Two types of Driving Force plots are constructed:

- 1) Plot of the approach temperature against the cold stream temperature for each ideal imaginary exchanger as indicated on the composite curves.
- 2) Plot of the hot stream temperature against the cold stream temperature for each imaginary exchanger.

For all the above graphical output, the user controls which plots are to be printed. The user also has the option of plotting the composite curves and a driving force plot to a plotter.

#### 4.8 Network Design and/or Rating

The above analyses are followed by network design. This design may be in the form of a grass-roots design or a retrofit of an existing network. For the two options:

- 1) *Grass-roots design*: The user would normally select the option of splitting the problem at the pinch (into two thermodynamically independent regions).
- 2) *Retrofit*: The user must specify a single matching region (i.e. consider the problem to be "unpinched"). This will allow the user to detect any cross pinch exchangers.

A special feature of UCTNET is the hands-on design of a network, using remaining problem analysis to guide in the selection of appropriate matches. Match selection is done graphically on the screen. The user must enter the hot and cold streams to be matched, the end of the stream on which the match must be placed (in a grass-roots design, this position may be either the end nearest the pinch or the end furthest from the pinch while in a retrofit study, this position may be either the stream supply temperature end or the stream target temperature end) and the duty of the match. It must be noted that no intermediate position on a stream may be selected to place the match since in a grass-roots design, the network is usually developed away from the most

constrained region (the pinch). The program then analyses the match specified.

If an invalid match is detected, the user is informed of the problem causing the invalid match and then allowed to specify a different match. Invalid matches typically arise when an incorrect duty is specified (usually larger than the duty available in the hot or the cold stream) or if the approach temperature at either end of the heat exchanger will be violated. If the match is valid, the program responds by displaying first a summary of the match (giving the area of the match, the new target area and the area efficiency) and then a graphical output showing all matches already placed (including the present match) and all intermediate temperatures and duties. The user then has the option of eliminating the last match specified or selecting a new match. As before the user controls the printing or plotting of output.

Once the network is complete, the placement of the exchangers specified is compared with their ideal placement on a driving force plot.

UCTNET has been specifically designed so that it may be used either in grass-roots design of new networks, or in retrofitting applications for existing networks. It compares favorably with existing commercial packages on the pinch analysis side, and goes beyond most of them in the design of networks using remaining problem analysis. It has been found to analyze unpinched (threshold) networks correctly where the two commercial packages tested so far have not.

## 5 POTENTIAL FOR ENERGY SAVINGS

The plant on which the project is based, is a local refinery. At present, the plant is split into a number of units. For a typical refinery these units are the Crude unit, the Vacuum unit, the Fluid Catalytic Cracking unit (FCCU) and the Hydrotreaters. The plant under investigation had a total of eight different defined units (For security reasons, the unit names will not be divulged but will rather be referred to as Plant X where X is a number in the range 1-8). The last plant is a utility plant. The work to be covered in this chapter will include the following:

- a) The stream data for each unit.
- b) The actual network as presently implemented on each unit.
- c) The optimum approach temperature used in the pinch analyses for each unit.
- d) The potential energy and financial savings for each individual unit.
- e) The potential energy and financial savings for combined units.
- f) An Energy-Area analysis for each unit.
- g) Raising steam below the pinch on each unit.

Although the data obtained (as described below) was based on different crude feed rates, all flowrates in the units were scaled according to the required feed rate to that unit. A nominal crude feed rate was used as a basis. Since heat capacity and temperature are not functions of flowrate, all flowrates could be corrected without adjusting the heat capacities and temperatures. Thus all data is consistent with a particular crude feed rate.

Parameters pertaining to utilities and costing equations cannot be disclosed since these parameters are of a sensitive nature. However, the factors relating the energy consumption to the actual costs were similar in magnitude to literature values obtained for projects involving oil

refineries. These values are presented below and have in fact been used to cost the energy consumptions. All costs in this thesis will be presented in dollars (\$) since the refinery on which the project is based uses this currency.

The utility costs have been extracted from Douglas, (1988) and assume the following values:

HP steam	\$4.52/1000 lb
MP steam	\$3.40/1000 lb
LP steam	\$2.28/1000 lb
Cooling water	\$0.03/1000 lb

Since cooling on all plants predominantly took place in fin fans, costing the actual and target cold utility consumption on the basis of cooling water costs, would represent an optimistic value. Using in-house data, it was calculated that the cost to run the fin fans was approximately 17% of the costs to achieve the same cooling using cooling water. For the purpose of this project, the cold utility requirements were costed using the above cooling water costs and then scaled to give the corresponding fin fan costs.

The fuel cost, as extracted from papers by Kojabasakis and Linnhoff (1988) and Trevedi et al (1989), has been averaged and used in all further work presented in this report. This value has been used since it represents the most recent work performed in similar projects.

Fuel cost	\$2.74/10 <sup>6</sup> Btu	Kojabasakis and Linnhoff, 1988
	\$1.83/10 <sup>6</sup> Btu	Trevedi et al, 1989
Average fuel cost	\$2.29/10 <sup>6</sup> Btu	

The equations used to cost the exchangers and furnaces have been extracted from the following different sources:

Heat exchanger costs:	420 A <sup>0.65</sup>	(Douglas, 1988)
	300 A <sup>0.66</sup>	(in-house values from AECI, 1987)

If the latter cost is scaled to a value in 1988 and averaged with the first equation, the cost of the exchanger is given by:

$$\text{Average heat exchanger cost: } 385 A^{0.65}$$

The installed exchanger cost on an existing plant is approximately 3.1 times greater than the purchased exchanger cost (Backhurst and Harker, 1977). Thus the installed cost is given by:

$$\text{Installed exchanger cost: } 1200 A^{0.65}$$

The furnace cost used was taken from Douglas (1988):

$$\text{Furnace cost: } 0.14 Q^{0.85}$$

The installed furnace cost used was also taken from Douglas (1988):

$$\text{Installed furnace cost: } 0.32 Q^{0.85}$$

### 5.1 Data Required for Each Unit

The data required to define the problem will be presented below. This will be followed by a discussion on how and where these values were obtained.

The following data was collected for the streams in each plant:

- a) Stream supply and target temperatures.
- b) Stream heat capacities.
- c) Stream flowrates.
- d) Stream film coefficients.

The following data was collected for the heat exchangers in each plant:

- a) Overall heat transfer coefficients.
- b) Heat exchange areas.
- c) The type of heat exchanger e.g. a kettle type reboiler, a thermosyphon reboiler or a shell and tube exchanger.

The following general data was collected:

- a) Hot and cold utility costs.
- b) Hot and cold utility supply and target temperatures.

- c) Hot and cold utility film coefficients.
- d) Fuel oil costs (i.e. cost of the heating medium used in the furnaces).
- e) Fuel oil calorific value.
- f) Coefficients A, B, C and D in the costing equation for heat exchangers and furnaces where the costs are given by:

$$\text{Cost}_{\text{hx}} = A \text{ Area}^B \quad \text{for heat exchangers}$$

$$\text{Cost}_{\text{furn}} = C \text{ Duty}^D \quad \text{for furnaces}$$

- g) The annual rate of return. The value used was 0.1.
- h) The hours lost due to down time per annum. The value used was 500.

The stream data (supply and target temperatures, heat capacities and flowrates) were obtained from a combination of three different sources. These sources were two flowsheeting packages and test run data.

The packages used were SimSci's "PROCESS" and Hyprotech's "HYSIM". These flowsheeting packages make use of a sequential modular technique to reach a solution. This type of solution is obtained by providing initial estimates for any recycle stream (tear stream) and then performing iterative calculations until the convergence criteria on the tear stream are met. This type of calculation sequence is in contrast to a simultaneous solution strategy where all mass and heat balance equations are lumped together and solved simultaneously.

Test run data is data obtained from a survey performed on a particular plant operating under steady state conditions. The test runs are performed on a regular basis for each plant. Data recorded in such a run include temperatures, flowrates and pressures. Normally heat and mass balances are performed to check the validity of the data.

For two of the more complicated plants (involving multicomponent distillation with several pump-arounds), the PROCESS package did not yield satisfactory solutions. Although it was possible to reach a solution, the data calculated for certain streams did not correspond to the actual values for those streams (Using test run data, it was possible to check flowrates, temperatures and occasionally heat capacities. When discrepancies were detected, the difference usually occurred in the stream flowrate). The solution obtained from PROCESS differed from the actual values since the models could not be modified to accurately simulate the actual plant operation. For these two plants, the heat capacities and film coefficients were obtained from the output produced by PROCESS (since these values are not functions of the flowrate which was the cause for the difference), while the remaining parameters (temperatures and flowrates) were taken from the test run.

In the case where no model of the plant was available, use was made of data from several test runs (to ensure that no spurious values were used). These test runs also had calculated stream duties with the corresponding stream heat capacities.

Data from "HYSIM" was used for two of the units. This data had already been checked against the corresponding actual values by plant personnel. Thus no modifications to the models were required. This package was only available at the refinery.

The data for each unit are presented in Tables A1 to A7 in Appendix 1. Since stream names cannot be mentioned (for security reasons), the type of stream will be provided as follows (Fraser, 1988):

C    Condensation  
G    Gas/vapour  
L    Liquid

P Partial  
S Sensible heat transfer  
V Vapourization  
W Water

In the case where a stream may be undergoing condensation or vapourization, or where mixed phases exist, a combination of codes is used. For example, the combination LGPC refers to a liquid-gas stream undergoing partial condensation. The composite curves for each plant are presented in Figures B1 to B7 in Appendix 2.

The following can be observed from the seven tables presented in Appendix 1:

- 1) Plants 1 and 2 each have one major cold stream. Plant 1 also has one major hot stream (hot stream 9). The streams have been classified as major streams on the basis that their duty is significantly higher than any of the other streams in that plant.
- 2) Plants 3 and 7 have very few streams which in turn would result in a simple network.
- 3) Plant 4 has many hot and many cold streams. Many of the hot streams occur at a low temperature level.

The heat exchanger data was obtained from the specification sheets provided for each exchanger in each plant. The data for the exchangers are presented in Appendix 3. As with the stream data, the exchangers have been given dummy numbers.

## 5.2 Current Plant Configuration

This section will present the actual networks as currently implemented on the various plants. To analyse the networks and produce graphical output, the networking section applied to retrofitting in UCTNET was used. The matches placed in each network were analysed in terms of area and energy efficiencies.

However, as explained in Chapter 3, a cross pinch exchanger often has an area efficiency greater than unity and always has an energy efficiency greater than unity. For this reason, the area efficiencies were not recorded but only the energy efficiencies (to easily identify any cross pinch exchangers). The matches have also been located on Driving Force Plots to give an indication of badly placed exchangers.

Match	Hot Stream	Cold Stream	Duty	Energy efficiency
7	1	1	0.98	1.0000
5	3	1	1.77	1.0000
3	2	1	2.66	1.0000
2	6	1	1.79	1.0000
1	5	1	1.67	1.0000
4	7	2	1.56	1.0000
6	4	3	1.18	1.0000

Table 5.1 Actual Match Data for Plant 1

Match	Hot Stream	Cold Stream	Duty	Energy efficiency
9	1	1	7.02	1.0000
7	4	1	3.78	1.0000
6	8	1	1.74	1.0396
5	2	1	3.02	1.1151
4	5	1	1.23	1.1151
3	9	1	0.21	1.1151
2	7	1	10.78	1.1151
1	3	1	2.15	1.1151
10	6	4	2.77	1.1151
8	8	4	2.65	1.1151

Table 5.2 Actual Match Data for Plant 2

The data used in the networks included all inter-unit streams (marked with a \*) in Tables A1 to A7 in Appendix 1 since the actual matching arrangement was being investigated. The summary for the matches in each unit will be presented in Tables 5.1 to 5.7 with the actual networks and Driving Force Plots presented

in Figures D1 to D14 in Appendix 4. (The stream numbers in Tables 5.1 to 5.7 correspond to those in Tables A1 to A7 while the match numbers correspond to those in Figures D1 to D7 in Appendix 4). The matches have been presented in the order in which they were initially specified when constructing the network.

Match	Hot Stream	Cold Stream	Duty	Energy efficiency
7	5	5	0.32	1.0000
5	4	2	0.21	1.0000
3	3	4	5.00	1.0558
2	2	3	0.59	1.0558

Match	Hot Stream	Cold Stream	Duty	Energy efficiency
1	1	1	6.98	1.0246
2	4	1	10.44	1.0636
4	2	5	0.54	1.0636
3	3	2	2.20	1.0636
5	6	3	1.36	1.1489

Table 5.3 Actual Match Data for Plant 3 Table 5.4 Actual Match Data for Plant 4

Match	Hot Stream	Cold Stream	Duty	Energy efficiency
2	5	4	2.02	1.0502
3	5	2	1.54	1.1047
4	4	2	1.67	1.1089
1	1	1	9.51	1.6875

Match	Hot Stream	Cold Stream	Duty	Energy efficiency
3	2	2	0.33	1.0000
1	1	2	4.62	1.4334
2	4	1	0.13	1.4334
4	4	3	2.02	1.4334
5	4	4	1.54	1.4334

Table 5.5 Actual Match Data for Plant 5 Table 5.6 Actual Match Data for Plant 6

Match	Hot Stream	Cold Stream	Duty	Energy efficiency
7	1	1	2.58	1.2264

Table 5.7 Actual Match Data for Plant 7

At this stage, the above results have merely been presented without any discussion. Although the actual networks will be discussed in detail in Chapter 6, the following can however, be noted:

- 1) Plant 1 is unpinched resulting in the absence of any cross-pinch exchangers.
- 2) Plant 2 has two cross-pinch exchangers - these are matches 1 and 4. Although this is not obvious from Table 5.10 since the change in energy efficiency does not correspond to these matches, this change in efficiency is due to a change in the pinch temperature after removing the match stream data (with different energy and area targets) rather than an increase in energy consumption (as discussed in Chapter 3).
- 3) Plant 3 has no cross-pinch exchangers. The change in energy efficiency is due to the same reason presented in (2) above.
- 4) In plant 4, matches 2 and 5 transfer energy across the pinch.
- 5) In plant 5, matches 1 and 3 transfer energy across the pinch.
- 6) Plant 6 is unpinched.

7) The only match in plant 7 transfers energy across the pinch.

### 5.3 $\Delta T_{\min}$ to be used

To obtain the optimum approach temperature on each plant, a costing analysis was performed. Once the optimum had been calculated, it could then be compared to the minimum approach temperature in an exchanger on that plant.

#### 5.3.1 Calculation of the Optimum Approach Temperature

In calculating the optimum  $\Delta T_{\min}$ , the tradeoff between capital and operating costs (on an annualised basis) is investigated. In determining the capital costs, the area used in costing the heat exchanger is the area of the imaginary heat exchanger between the hot and cold composite curves (Note: the actual area already present on the plant is not used). The operating cost is the sum of the hot and cold utility target costs.

In determining the targets for each unit, the streams from other plants were excluded from the stream set used in the pinch analysis. The reason was that the optimum  $\Delta T_{\min}$  for the actual unit, encompassing only streams originating in that unit and not elsewhere, was desired.

The costing equation used yielded an average value for the costs of several exchangers. However, this equation does not account for the variation in cost of high pressure exchangers or exchangers constructed from different materials (Douglas, 1988). For this reason it was decided to investigate the effect of increasing or decreasing the average cost for an exchanger and hence the capital

cost. This was particularly important on plants 4 and 5 which featured several high pressure streams. Although the largest variation in cost is due to different materials of construction (can increase by a factor of 3), this factor was never very large (since most of the exchangers were constructed from the same material) and hence a 50% increase in cost was considered sufficient to take into account the pressure effects and materials of construction (Douglas, 1988 suggests a 40% increase for high pressure exchangers and since the material of construction was predominantly carbon steel, a further 10% was added to account for exchangers constructed from different materials).

Three values of the optimum  $\Delta T_{\min}$  were calculated. The first value was the optimum obtained using an unmodified coefficient in the heat exchanger costing equation, while the second and third values corresponded to the optimum obtained using a modified coefficient in the equation. The coefficient A in the costing equation  $C = A \text{ Area}^B$  was increased by 50% for the second optimum value and decreased by 10% for the third optimum value.

The three optimum  $\Delta T_{\min}$  values for each unit are presented in Table 5.8 with the plots of the approach temperature versus the overall cost presented in Figures E1 to E7 in Appendix 5.

From the table below it can be noted that plants 1 and 6 are unpinched (require no hot utility) and hence a range of optimum  $\Delta T_{\min}$  exist where no change in overall cost is experienced. However, above the upper threshold value of the approach temperature, the problem is no longer unpinched and the overall cost increases.

As can be seen, the optimum  $\Delta T_{\min}$  does not change significantly with a change in capital cost. Thus the values presented in the

first column of the table may be taken as the optimum for each plant.

Plant Number	Approach Temperature ( $^{\circ}\text{C}$ )		
	Unmodified coefficient	50% increase	10% decrease
1	0 $\rightarrow$ 30	0 $\rightarrow$ 30	0 $\rightarrow$ 30
2	9.4	13.3	8.9
3	7.8	8.3	7.2
4	5.0	6.7	3.9
5	8.3	11.1	7.8
6	0 $\rightarrow$ 13	0 $\rightarrow$ 13	0 $\rightarrow$ 13
7	5.0	6.1	5.0

Table 5.8 Optimum  $\Delta T_{\min}$  for the Different Plants

### 5.3.2 EMAT versus HRAT

The exchanger minimum approach temperature (EMAT) for each plant is the smallest approach temperature in any actual heat exchanger on that plant. Since it is difficult to obtain an accurate EMAT value (the actual value may change due to fouling in the exchanger), the value used is an approximate value. The heat recovery approach temperature (HRAT), on the other hand, is easier to obtain. By definition, the HRAT is the approach temperature between the composite curves. In the previous section, the optimum  $\Delta T_{\min}$  values for each plant were calculated. The HRAT for each

plant was set equal to the corresponding optimum  $\Delta T_{\min}$ . The EMAT and HRAT values are tabulated in Table 5.9 below.

Plant	HRAT	EMAT
1	0 --> 30	6.7
2	9.4	11.1
3	7.8	8.3
4	5.0	5.6
5	8.3	8.3
6	0 --> 13	5.6
7	5.0	5.6

Table 5.9 Comparison of HRAT to EMAT

From the results shown in the above table, it is immediately evident that the HRAT and EMAT values are very similar although the EMAT values are always greater than or equal to the HRAT values. Thus for all the work done in this project, the HRAT value and hence the  $\Delta T_{\min}$  for each plant was set equal to the EMAT value for that plant. All targets obtained are thus based on the EMAT value.

#### 5.4 Potential Energy and Financial Savings (Individual Plants)

In this section, the actual plant utility requirements are compared to the target utility requirements, with the difference being the potential energy savings possible. By costing these

in cold utility (Linnhoff, 1982). In the plants featuring no inter-unit integration (not using hot or cold streams from different plants), the difference between the actual hot utility requirement and target hot utility requirement was the same as the difference between the actual cold utility requirement and the target cold utility requirement. At this stage, no attempt will be made to explain the difference between the actual and target values since the purpose of this section is to establish the potential savings. An explanation will be provided in Chapter 6. The actual and target energy consumptions are tabulated in Table 5.10 below.

Plant	Hot Utility (kW) * 10 <sup>-3</sup>			Cold Utility (kW) * 10 <sup>-3</sup>			Duty associated with streams from other plants (kW) * 10 <sup>-3</sup>	
	(1)	(2)	(3)	(4)	(5)	(6)	Hot stream duty	Cold stream duty
	Target	Actual	Diff.	Target	Actual	Diff.		
1	0.00	1.40	1.40	15.34	16.74	1.40	0.00	0.00
2	41.20	44.40	3.20	24.76	21.15	-3.61	0.29	7.10
3	4.78	5.34	0.56	8.26	2.62	-5.64	0.00	0.29+5.92
4	13.48	15.35	1.87	6.29	8.16	1.87	0.00	0.00
5	5.77	6.41	0.64	4.75	8.94	4.22	1.53+2.03 = 3.56	0.00
6	0.00	0.45	0.45	5.61	2.50	-3.11	0.00	1.53+2.03 = 3.56
7	0.54	0.96	0.42	3.14	3.56	0.42	0.00	0.00
8							7.10+5.92	0.00

Table 5.10 Comparison of Actual Utility Consumption to Target Utility Consumption

The following can be noted from the above table:

- 1) Plants 1 and 7 have equal differences in the hot and cold utility sections (columns 3 and 6 in Table 5.10). These plants feature no inter-unit integration.
- 2) Each external hot stream duty has a corresponding external cold stream duty.
- 3) The hot utility difference (column 3) plus any external hot stream duty must equal the cold utility difference (column 6) plus any external cold stream duty. This calculation was used as a consistency check on the data.
- 4) In plants 2, 3 and 6, already featuring inter-unit integration (incorporating hot and/or cold streams from different plants), the actual hot or cold utility requirement was less than the corresponding predicted target. This phenomena is due to the fact that the external process stream acts as additional utility so reducing the requirement.

#### 5.4.2 Financial Savings

The potential financial savings were calculated as follows:

- a) For each plant, the target hot and cold utility were costed.
- b) For each plant, the actual hot and cold utility requirements were costed based on only those streams originating in that plant (i.e. all inter-unit streams were ignored).
- c) For each plant, the actual hot and cold utility requirements were costed based on all streams associated with that plant (i.e. all inter-unit streams were included).

- d) The difference between (b) and (a) gave the potential savings possible before any integration had been considered.
- e) The difference between (c) and (a) gave the potential savings possible from the present operation. This value corresponds to the potential savings possible at present.

For the plants featuring no inter-unit integration, the potentials calculated in (d) and (e) would be the same. The target costs and potential savings are tabulated in Tables 5.11 and 5.12 below.

	HOT UTILITY (dollars)					COLD UTILITY (dollars)				
	Target cost	Actual cost with inter-unit streams	Actual cost without inter-unit streams	Actual saving with inter-unit streams	Actual saving without inter-unit streams	Target cost	Actual cost with inter-unit streams	Actual cost without inter-unit streams	Actual saving with inter-unit streams	Actual saving without inter-unit streams
1	0	120400	120400	120400	120400	13900	15200	15200	1300	1300
2	3542800	3818000	4268600	275200	725800	22500	19200	30100	-3300	7600
3	411000	459200	459200	48200	48200	7500	2400	8000	-5100	500
4	1159200	1320000	1320000	160800	160800	5700	7400	7400	1700	1700
5	496200	551200	857300	55000	361100	4300	8100	8100	3800	3800
6	0	38900	38900	38900	38900	5100	2300	5500	-2800	400
7	46400	82600	82600	36200	36200	2900	3200	3200	300	300
8	0	0	687500	0	687500	0	0	0	0	0

Table 5.11 Hot and Cold Utility Costs and Potential Savings

	Total Potential saving without inter-unit streams	Total Potential saving with inter-unit streams
1	121700	121700
2	733400	271900
3	48700	43100
4	162500	162500
5	364900	58800
6	39300	36100
7	36500	36500
8	687500	0
Total	2194500	730600

Table 5.12 Total Savings for the Different Plants

(Plant 8 is a utility plant). Inspection of Table 5.12 yields the following observations:

- 1) The difference between the totals of column 1 and column 2 gives the degree of integration already achieved. This value corresponds to a saving of \$1 463 900 per annum.
- 2) The largest savings are due to integration of the utility streams. Briefly, this is achieved as follows:

a) In plant 3, medium pressure steam (MP) is being generated. This has the effect of reducing the steam production in the boilers. The saving in hot utility is \$456 400 per annum.

b) In plant 2, boiler feed is being heated. If this utility stream had not been integrated into the process, a corresponding duty in steam would have been required to heat the utility stream to its supply temperature. The saving in hot utility is \$231 100 per annum.

Thus by integrating the utility streams into the process, a total saving of \$687 500 per annum has been achieved. This represents 47% of the total savings already achieved by inter-unit integration. It should be noted that the integration of utility streams into the process makes a significant contribution to the possible potential savings being achieved. This, however is more significant if the integration leads to a decrease in the hot utility requirement and not the cold utility requirement since the cost of cooling water/fin fan operation is far less than that of steam.

- 3) Plants 2 and 5 exhibit the largest degree of inter-unit integration (apart from utility stream integration). Plant 2 has had 63% of its total potential savings realised by inter-unit integration while plant 5 has had 83% of its possible savings realised. Together these plants contributed 52% towards the savings already achieved.
- 4) Plants 1, 4 and 7 have no inter-unit integration with the result that no savings have yet been achieved.

The anticipated improvement was confirmed using the actual plant data. These values are listed in Table 5.13 below. The differences in utility consumptions between the individual plants and the combined plants are represented in Table 5.14 below.

Plant	Hot Utility (kW) * 10 <sup>-3</sup>			Cold Utility (kW) * 10 <sup>-3</sup>			Duty associated with streams from other plants (kW) * 10 <sup>-3</sup>	
	(1)	(2)	(3)	(4)	(5)	(6)	Hot stream duty	Cold stream duty
	Target	Actual	Diff.	Target	Actual	Diff.		
A	43.10	49.75	6.65	30.13	23.76	-6.37	0.00	7.10+5.92
B	13.93	22.21	8.28	11.32	19.56	8.24	0.00	0.00

Table 5.13 Comparison of Actual Utility Consumption to Target Utility Consumption

From Table 5.14, the following can be noted:

- 1) The difference between the hot and cold utilities for the individual and combined plants were the same.
- 2) The energy saving in the second combined plant is greater than that in the first combined plant. This is due to the fact that many more streams exist in the second combined plant.

The potential savings after combining plants are presented in Tables 5.15 and 5.16 below.

	Hot Utility	Cold Utility
A	43.10	30.13
2+3	45.98	33.02
Difference	2.88	2.89
B	13.93	11.32
4+5+6	19.25	16.65
Difference	5.32	5.33

Table 5.14 Comparison of Target Utility Requirement for Individual and Combined Plants

Inspection of Table 5.16 yields the following:

- a) The utility plant (plant 8) savings have been integrated into plant A.
- b) The potential for improvement (of the combined plants), from the present position, has improved significantly compared to the sum of the individual plant potentials.
- c) The total potential for improvement (\$1 443 700 per annum) has increased by a factor of 2 compared to the total of the individual potentials (\$730 600 per annum).

	HOT UTILITY (dollars)					COLD UTILITY (dollars)				
	Target cost	Actual cost with inter- unit streams	Actual cost without inter- unit streams	Actual saving with inter- unit streams	Actual saving without inter- unit streams	Target cost	Actual cost with inter- unit streams	Actual cost without inter- unit streams	Actual saving with inter- unit streams	Actual saving without inter- unit streams
A	3706200	4278000	4278000	571800	571800	27400	21600	33400	-5800	6000
B	1197800	1909800	1909800	712000	712000	10300	17800	17800	7500	7500
2+3	3953800	4277200	4727800	323400	774000	30000	21600	38200	-8400	8200
4+5 +6	1655400	1910100	2216200	254700	560800	15100	17800	21000	2700	5900

Table 5.15 Hot and Cold Utility Costs and Potential Savings for Combined and Individual plants

- d) The total potential for improvement of the combined plants before integration (\$2 143 000) is less than the corresponding value for the individual plants (\$2 194 500). This is due to the fact that combined plant A (consisting of plant 3), makes better use of the available process to process exchange. Plant 3, considered individually, has very little process to process exchange and thus has a large potential for improvement.

	Total Potential saving without inter-unit streams (dollars)	Total Potential saving with inter-unit streams (dollars)
1	121700	121700
7	36500	36500
A	577800	566000
B	719500	719500
8	687500	0
Total	2143000	1443700

Table 5.16 Total Savings for the combined plants

In the extreme, one may combine all plants into a single unit (i.e. consider the whole refinery as one unit) and obtain the total potential savings possible. This however was considered impractical for the following reasons:

- 1) None of the available HEN packages can handle a problem having as many hot and cold streams.
- 2) UCTNET is limited by the number of streams that could realistically fit on the screen (approximately 40 streams if and Enhanced Graphics Adapter monitor is used).
- 3) Matching streams in plants not situated close to each other will result in additional pipework and pumps with a greater head (to overcome pressure drops). These two hardware requirements would significantly increase the investment needed to achieve the energy savings possible.

For the above reasons, no greater combinations were considered (i.e. no additional units were combined). At this stage, it suffices to say that by combining plants, an upper limit on the total potential savings has been established. A discussion of possible modifications to the combined plants will be presented in Chapter 6.

#### 5.6 Scope for Improvement Using an Energy-Area Analysis

A second means of observing the inter-unit integration already achieved, and the scope for further improvement on each plant, is to locate the plant on an Energy-Area plot. This technique provides a visual indication as to how effectively the actual energy and area is being used compared to the target energy and area. This method complements the previous analytical method.

To obtain the optimum Energy-Area tradeoff for each plant (i.e. the energy and area targets), only the process to process heat exchanger area was considered. The reason was as follows:

In establishing the area targets, three regions may be identified. The first is the process to process exchange, the second is the process to cold utility exchange and the third is the hot utility to process exchange. Very often the hot utility requirement was satisfied using a furnace and the cold utility requirement satisfied using fin fans. As the areas of these systems are either much larger (fin fans) or smaller (furnaces) than the process heat exchangers, their inclusion would make comparisons meaningless. The utility exchangers were accordingly left out.

For plants having inter-unit integration, two curves were constructed. The first curve established the Energy-Area tradeoff

using only those streams originating from the plant while the second curve established the tradeoff using all streams in the plant (including the inter-unit streams). It must be noted that the ideal area was used to obtain the curves. Thus the non-integrated plant could be compared against the first curve while the integrated plant could be compared against the second curve. These plots (including the location of the actual plants) are illustrated in Figures F1 to F7 in Appendix 6. Inspection of the figures leads to the following findings:

- a) Those plants having no inter-unit integration confirm the scope for improvement in that the point representing the actual plant does not lie on the curve.
- b) Plant 2 (although not immediately obvious from the graph), has not effectively utilised the potential available for improvement. This is best illustrated by comparing Figure F2 to Figure F3. The curve representing the integrated plant targets has not shifted significantly compared to the curve of the non-integrated plant. This can be explained as follows:

Plant 2 has a pinch temperature of 271.1°C before and after integration of the process streams. The hot streams (marked with a \* in Table A2) being integrated into the plant are being added below the pinch. Since only cold utility is required below the pinch, the introduction of any hot stream increases this utility. However, a cold stream is also being added below the pinch which has the effect of decreasing the cold utility requirement. Since the duty of the cold stream is larger than that of the combined hot stream duties, the overall effect results in a net decrease in cold utility.

If the cold process stream was not present, the integration of most hot streams (since the supply temperature is seldom larger than 271.1°C) would result in an increased utility

requirement which would in fact increase the potential savings.

- c) Plant 3 appears to achieve the minimum targets before integration of inter-unit streams has been considered. This is due to the fact that before integration of the streams, the plant has no process to process exchangers resulting in a zero area requirement. However, the actual energy requirement is larger than the targets obtained using pinch technology. Thus, although it appears as if there is no scope for improvement, a closer examination of the graph shows that a potential energy saving is possible by moving in a horizontal direction.

In contrast with plant 2, only cold inter-unit process streams are being integrated. These streams are being added below the pinch and hence the large shift in the integrated curve. The actual integrated plant is in fact using less energy than the predicted targets for the non-integrated plant.

- d) Plant 5 has a hot pinch temperature of  $168.9^{\circ}\text{C}$ . The hot stream integrated into the plant extends across the pinch. The portion of the hot stream added above the pinch reduces the hot utility requirement while the portion added below the pinch increases the cold utility requirement. However, the decrease in hot utility is greater than the increase in cold utility resulting in a net decrease in energy with a decrease in the total potential savings.
- e) Plant 6 is unpinched and thus the cold streams added reduce the cold utility requirement. As with plant 3, the actual plant after integration uses less energy than the minimum requirement for the non-integrated plant.

The general conclusions drawn are:

- 1) Where streams are integrated into the process, the net result ought to be a decrease in the energy requirement. Any increase will not result in a decrease in the potential savings, but rather an increase. If the energy requirement were to increase, the target curve of the integrated plant would lie to the right of the curve for the non-integrated plant.
- 2) When the target curve of the integrated plant shifts very little compared to the target curve of the non-integrated plant, very little saving in energy has been achieved.
- 3) When the actual energy consumption of the integrated plant is less than the target for the non-integrated plant, the inclusion of the inter-unit streams has resulted in a decrease in the utility requirements.

#### 5.7 Steam Generation Below the Pinch

As explained in Section 2.5 in Chapter 2, it is possible to raise different levels of steam below the pinch. The grand composite curve is used to give an indication of the energy available at different temperature levels below the pinch. Once the level of steam required has been set, the additional heat required to heat the feed water to that temperature must be included in the analysis.

The grand composite curves for the plants are presented in Figures G1 to G7 in Appendix 7. Also shown on these curves are the different levels of steam which may be generated with the slanted lines representing the feed water pre-heat. These curves were constructed using all streams listed in Tables A1 to A7 in Appendix 1 (including inter-unit streams) since the potential to

raise steam from the present position was being calculated. Inspection of the figures in Appendix 7 shows the following:

- 1) On plant 1, either high pressure (HP), medium pressure (MP) or low pressure (LP) steam could be generated, but not a combination of steam levels. Due to the pre-heat curve, more LP steam could be produced than either MP or HP steam. However, the largest savings in steam were based on the HP steam production due to its larger costs. The savings associated with the above three cases may be summarised as follows:

	Case 1	Case 2	Case 3
HP steam (kW)	2500	0	0
MP steam (kW)	0	2500	0
LP steam (kW)	0	0	3000
Total value (\$)	257500	193700	155800

- 2) Plant 2 was similar to plant 1 in that either HP, MP or LP steam could be generated. The largest steam production was in the form of LP steam while the largest savings were based on the MP steam production. The savings associated with the above three cases may be summarised as follows:

	Case 1	Case 2	Case 3
HP steam (kW)	1300	0	0
MP steam (kW)	0	5000	0
LP steam (kW)	0	0	5800
Total value (\$)	133900	387300	301300

- 3) No steam of any level could be raised below the pinch on plants 3 and 4 after integration.

- 4) Plants 5 and 7 could only produce LP steam below the pinch. The steam productions and associated costs may be summarised as follows:

	Plant 5	Plant 7
LP Steam (kW)	960	380
Value (\$)	49900	19700

- 5) On plant 6, three combinations of steam levels were possible. These combinations were as follows:

	Combination 1	Combination 2	Combination 3
HP steam (kW)	285	0	0
MP steam (kW)	275	710	0
LP steam (kW)	285	285	1110
Total steam (kW)	845	995	1110
Total value (\$)	65500	69800	57700

Combination 2 (although not giving the largest steam production) resulted in the largest steam savings. The savings in steam were thus based on this option.

The theoretical and actual savings are listed in Table 5.17. The actual savings have already been achieved while the theoretical savings correspond to the actual steam production possible from the present operation. The steam savings possible before inter-unit integration were calculated in the same way as presented above.

Plant	Theoretical savings before inter-unit integrat	Theoretical savings after inter-unit integrat	Actual Production
1	257500	257500	0
2	236300	387300	0
3	430000	0	430000
4	0	0	0
5	8300	49900	0
6	200700	69800	0
7	19700	19700	0
Total	1152500	784200	430000

Table 5.17 Potential and Actual Steam Savings Below the Pinch

From the above table, it is noted that the total potential to raise steam below the pinch decreases after inter-unit integration. In plants 2 and 5 however, the potential to raise steam has in fact increased after integration. This is the result, once again, of the addition of hot streams below the pinch (so increasing the overall cold utility). For the non-integrated plants, the potential has remained the same. The full potential to raise steam in plant 3 has been realised by integration of a utility stream.

The potential to raise steam below the pinch (and thus also save on cold utility) is \$784 200 per annum.

To partly realise this possible steam production, there are at present inoperative steam generators located on plants 1 and 2. These generators are designed to produce low pressure steam. If only savings associated with LP steam production are considered on each plant, the possible savings (including inter-unit streams) will be as follows:

Plant	Theoretical savings after inter-unit integrat
1	155800
2	301300
3	0
4	0
5	49900
6	57700
7	19700
Total	584400

Table 5.18 Actual LP Steam Savings Below the Pinch

From this table it can be seen that approximately 75% of the total steam savings could be achieved if only LP steam production was considered.

The material dealt with in this chapter has covered the following topics:

- 1) The cost parameters used (for the hot and cold utility requirements).
- 2) The stream data for each plant.
- 3) The present mode of operation in terms of the network currently implemented on each plant.
- 4) Calculation of the optimum approach temperature on each plant.
- 5) The potential energy savings on each plant.
- 6) The potential financial savings on each plant.
- 7) The potential energy and financial savings possible after combining individual plants.
- 8) An energy-area investigation on each plant.
- 9) The potential to raise steam below the pinch on each plant.

The next chapter will deal with actual plant modifications considered to achieve the calculated savings. The modifications considered are subject to both physical and financial constraints. The subject of Chapter 6 will be to present possible physical and financial constraints and then discuss possible modifications on the individual and combined units. Finally, steam production below the pinch on the different plants will be considered.

## 6 REALISTIC PLANT MODIFICATIONS.

The first part of this chapter deals with plant modifications which may be considered on a financial and physical basis. By considering the financial savings possible on each plant, the degree of integration involving additional hardware will be considered. Any additional integration will also be governed by physical constraints and hence a compromise between the two will have to be established. The rest of the chapter deals with steam production in the different units.

### 6.1 Financial Constraints

If a payback period of three years is considered, the total capital expenditure on each plant cannot exceed the values presented in Table 6.1 below (the potential savings presented in Tables 5.14 and 5.16 in Chapter 5 multiplied by three):

An inspection of the table below shows that the largest scope for improvement lies in plants 1, 2 and 4. Plant 2, allowing for a total expenditure of approximately \$820 000, shows the most promise.

Using the installed exchanger costs presented in Chapter 5, exchangers with a total area presented in Table 6.2 below may be installed.

Plant no.	Capital expenditure
1	365100
2	815700
3	129300
4	487500
5	176400
6	108300
7	109500
A	1698000
B	2158500

Table 6.1 Capital Expenditure Resulting in a Three Year Payback

On the basis of the areas presented in Table 6.2, it would appear that only the installation of a new LP exchanger or a new, small HP exchanger will be economically justifiable. At this stage, it appears as if the addition of LP exchangers on plant 2 might be a feasible option, whereas the addition of HP exchangers on plants 4 and 5 may result in large payback periods.

An additional financial constraint lies in matching high pressure streams - either two HP streams or a single HP stream. The hardware required is more expensive than that for LP exchangers. Modifications involving high pressure stream matches will thus be dictated by the payback period.

Plant	Area (m <sup>2</sup> )
1	77
2	200
3	23
4	109
5	33
6	19
7	19
A	473
B	627

Table 6.2 Installed Area resulting in a Three Year Payback

Due to the relatively low capital expenditure allowed, complex modifications may also result in large payback periods. These modifications could include the following:

- 1) Adding several exchangers on a single plant.
- 2) Installation of new columns.

Modifications using the existing hardware would result in the most successful retrofit. These modifications could include the following:

- 1) Rerouting streams.
- 2) Changing stream mixing points.
- 3) Changing operating conditions (temperature and pressure).
- 4) Stream splitting requiring tight control.

As mentioned in Section 5.5, several plants were combined resulting in larger savings (approximately twice that possible in the individual plants). However, to achieve these financial savings, a greater saving in energy must be achieved compared to the individual plants. This must be affected by matching streams between the combined plants (else one is merely considering integration of an individual unit).

## 6.2 Physical Constraints

The physical constraints are limitations placed on actual process to process matches. This constraint is important when considering matching an overhead stream against a reboiler stream. At present, many overhead streams are cooled in fin fans while several reboilers make use of steam. To eliminate this utility consumption, it is often desirable to match these streams.

Since the overhead streams undergo condensation, the pipework taking this stream to the overhead condenser must always slope downwards. Typically these condensers are located near to the top of the column.

Many of the reboilers are thermosyphon reboilers. Due to the thermosyphon action, it is not possible to raise the reboiler to the level of the overhead stream without installing a pump. The expenses associated with this type of match include the following:

- a) Installing the same reboiler (or a new one depending on the different operating conditions) on the same level as the overhead drum.
- b) Installing a new pump to meet the increased head.

Any modifications based on matching an overhead stream with a reboiler stream will not be expected to yield a favorable payback

period due to the financial implications. Due to the imposed physical constraint, it was decided to re-analyse the stream data with the overhead streams removed. It was anticipated that this may give an energy saving which would be easier to achieve in practice. The new energy targets are tabulated in Table 6.3 below.

Plant	Present targets		Targets without Overhead streams		Diff. in Cold Utility (kW)	Fin Fan Duty (kW)
	Cold Utility (kW)	Hot Utility (kW)	Cold Utility (kW)	Hot Utility (kW)		
1	15340	0	1950	190	13390	13580
2	14390	41200	0	44400	16250	17590
3	2410	5140	870	5140	1540	1540
4	6280	13490	1710	13570	4570	4650
5	5810	3280	410	3620	5400	5740
6	2050	0	1760	0	290	290
7	3140	550	3130	550	10	10

Table 6.3 Targets with and without Overhead Streams

From the above table it can be seen that the hot utility target after removing the overhead streams is similar to the hot utility target with the streams included. Since the largest savings are associated with this target (the cold utility is in the form of fin fan cooling), the potential for improvement will not be significantly affected.

The following section will deal with different modifications considered on each plant as well as modifications on the combined plants. For each of the plants, the following preliminary work will be presented before the modifications are discussed:

- 1) The stream data will be analysed in terms of energy levels. This is a new technique developed to aid in the analysis of actual matches. By investigating these levels, it can be seen if the rule of matching the coldest hot streams against the coldest portion of a cold stream (or matching the hottest hot streams against the hottest portion of the cold stream) is obeyed.
- 2) Any cross pinch exchangers in the actual network will be identified. Possible modifications to eliminate these exchangers are presented.

Once the above investigations have been completed, possible modifications (including changing operating parameters) will be discussed. As discussed above, it is not always possible to match the overhead streams. However, if additional duty could be removed in a top pump-around stream, the duty in the overhead stream would be reduced which would lead to an energy saving. This is a general modification which will be considered on plant 1. The detailed discussion on each plant is presented in Appendix 8 while the findings for each plant are summarised below.

### **6.3 Modifications on the Individual Plants**

#### **6.3.1 Plant 1**

The plant is unpinched. The target hot utility consumption is zero while the target cold utility consumption is 15 340 kW. The actual hot utility consumption is 1 400 kW while the actual cold utility consumption is 16 740 kW. A feature of this plant is a dominant cold stream (in terms of its duty). The plant is discussed in

Section 1 in Appendix 8. The findings for this plant are as follows:

- 1) The matches against the dominant cold stream are arranged in order of ascending temperature levels. There is, however, one anomaly in this arrangement, but relocating this match could not be justified on a physical or a financial basis.
- 2) No process modifications were considered due to the problem being unpinched.
- 3) A slightly different matching arrangement was considered to the present, but this had the drawback that additional hot utility would be required compared to the present consumption.
- 4) An arrangement where a pump-around stream could be used to supply the actual steam consumption (LP steam) would result in a saving of approximately \$72 700 per annum. Possible constraints which could cause this modification to be a non-viable option include the following:
  - 1) Different column operating conditions due to two pump-around streams being returned at significantly lower temperatures. This new mode of operation would have to be investigated using a package similar to PROCESS or HYSIM.
  - 2) Additional pipework and controllers.

The exchanger in which steam is presently being used would have sufficient area to meet the requirements of the new proposed match.

With the exception of the above modification, no simple improvement over the existing network could be found. However, by introducing a feed stream (from plant 2) into this plant at a higher temperature than at present, approximately \$63 000 per

annum in energy savings could be achieved. This modification will be discussed in the analysis of plant 2 in the following section.

### 6.3.2 Plant 2

The plant is pinched with a hot pinch temperature of 272°C and a cold pinch temperature of 261°C. The target hot utility consumption is 41 200 kW while the target cold utility consumption is 24 760 kW. The actual hot utility consumption is 44 400 kW while the actual cold utility consumption is 21 150 kW. A feature of this plant is dominant cold stream 1 (in terms of its duty). As mentioned in Section 5.7 in Chapter 5, both hot and cold streams were added below the pinch. As discussed in section 2.1 in Appendix 8, integration of the streams into the problem is slightly less efficient (3% increase in the overall area) than if they exchanged heat solely amongst themselves. The plant is discussed in Section 2 in Appendix 8. The findings for this plant are as follows:

- 1) With the exception of a single match, the hot streams are matched against the dominant cold stream in order of increasing temperature levels. The incorrectly placed match was a recent addition to the plant, but due to reduced driving forces, the desired heating was not achieved. As discussed in Section 2 in Appendix 8, it would not be economically feasible to move this match.
- 2) Two exchangers transfer energy across the pinch. One of the hot streams is a pump-around stream while the other is a liquid stream. Since the supply temperature of the pump-around stream is 39°C above the hot pinch temperature, the stream cannot be easily integrated below the pinch (without changing the column operating conditions). For the existing network, integration above the pinch results in a simultaneous decrease

- 6) By removing the overhead streams from the stream data, the actual and target hot utility consumptions were the same. This confirmed the fact that only modifications involving the overhead streams would result in a hot utility saving.

From the above discussion, no minor plant modifications would result in an energy saving. It was found that although savings were possible, they always resulted in a simultaneous increase in hot utility in a different stream or plant.

### 6.3.3 Plant 3

The plant is pinched with a hot pinch temperature of 135°C and a cold pinch temperature of 126.7°C. The pinch is a utility pinch since it is caused by a cold utility stream with a large duty. The target hot utility consumption is 4 780 kW while the target cold utility consumption is 8 260 kW. The actual hot utility consumption is 5 340 kW while the actual cold utility consumption is 2 620 kW. The plant is discussed in Section 3 in Appendix 8. The findings for this plant are as follows:

- 1) The matches make good use of the available temperature levels.
- 2) Match 3 appears to be badly placed but since this is the only available cold stream to be matched against the hot stream, no alternative match exists.
- 3) No columns straddle the pinch and no pump-around streams transfer energy across the pinch.
- 4) Due to the reduced stream data set (few hot and cold streams), no general modifications could be found which would result in an energy saving.

- 3) Two exchangers transfer energy across the pinch. The first transfers 4% (400 kW) of its duty across the pinch. However, the above modification would result in only 0.5% of its duty being transferred across the pinch. Thus no further attempt was made to reduce the energy transferred across the pinch.

The second cross-pinch exchanger could be integrated below the pinch by using a different hot stream in the exchanger. However, no cold stream existed above the pinch against which the discarded hot stream could be totally matched thus eliminating the possibility of totally reducing the cross-pinch exchange. By installing additional area, a portion of hot stream 4 (lying below the pinch) could be used to partially reduce the energy transferred across the pinch. The fuel oil savings would be approximately \$49 000 per annum while the cost of the installed exchanger would be approximately \$75 000.

- 4) Although several columns straddled the pinch, the overhead streams are cooled with fin fans. Thus integration of these columns above or below the pinch would not lead to significant energy savings unless a suitable liquid stream could be matched against an overhead stream.
- 5) A feed stream (from plant 5) could be introduced at a higher temperature into the plant. At present, this stream is first mixed with a cold recycle stream before being matched. If the recycle stream was first matched against a hot stream before being mixed with the now hotter feed stream, a fuel oil saving of approximately \$30 000 per annum could be achieved. However, an additional 1500 kW of cooling would be required in the fin fan and since its present mode of operation is marginal in summer, is expected that problems could arise during these months. However, if this modification is considered in conjunction with modification (2) above, the fin fan operation would not be affected.

By installing additional area, match 1 will also transfer less energy across the pinch. To achieve an energy saving of \$135 000 per annum, an exchanger costing \$200 000 would have to be installed giving a payback period of approximately 1.5 years.

- 3) A single column straddles the pinch, but as was the case in plant 4, the overhead stream is cooled using fin fans. Thus integration of this column above or below the pinch will not result in any energy savings.
- 4) A general modification, which must be considered in conjunction with plant 4, involves introducing the feed stream to plant 4 at a higher temperature. However, the net result in plant 4 is an increased fin fan duty since the stream to the fin fan enters 33°C higher than at present. The fin fan operation is apparently marginal in summer and this new operating condition would lead to problems. However, if a solution to this problem was found, an energy saving of \$60 000 per annum in plant 4 could be achieved by installing an additional exchanger in plant 5. The installed cost of this exchanger would be approximately \$250 000. Due to the increased fin fan duty and the approximate four year payback period, the modification does not seem feasible.

Since most of the modifications discussed above have resulted in long payback periods (with the exception of modification 2), it was decided that this modification would be the only feasible change.

#### 6.3.6 Plant 6

The plant is unpinched. The target hot utility consumption is zero while the target cold utility consumption is 5 610 kW. The actual hot utility consumption is 450 kW while the actual cold utility

consumption is 2 500 kW. The plant is discussed in Section 6 in Appendix 8.

With a potential saving of only \$36 100 per annum and the fact that no further matches are possible (the present matches would have to be re-arranged and additional matches introduced to further reduce the energy consumption), no minor plant modifications would result in the savings being achieved.

### 6.3.7 Plant 7

The plant is pinched with a hot pinch temperature of 176.7°C and a cold pinch temperature of 171.1°C. The target hot utility consumption is 540 kW while the target cold utility consumption is 3 140 kW. The actual hot utility consumption is 960 kW while the actual cold utility consumption is 3 560 kW. The plant is discussed in Section 7 in Appendix 8. The findings for this plant are as follows:

- 1) The plant consists of only five streams - four of these being hot streams. The unmatched hot streams cannot be matched against the cold stream since their temperature levels are incorrect.
- 2) The single exchanger transfers energy across the pinch. By matching an additional hot stream below the pinch and increasing the area, additional energy can be saved. The energy savings amount to \$23 700 per annum while the cost of an installed, high pressure exchanger with sufficient area amounts to \$132 000. This results in an approximate 4.5 year payback period.

Due to the long payback period associated with modification 2, it was decided that the present mode of operation on this plant should continue.

#### **6.4 Summary of the Modifications on the Individual Units**

An analysis of the seven plants has shown nine possible modifications. In three cases the capital expense was not calculated since it involved the installation of additional pipework and controllers, while three modifications appear to be feasible (although the payback period may be too long). The modifications are listed in Table 6.4 below in order of increasing payback period. From this table, it can be noted that projects with a payback period of less than two years will give a saving of approximately \$344 000 per annum while the investment required would be approximately \$410 000.

#### **6.5 Modifications on the Combined Plants**

##### **6.5.1 Combined Plant A**

The plant is pinched with a hot pinch temperature of 272°C and a cold pinch temperature of 261°C. The target hot utility consumption is 43 100 kW while the target cold utility consumption is 30 130 kW. The actual hot utility consumption is 49 750 kW while the actual cold utility consumption is 23 760 kW. The findings for this plant are as follows:

The actual network for this plant is shown in Figure 6.1 below.

Plant	Type of match	Reason for modific.	Energy savings (\$ per annum)	Installed exchanger cost (\$)	Payback period
1	low press liquid-liquid	general mod.	72700	0	---
1+2	introduce feed hotter	general mod.	39000	0	---
4	low press liquid-liquid	general mod.	11000	0	---
4	increase area	reduce cross-pinch exchange	160000	135000	0.8
4	increase area	reduce cross-pinch exchange	49000	75000	1.5
5	increase area	reduce cross-pinch exchange	135000	200000	1.5
5	introduce feed hotter	general mod.	60000	250000	4.2
5	increase area	reduce cross-pinch exchange	20600	96000	4.7
7	high press liquid-liquid	reduce cross-pinch exchange	23700	132000	5.6

Table 6.4 Summary of Possible Plant Modifications for the Individual Plants



problem. The new hot utility target was 48 670 kW which allows for an approximate energy saving of \$60 000 per annum.

6.5.2 Combined Plant B

The plant is pinched with a hot pinch temperature of 101.7°C and a cold pinch temperature of 96.1°C. The target hot utility consumption is 13 930 kW while the target cold utility consumption is 11 320 kW. The actual hot utility consumption is 22 210 kW while the actual cold utility consumption is 19 560 kW. The findings for this plant are as follows:

The actual network for this plant is shown in Figure 6.2 below.

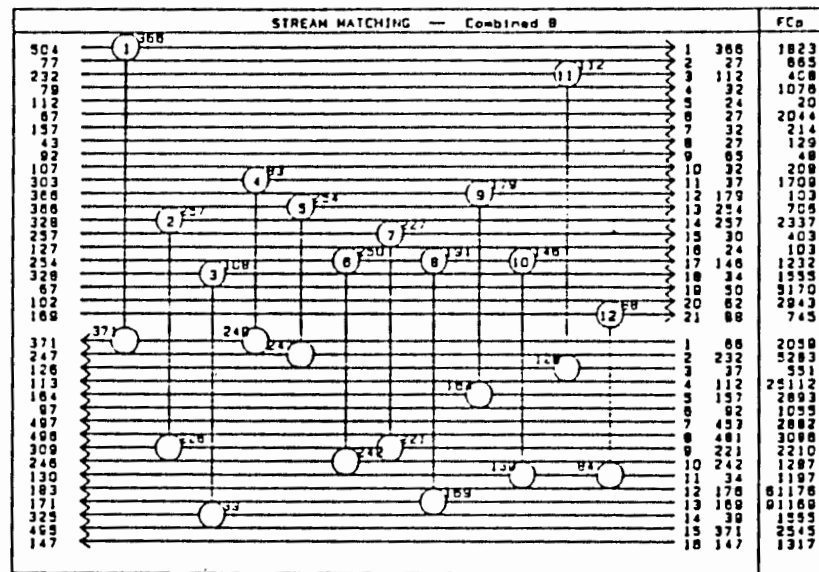


Figure 6.2 Actual Network for Combined Plant B

An inspection of unmatched streams shows that cold streams 4 and 6 exist at a low enough temperature level to be matched against either of hot streams 7, 15 or 16. However, the duty of hot stream 16 is insufficient to meet the requirements of either the two cold streams. A match involving hot stream 7 with cold stream 6 has already been considered in Section 6.3.4. The

would involve matching a portion of hot stream 15 against a portion of cold stream 4 to avoid a violation of the approach temperature. At present, cold stream 4 has its duty supplied by steam. If 80% of its duty is provided by hot stream 15 (with the other 20% still being provided by steam), a saving of 1200 kW in steam could be achieved. This would represent a saving of approximately \$62 400 per annum. The cost of installing an additional exchanger would be approximately \$75 000 which would result in a payback period of approximately 1.2 years.

Apart from the above possible modifications, no other feasible matches exist with the result that no additional modifications were considered.

The feasible modification presented above may be summarised in Table 6.5 below:

Plant	Type of match	Reason for modific.	Energy savings (\$ per annum)	Installed exchanger cost (\$)	Payback period
B	low press gas-liquid	general mod.	62400	75000	1.2

Table 6.5 Summary of Possible Plant Modifications for the Combined Plants

## 6.6 Possible Sources of Steam Generation

As discussed in Section 5.8 in Chapter 5, there is a potential to raise steam below the pinch on several plants. The questions which arise in connection with this are:

- a) How is the steam to be raised?
- b) Where would the additional steam be used?

To answer the first question, one must first consider the second problem. A number of pumps (using electrically driven motors) have backup turbines which make use of HP steam. Thus any additional HP steam production may be used to drive these turbines. An added bonus would be that the potential savings would increase slightly since a saving in electrical power would also be achieved. Any additional LP or MP steam produced can be expressed in terms of a financial saving, but the quantity produced may be limited by the actual utilisation of this steam on the refinery.

To answer the second question, the production of HP steam would be most favorable. However, the production of LP or MP steam will also be considered. The potential to raise steam on plant 3 has already been realised leaving a potential of zero. Steam production on the remaining plants will be discussed below:

Plant 1: As stated, two inoperative LP steam generators are already located on the plant. The first of these generators is located on a pump-around stream. By splitting this stream, LP steam could be produced. This would, however, result in cold stream 1 being heated to a lower target temperature which would not suit the current mode of operation. On the other hand, the hot stream bypassing the second generator is being cooled in a fin fan located directly after this generator. Using the pipework and controllers already installed, this stream may be redirected

through the generator. At present, the duty lost in the fin fan is 405 kW. By passing the stream through the generator, a duty of 302 kW can be used to produce LP steam with an associated saving of approximately \$15 700 per annum. An alternative mode of operation, in which MP steam is generated, is limited in that only 80 kW (\$6 100 saving per annum) of steam could be produced. No HP steam production is possible.

Plant 2: As with plant 1, two inoperative LP steam generators are present. These generators use hot pump-around streams drawn from the bottom of distillation columns. However, by returning the streams colder to the columns, additional stripping steam and an increased furnace duty will result. The savings achieved by the steam production would be offset by the increased hot utility.

Plant 4: Only one unmatched hot stream exists at a high enough temperature level to produce LP steam. The duty associated with this steam would be approximately 30 kW which would obviously not warrant the installation of an LP generator.

Plant 5: No unmatched hot streams exist at a high enough temperature level to raise steam on any level.

Plant 6: No steam generator is present. After matching hot stream 2 against cold stream 1, its new supply temperature is approximately 225°C which is sufficient to produce either MP or LP steam. Both levels of steam production would have a duty of 1000 kW. The savings associated with the MP steam production would be approximately \$77 500 per annum while the savings in LP steam would be approximately \$52 000 per annum. The installed cost of an MP steam generator would be approximately \$70 000 while the installed cost of an LP steam generator would be approximately \$57 000 resulting in an approximate one year payback period in both cases.

From the above discussion, LP steam may be produced on plant 1 without installing additional hardware, while LP or MP steam may be generated on plant 6 with an approximate one year payback period.

## 7 CONCLUSIONS AND RECOMMENDATIONS

The conclusions drawn from work in this study will be presented in four sub-sections. These will be the package (UCTNET) written, the use of Remaining Problem Analysis, the current plant energy recovery status and realistic retrofit modifications. Finally possible recommendations will be presented.

### 7.1 UCTNET

A package, UCTNET was written to perform pinch analysis and design/rate heat exchanger networks. Tools using pinch technology (Cost analysis, Energy-Area analysis and Driving Force Plots) were also incorporated into the package. The following conclusions were drawn:

- 1) An easy programming environment was chosen in Turbo Pascal.
- 2) UCTNET can run on most IBM or IBM compatible PC's or AT's since four different graphics cards are supported - these being an Hercules card, a CGA, an EGA and a VGA card.
- 3) UCTNET is best mounted on a hard drive.
- 4) UCTNET is very user-friendly in that all options are selected via menus.
- 5) UCTNET has many features - these being:
  - 1) Construction of Composite and Grand Composite Curves.
  - 2) Construction of Driving Force Plots.
  - 3) Calculation of an optimum  $\Delta T_{min}$ .
  - 4) An Energy-Area analysis.
  - 5) A grass-roots network design guided by Remaining Problem Analysis
  - 6) A retrofit section.
- 6) When dealing with threshold problems, UCTNET identifies the problem to be unpinched. HEATNET and CHEMCALC-5 both calculate hot and cold energy targets.

## 7.2 Use of Remaining Problem Analysis

Remaining Problem Analysis (RPA) provides a tool to study the effectiveness of a proposed match. This tool was developed by Ahmad (1985) and used in the design of grass-roots networks. In this project, RPA has been further investigated in grass-roots design as well as in retrofit projects. The conclusions drawn were:

- 1) When designing a grass-roots network, several matching options may exist at the pinch. If the matches are analysed using RPA until all streams starting and ending at the pinch have been matched, the network with the highest intermediate area efficiency will produce a network with the lowest overall capital cost.
- 2) In designing a grass-roots network, an area efficiency just larger than unity may result. This is the consequence of using an incorrect equation to derive the minimum area target (the "Bath" formula allows different stream film coefficients to be used, but this is not correct. The cold streams must have the same coefficient while the hot streams may have the same or a different coefficient.).
- 3) In a retrofit, the application of RPA may lead to misleading results. An energy efficiency far larger than unity may result for the following two reasons:
  - a) An exchanger may transfer energy across the pinch. This energy penalty results in a decreased efficiency corresponding to a value larger than unity (by definition of the energy efficiency in section 3.1 in Chapter 3).
  - b) The pinch may change resulting in different area and energy targets compared to the targets for the unmodified stream data.

### 7.3 Current Plant Energy Recovery Status

The plant on which the project is based, consists of seven different units. The energy and financial savings on each of these units was calculated using pinch technology. These savings were confirmed using an Energy-Area analysis where the actual unit (in terms of energy and area) was located relative to the ideal for that unit. Several units were combined into two combined units. The conclusions drawn for the individual and combined units was as follows:

- 1) For each of the units considered, the exchanger minimum approach temperature (EMAT) was similar to the heat exchanger recovery approach temperature (HRAT). All pinch analyses were based on the EMAT value.
- 2) In calculating the potential energy savings on each plant, the savings due to inter-unit integration had to be considered. The total saving possible from the present position was approximately \$730 600 per annum. The largest savings already achieved was due to integration of utility streams (\$687 500 per annum). Of the seven units considered, units 2 and 5 showed the largest inter-unit integration which have resulted in a significant amount of the possible energy savings having already been achieved.
- 2) The potential financial savings on each unit are far less than those quoted in the literature. This is due to the current low energy costs in this country. The values used were approximately 25% less than those used in similar projects overseas.
- 3) Units 1, 2 and 4 show the largest remaining potential to save energy. The remaining units have a far smaller potential.

- 4) By combining individual units, the potential energy savings approximately doubled. The total financial savings possible for the combined units from the present position is approximately \$1 443 700 per annum.
- 5) If hot streams are added below the pinch, the cold utility requirement increases since only cold utility is required below the pinch. Similarly the addition of cold streams above the pinch leads to an increase in the hot utility requirement since only hot utility is required. On plant 2, hot and cold streams were added below the pinch with the net effect being a decrease in the cold utility requirement.

#### 7.4 Realistic Retrofit Modifications

Modifications on the individual and combined units were analysed in terms of financial savings and where possible, a capital investment. Several modifications could not be considered due to physical and financial constraints. The conclusions drawn were:

- 1) Overhead streams were not matched against liquid reboiler streams since the pipework taking the overhead streams to the overhead drum always had to slope downwards. To raise the reboiler to the level of the overhead drum would have been an expensive modification.
- 2) To account for the non-feasible matches with the overhead streams, they were removed from the stream data and the energy targets re-calculated. It was found that the hot utility requirement did not change significantly thus indicating that the savings would not change significantly either.
- 3) On plant 2, integration of the inter-unit streams was not very effective since hot streams were added below the pinch. This had the effect of increasing the cold utility

requirement. This increase was, however, offset by the duties of the cold streams added below the pinch.

- 4) With the exception of plants 3 and 4, steam could be raised on all the plants.
- 5) Using an existing inoperative LP steam generator on plant 1, an additional 302 kW of LP steam could be generated. The financial savings associated with this level of steam amounted to approximately \$15 700 per annum.
- 6) It was possible to raise either LP or MP steam on plant 6. The financial savings associated with the LP steam generation would be approximately \$52 000 with the installation costs of the generator being approximately \$57 000. On the other hand, the financial savings associated with the MP steam production would be approximately \$77 500 with the installed cost of the generator being approximately \$70 000.
- 7) On plant 1, an approximate saving of \$72 700 per annum can be achieved by rerouting streams and increasing pump-around duties (by returning the stream to the column at a lower temperature). The drawback concerning this modification would lie in the different column operating conditions.
- 8) By installing additional area, the duty in one of the furnaces on plant 4 would be reduced. The fuel oil savings would be approximately \$172 000 per annum while the cost of the exchanger would be approximately \$135 000.
- 9) On plant 4 it was possible to match a hot liquid stream against a reboiler liquid stream thus eliminating the steam requirement. This match would result in a saving of approximately \$11 000 per annum.

- 10) On plant 5 it is possible to partly eliminate energy transferred across the pinch by installing additional area. The energy savings would be approximately \$135 000 per annum while the installed exchanger would cost approximately \$200 000. On plant 7, energy transferred across the pinch may also be reduced by installing additional area. The savings would be approximately \$23 700 while the exchanger would cost approximately \$132 000.
  
- 11) On combined plant B, it is possible to eliminate 80% of the steam requirement in a reboiler by installing an additional exchanger. The steam savings would be approximately \$62 400 per annum while the cost of the exchanger would be approximately \$75 000.

## 7.5 Recommendations

From insight gained during completion of the project, the following is recommended:

- 1) The "Bath" formula in RPA should be replaced or revised.
- 2) RPA does not provided a very effective tool when analysing retrofit projects.
- 3) An energy level plot is very helpful in analysing actual plant matches. This plot gives an indication of the temperature levels of the hot and cold streams involved in a match.
- 4) A pinch analysis should be used in plant modification studies (retrofits) to prevent misplacing new matches.
- 5) The effect of change pump-around rates on certain of the columns should be investigated.
- 6) A number of viable retrofit possibilities have been identified using approximate costing. These will need to be designed and costed in detail.

- 7) A detailed knowledge of the process is essential to identifying the best possibility where several modifications are possible.

**REFERENCES**

- Ahmad, S.**, "Heat Exchanger Networks: Cost Tradeoffs in Energy and Capital", Ph.D. Thesis, UMIST, 1985.
- Ahmad, S. and Petela, E.A.**, "SUPERTARGET: Applications Software for Oil Refinery Retrofit", AIChE Meeting, Houston, Texas, March 20 - April 2, 1987
- Ahmad, S., Polley, G.T. and Petela, E.A.**, "Retrofit of Heat Exchanger Networks subject to Pressure Drop Constraints", Paper No. 34a, AIChE Spring Meeting, Houston, April 1989.
- Backhurst, J.R. and Harker, J.H.**, "Process Plant Design", Heinemann Educational Books, London, 1977.
- Boland, D.**, "Energy Management: Emphasis in the 80s", The Chem. Eng., (390), pp 24-28, March 1983.
- Boland, D., and Hindmarsh, E.**, "Heat Exchanger Network Improvements", Chem. Eng. Prog., 80 (7), pp 27-32, July 1985.
- Challand, T.B. and O'Reilley, M.G.**, "New Engineering Software for Energy-Conservation Projects.", Simulation Sciences Inc.
- Ciric, A.R. and Floudas, C.A.**, "A Retrofit Approach for Heat Exchanger Networks", Computers chem. Engng., Vol. 13, No. 6, pp 703-715, 1989
- Douglas, J.M.**, "Conceptual Design of Chemical Processes", McGraw-Hill, New York, 1988.
- Fraser, D.M.**, "The Use of Minimum Flux Instead of Minimum Approach Temperature as a Design Specification for Heat Exchanger Networks", Chem. Eng. Sci., Vol. 44, No. 5, pp 1121-1127, 1989

- Gillespie, N.E. and Fraser, D.M., "UCTNET - A Program for the Analysis and Design of Heat Exchanger Networks", Symposium on Personal Computers and the Process Industry, SAChE, April 1989.
- Grimes, L.E., Rychener, M.D. and Westerberg, A.W., "The Synthesis and Evolution of Networks of Heat Exchange That Feature the Minimum Number of Units", Chem. Eng. Commun., Vol. 14, pp 339-360, 1982.
- Gundersen, T. and Naess, L., "The Synthesis of Cost Optimal Heat Exchanger Networks.", The Use of Computers in Chemical Engineering, XVIII Congress, pp 675-704, April 1987.
- Hindmarsh, E., "A Practical Application of a Distillation System Retrofit.", November 1983.
- Hohmann, E.C., "Optimal Network for Heat Exchange", Ph.D. Thesis, University of Southern California, 1971.
- Linnhoff, B., "New Concepts in Thermodynamics for Better Chemical Process Design.", Chem. Eng. Res. Des., Vol 61, pp 207-223, July 1983.
- Linnhoff, B., Dunford, H. and Smith, R., "Heat Integration of Distillation Columns into Overall Processes.", Chem. Eng. Sci., Vol. 38, No. 8, pp 1175-1188, 1983.
- Linnhoff, B, Townsend, D.W, Boland, D., Hewitt, G.F., Thomas, B.E.A., Guy, A.R. and Marsland, R.H., "User Guide on Process Integration for the Efficient Use of Energy", Institution of Chemical Engineers, London, 1982.
- Linnhoff, B. and Flower, J.R., "Synthesis of Heat Exchanger Networks.", AIChE Journal, Vol. 24, No. 4, pp 633-654, July 1978.

- Linnhoff, B. and Hindmarsh, E., "The Pinch Design Method for Heat Exchanger Networks.", Chem. Eng. Sci., Vol. 38, No. 5, pp 745-763, 1983.
- Linnhoff, B. and Kotjabasakis, E., "Sensitivity Tables for the Design of Flexible Heat Exchanger Networks: Systems with Variable Physical Properties", Paper No. 39b, AIChE, Spring Meeting, March 1988.
- Linnhoff, B., Mason, D.R. and Wardle, I., "Understanding Heat Exchanger Networks.", Computers and Chemical Engineering, Vol. 3, pp 295-302, 1979
- Linnhoff, B., and Turner, J.A., "Heat Recovery Networks: New Insights Yield Big Savings", Chem Eng., No. 88 (22), pp 56-70, November 1981.
- Linnhoff, B. and Vredeveld, D.R., "Pinch Technology Has Come of Age.", CEP, pp 33-40, July 1984.
- Ponton, J.W. and Donaldson, R.A.B., "A Fast Method for the Synthesis of Optimal Heat Exchanger Networks", Chem. Eng. Sci., 29, 2375, 1979.
- Saboo, A.K., Morai, M., and Colberg, R.D., "RESHEX: An Interactive Software Package for the Synthesis and Analysis of Resilient Heat-Exchanger Networks - I", Computers and Chemical Engineering, 10 (6), pp 577-589, 1986.
- Smith, J.M. and van Ness, H.C., "Introduction to Chemical Engineering Thermodynamics", McGraw-Hill, Singapore, Third Edition, 1984.
- Su, J. and Motard, R.L., "Evolutionary Synthesis of Heat Exchanger Networks.", Computers and Chemical Engineering, Vol. 8, No. 2, pp 67-80, 1984.

Tjoe, T.N., "Retrofit of Heat Exchanger Networks", Ph.D. Thesis, UMIST, 1985.

Townsend, D.W. and Linnhoff, B., "Surface Area Targets for Heat Exchanger Networks.", I Chem Eng Annual Res. Meeting, 1984.

Trevedi, K.K., O'Neill, B.K. and Roach, J.R., "A New Dual Temperature Design Method for the Synthesis of Heat Exchanger Networks", Computers chem. Engng. Vol. 13, No. 6, pp 667-685, 1989.

Wood, R.M., "The Effect of Distillation Column Conditions on the Performance of Heat Exchanger Networks - A Case Study", The Arabian Journal for Science and Engineering, Vol. 11, No. 3, 1986

Private Communication by AECI, 1987.

**APPENDIX 1**

(Note: In Tables A1 to A7, (\*) refers to a stream from another unit)

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kJ/°C.hr.m <sup>2</sup> )	Heat Capacity Flowrate (kJ/hr.°C) *10 <sup>-4</sup>	Duty (kJ/hr) *10 <sup>-6</sup>	Code
Hot 1	165.5	90.0	327	4.660	3.519	LS
Hot 2	282.0	196.5	1770	11.207	9.581	LS
Hot 3	274.0	37.5	275	1.888	4.467	LS
Hot 4	164.0	27.0	2200	7.447	10.201	LS
Hot 5	327.0	261.0	3950	9.132	6.029	LS
Hot 6	363.0	246.0	1175	5.514	6.452	LS
Hot 7	327.0	165.0	2200	3.456	5.598	LS
Hot 8	204.0	104.0	3950	1.460	1.458	LS
Hot 9	140.9	38.0	1800	43.764	45.036	LGPC
Hot 10	144.5	51.0	2000	4.119	3.852	LGPC
Cold 1	74.0	295.0	1100	12.870	28.443	LS
Cold 2	143.0	164.0	2200	26.660	5.598	LGPV
Cold 3	94.0	125.0	2200	26.053	8.076	LGPV

Table A1 Stream Data for Plant 1

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kJ/°C.hr.m <sup>2</sup> )	Heat Capacity Flowrate (kJ/hr.°C) *10 <sup>-4</sup>	Duty (kJ/hr) *10 <sup>-6</sup>	Code
Hot 1	172.5	67.6	2760	24.098	25.27	LS
Hot 2	260.0	189.8	2390	15.475	10.88	LS
Hot 3	309.2	269.5	1490	19.604	7.72	LS
Hot 4*	189.0	94.2	2200	14.355	13.60	LS
Hot 5	333.4	189.4	1150	3.071	4.43	LS
Hot 6	116.8	49.7	2190	14.885	9.97	LS
Hot 7	272.0	210.0	1940	62.580	38.81	LS
Hot 8	210.0	79.8	1940	12.116	15.76	LS
Hot 9*	198.9	171.1	715	2.783	0.79	LS
Hot 10	146.0	18.2	2450	39.136	50.00	LGPC
Hot 11	50.5	18.2	2150	41.234	13.28	LGPC
Hot 12	189.0	26.1	2200	18.812	30.64	LS
Cold 1	26.0	261.7	2250	45.720	107.78	LS
Cold 2	261.7	356.5	2250	116.176	109.73	LGPV
Cold 3	338.2	409.8	1595	69.444	49.68	LS
Cold 4*	26.7	96.1	1020	28.081	19.47	LS

Table A2 Stream Data for Plant 2

(It must be noted that cold streams 1 and 2 are the same stream)

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kJ/°C.hr.m <sup>2</sup> )	Heat Capacity Flowrate (kJ/hr.°C) *10 <sup>-4</sup>	Duty (kJ/hr) *10 <sup>-6</sup>	Code
Hot 1	135.6	30.0	4100	5.278	5.58	GPC
Hot 2	255.0	176.1	2760	2.675	2.12	LS
Hot 3	353.3	198.9	1225	11.678	18.04	LS
Hot 4	198.9	171.1	920	2.783	0.77	LS
Hot 5	171.1	75.0	920	5.216	5.00	LS
Cold 1	327.8	457.8	1225	14.796	19.22	LGPV
Cold 2 *	158.3	160.0	2250	45.720	0.77	LS
Cold 3 *	126.7	176.7	1020	40.288	20.16	LGPV
Cold 4 *	126.7	146.7	1020	5.782	1.15	LGPV

Table A3 Stream Data for Plant 3

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kJ/°C.hr.m <sup>2</sup> )	Heat Capacity Flowrate (kJ/hr.°C) *10 <sup>-4</sup>	Duty (kJ/hr) *10 <sup>-6</sup>	Code
Hot 1	503.9	366.1	4100	18.229	25.09	G
Hot 2	366.1	178.9	4100	1.030	1.94	LGPC
Hot 3	366.1	253.9	4100	7.059	7.92	LGPC
Hot 4	303.3	36.7	4100	17.091	45.58	LGPC
Hot 5	76.7	26.7	4100	6.647	3.31	GPC
Hot 6	232.2	112.2	4100	4.087	4.90	LS
Hot 7	79.4	32.2	4100	10.762	5.11	GPC
Hot 8	112.0	23.9	4100	0.199	0.18	LS
Hot 9	67.2	27.2	4100	20.441	8.17	GPC
Hot 10	157.2	32.2	4100	2.139	2.66	LS
Hot 11	43.3	26.7	4100	1.291	0.22	GPC
Hot 12	92.0	65.0	4100	0.480	0.14	LS
Hot 13	107.0	32.2	4100	2.075	1.55	LS
Cold 1	66.1	370.6	4100	20.593	62.68	LGPV
Cold 2	232.2	247.2	4100	52.827	7.92	LGPV
Cold 3	36.7	125.6	4100	5.513	4.90	LS
Cold 4	112.0	112.8	4100	678.214	5.29	LGPV
Cold 5	157.2	163.9	4100	28.928	1.94	LGPV
Cold 6	92.0	97.2	4100	10.545	0.54	LGPV
Cold 7	370.6	495.6	4100	25.455	31.82	LGPV
Cold 8	452.8	497.2	4100	28.817	12.82	LGPV
Cold 9	480.6	496.1	4100	30.859	4.79	LGPV

Table A4 Stream Data for Plant 4  
(see next page for linked streams)

It must be noted that hot streams 1, 2, 3 and 4 are the same stream. Hot stream 1 has been split into hot streams 2 and 3 (which undergo and enthalpy change) and an additional stream which does not undergo and enthalpy change. When these three streams are combined, hot stream 4 results. Cold streams 1 and 7 are also the same stream.

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kJ/°C.hr.m <sup>2</sup> )	Heat Capacity Flowrate (kJ/hr.°C) *10 <sup>-4</sup>	Duty (kJ/hr) *10 <sup>-6</sup>	Code
Hot 1	328.3	33.9	4100	15.548	45.79	GPC
Hot 2	67.2	50.0	4100	51.696	8.89	GPC
Hot 3	101.7	61.7	4100	29.432	11.77	GPC
Hot 4	168.9	88.3	4100	7.447	5.98	LS
Hot 5*	250.0	146.1	4100	12.325	12.82	LS
Cold 1	39.1	325.0	4100	15.650	44.75	LGPV
Cold 2	33.9	130.3	4100	11.972	11.56	LS
Cold 3	175.6	183.5	4100	159.515	12.60	LGPV
Cold 4	168.9	171.1	4100	326.843	7.27	LGPV

Table A5 Stream Data for Plant 5

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kJ/°C.hr.m <sup>2</sup> )	Heat Capacity Flowrate (kJ/hr.°C) *10 <sup>-4</sup>	Duty (kJ/hr) *10 <sup>-6</sup>	Code
Hot 1	327.8	256.7	4100	23.367	16.63	G
Hot 2	256.7	30.0	4100	4.026	9.11	GPC
Hot 3	127.2	24.4	4100	1.032	1.04	GPC
Hot 4	253.9	146.1	4100	12.325	13.28	LS
Cold 1	241.9	245.6	4100	12.866	0.47	LS
Cold 2	221.1	308.9	4100	22.103	19.40	LGPV
Cold 3	168.9	171.1	4100	326.843	7.27	LGPV
Cold 4 *	83.9	130.3	4100	11.972	5.54	LS

Table A6 Stream Data for Plant 6

Stream Type	Supply Temp. (°C)	Target Temp. (°C)	Film Coeff. (kJ/°C.hr.m <sup>2</sup> )	Heat Capacity Flowrate (kJ/hr.°C) *10 <sup>-4</sup>	Duty (kJ/hr) *10 <sup>-6</sup>	Code
Hot 1	312.8	205.0	2660	8.630	9.29	GPC
Hot 2	205.0	30.0	2660	1.362	2.38	LGPC
Hot 3	136.1	27.2	4500	0.048	0.04	LGPC
Hot 4	176.7	33.3	2045	7.250	10.40	LS
Cold 1	157.8	310.0	2660	8.391	12.78	LGPV

Table A7 Stream Data for Plant 7

**APPENDIX 2**

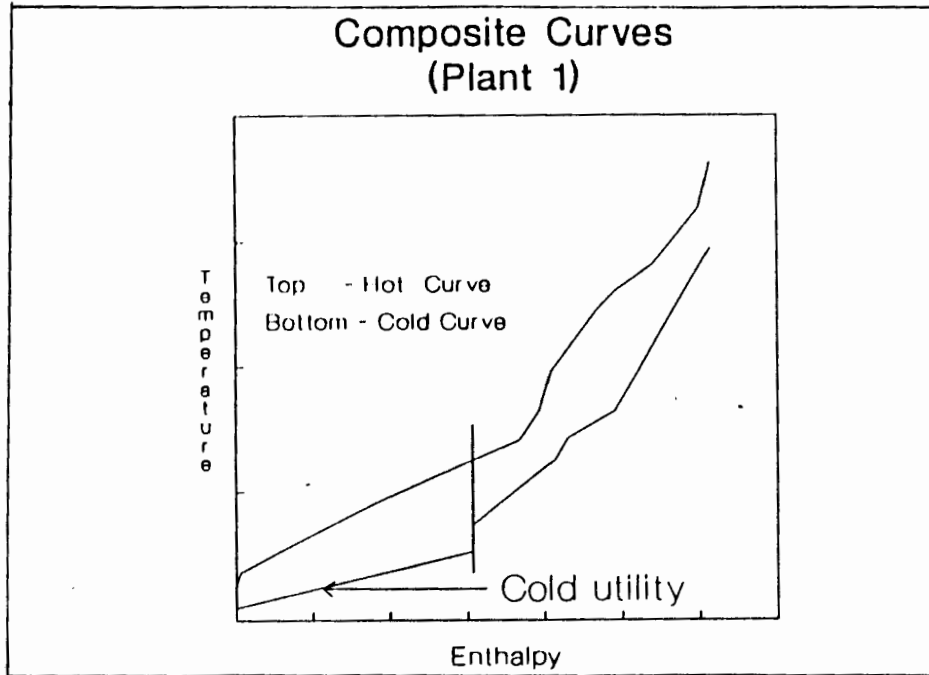


Figure B1 Composite Curves for Plant 1

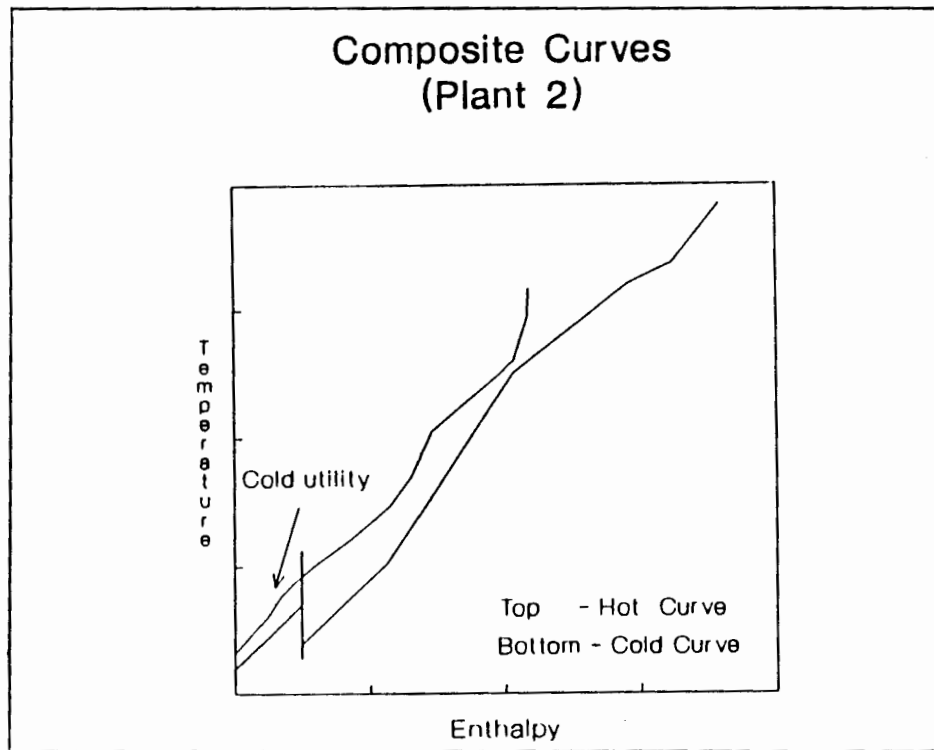


Figure B2 Composite Curves for Plant 2

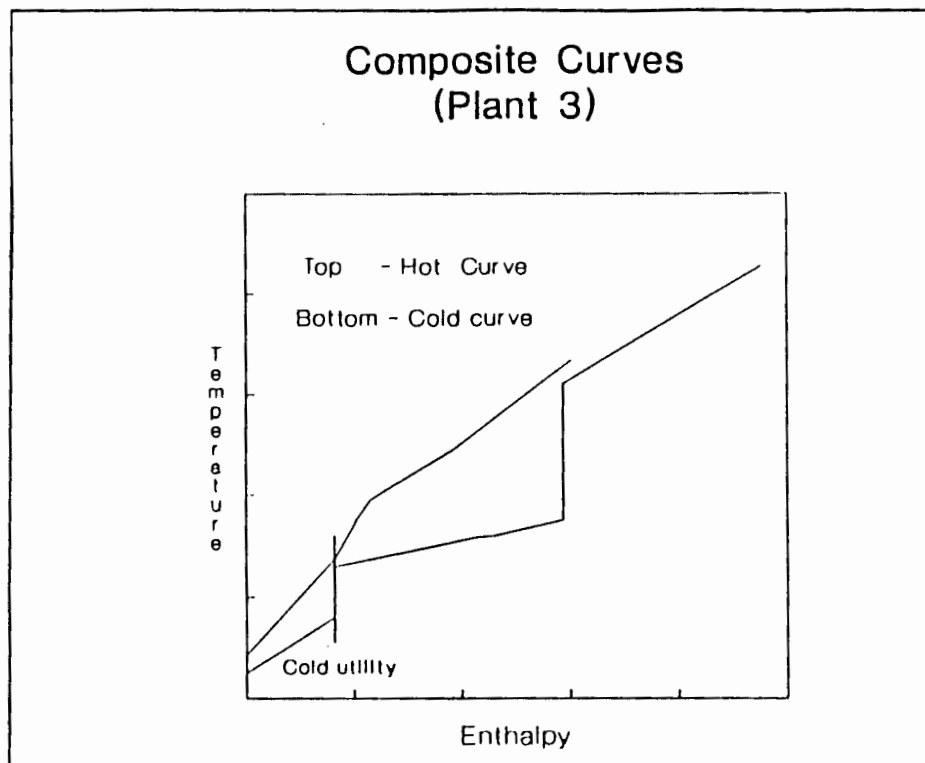


Figure B3 Composite Curves for Plant 3

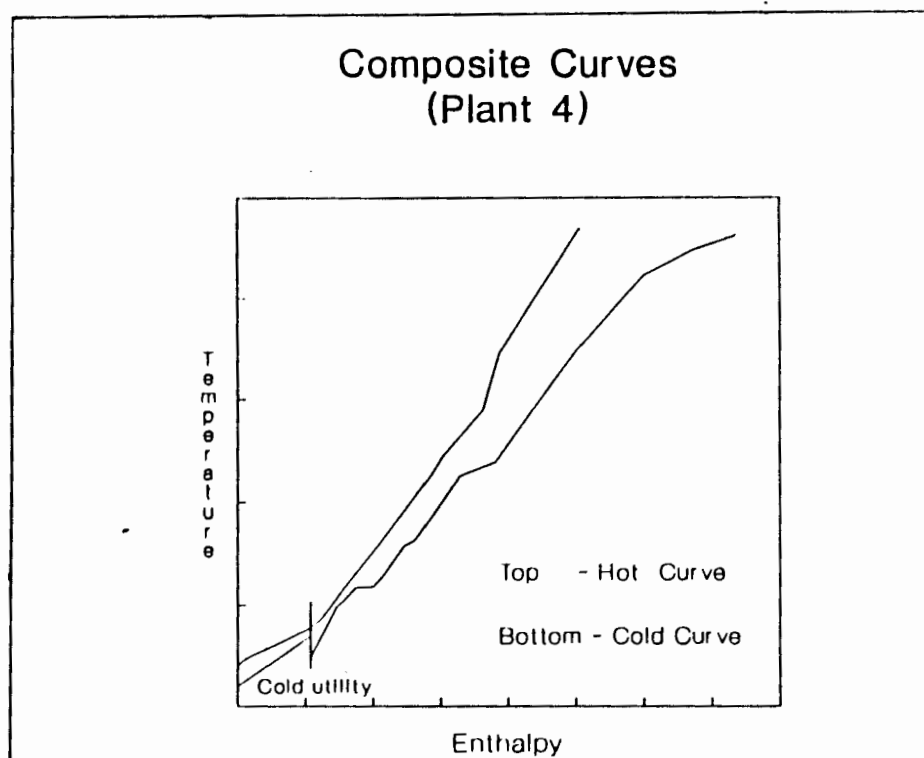


Figure B4 Composite Curves for Plant 4

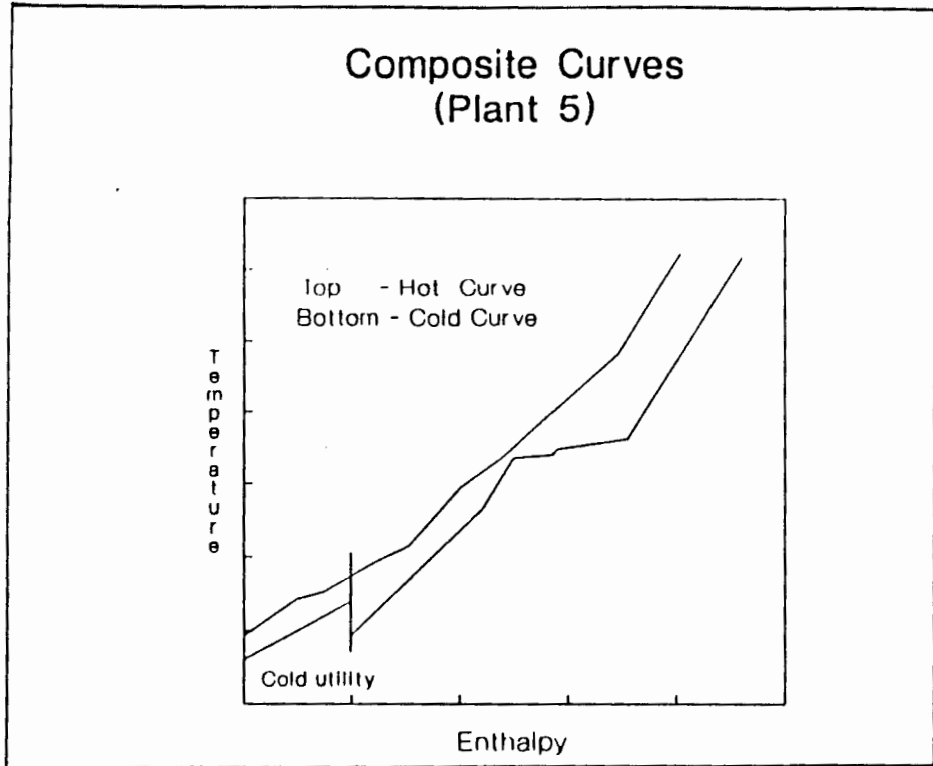


Figure B5 Composite Curves for Plant 5

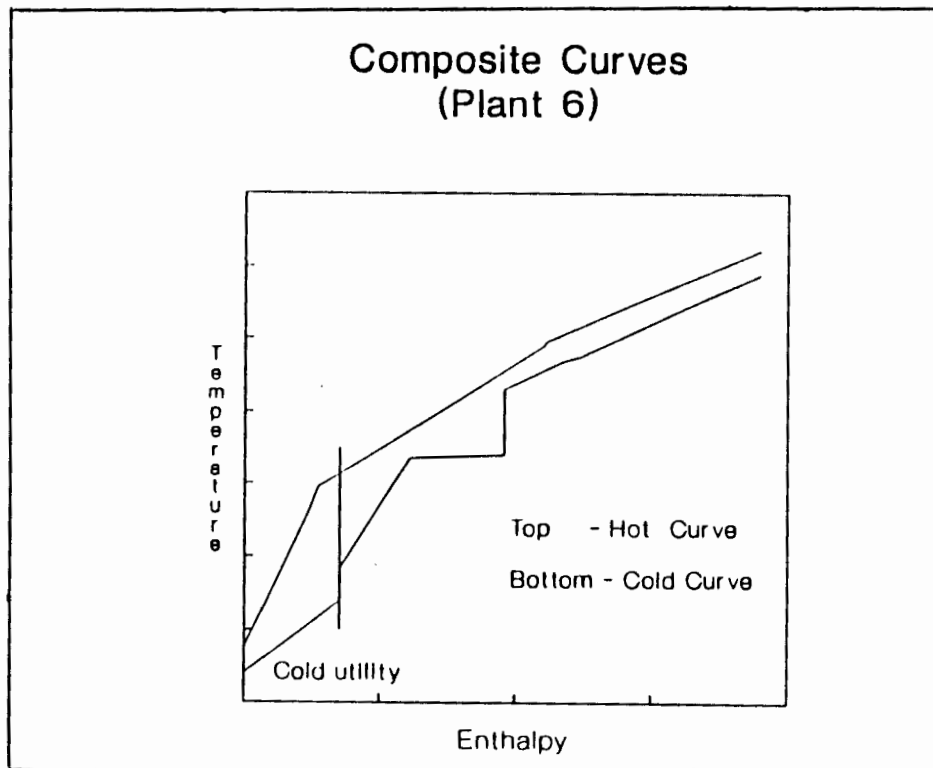


Figure B6 Composite Curves for Plant 6

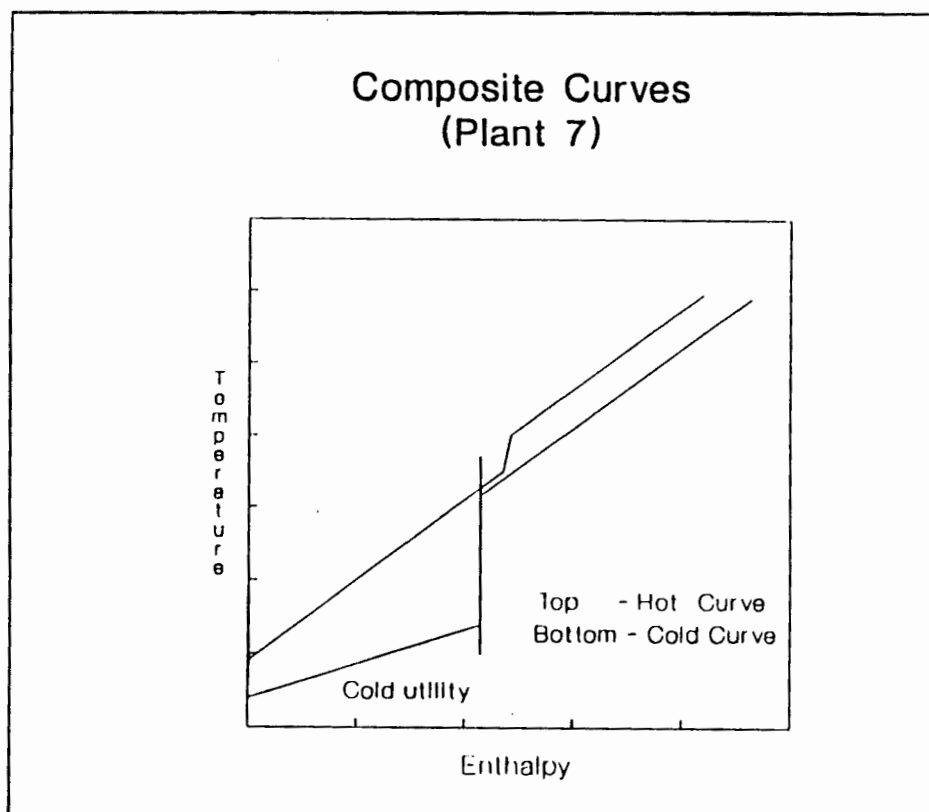


Figure B7 Composite Curves for Plant 7

Exchanger Number	HX Type Code	Design Film Coefficient (kW/m <sup>2</sup> .K)	Total Area (m <sup>2</sup> )
1	AFS	0.0681	1085
2	AFS	0.0664	327
3	AFS	0.2134	235
4	AFS	0.1805	235
5	AES	0.2452	274
6	AKT	0.5075	200
7	AKU	0.5195	48
8	AHU	0.4099	119
9	AJS	0.2992	116
10	AHU	0.5087	88

Table C1 Heat Exchanger Data for Plant 1

Exchanger Number	HX Type Code	Design Film Coefficient (kW/m <sup>2</sup> .K)	Total Area (m <sup>2</sup> )
1	FF	0.0210	5045
2	BES	0.4678	94
3	BES	0.1754	464
4	AKU	0.3287	272
5	AKU	0.2458	249

Table C3 Heat Exchanger Data for Plant 3

Exchanger Number	HX Type Code	Design Film Coefficient (kW/m <sup>2</sup> .K)	Total Area (m <sup>2</sup> )
1	BFU	0.4008	325
2	BEU	0.5223	171
3	BEU	0.6643	201
4	FF	0.0249	15367
5	AES	0.5393	61
6	TR	0.5053	173
7	FF	0.0244	7711
8	FF	0.0147	1468
9	TR	0.4996	102
10	FF	0.0210	1087
11	FF	0.0193	1486
12	FF	0.0300	201
13	TR	0.7665	29
14	FF	0.0232	3224
15	FF	0.0249	173
16	K	0.8857	7
17	FF	0.0227	491

Table C4 Heat Exchanger Data for Plant 4

Exchanger Number	HX Type Code	Design Film Coefficient (kW/m <sup>2</sup> .K)	Total Area (m <sup>2</sup> )
1	BFU	0.3236	976
2	FF	0.0238	7024
3	BES	0.5019	106
4	BFS	0.3514	138
5	FF	0.0198	7247
6	BHS	0.6103	124
7	FF	0.0210	7628

Table C5 Heat Exchanger Data for Plant 5

Exchanger Number	HX Type Code	Design Film Coefficient (kW/m <sup>2</sup> .K)	Total Area (m <sup>2</sup> )
1	AES	0.4178	455
2	FF	0.0187	5556
3	FF	0.0215	1273
4	AES	0.4232	173
5	AEU	0.4002	179

Table C6 Heat Exchanger Data for Plant 6

Exchanger Number	HX Type Code	Design Film Coefficient (kW/m <sup>2</sup> .K)	Total Area (m <sup>2</sup> )
1	BEU	0.3633	228
2	FF	0.0198	2007
3	FF	0.0210	1068
4	FF	0.0164	3084
5	AEU	0.4872	114
6	AES	0.4485	343

Table C7 Heat Exchanger Data for Plant 7

APPENDIX 4

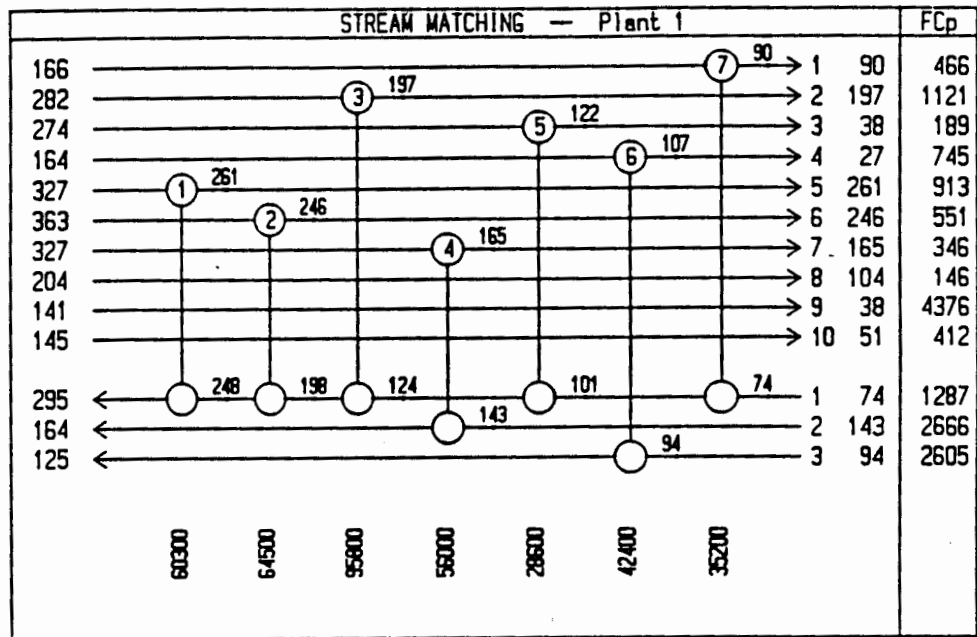


Figure D1 Actual Network for Plant 1

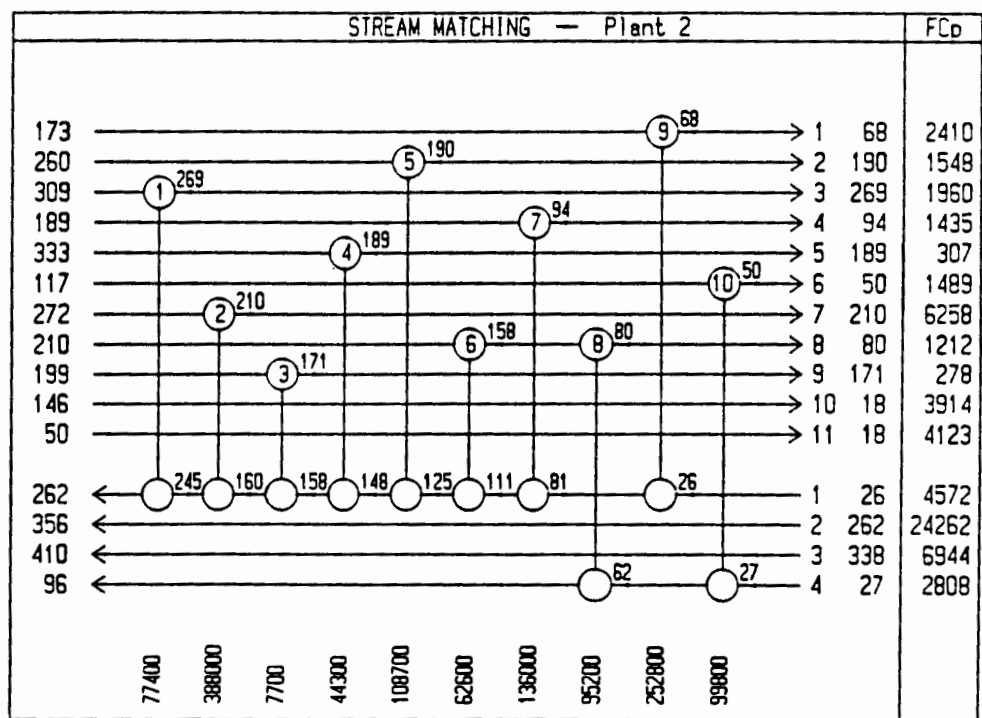


Figure D2 Actual Network for Plant 2

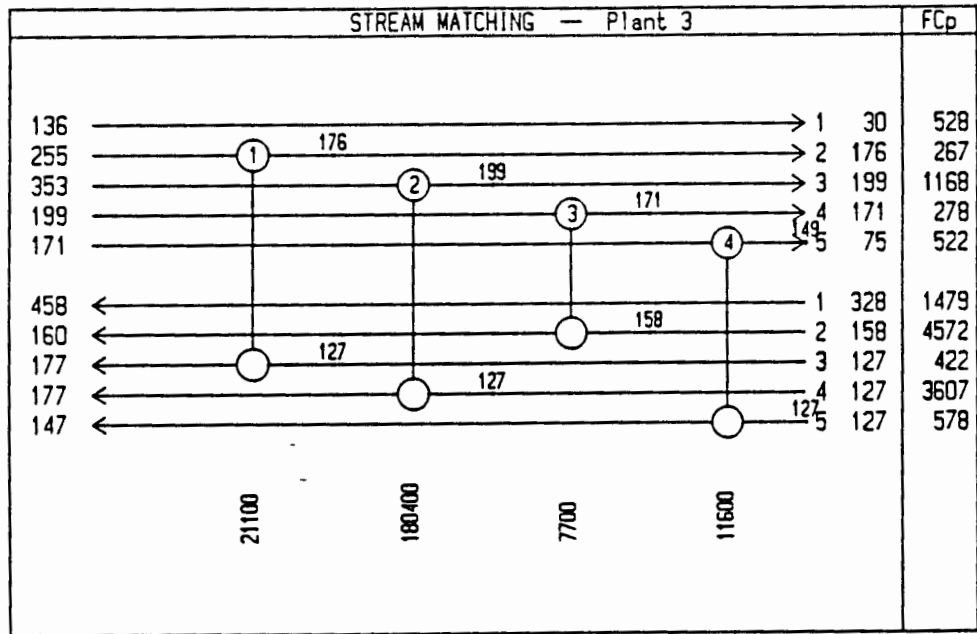


Figure D3 Actual Network for Plant 3

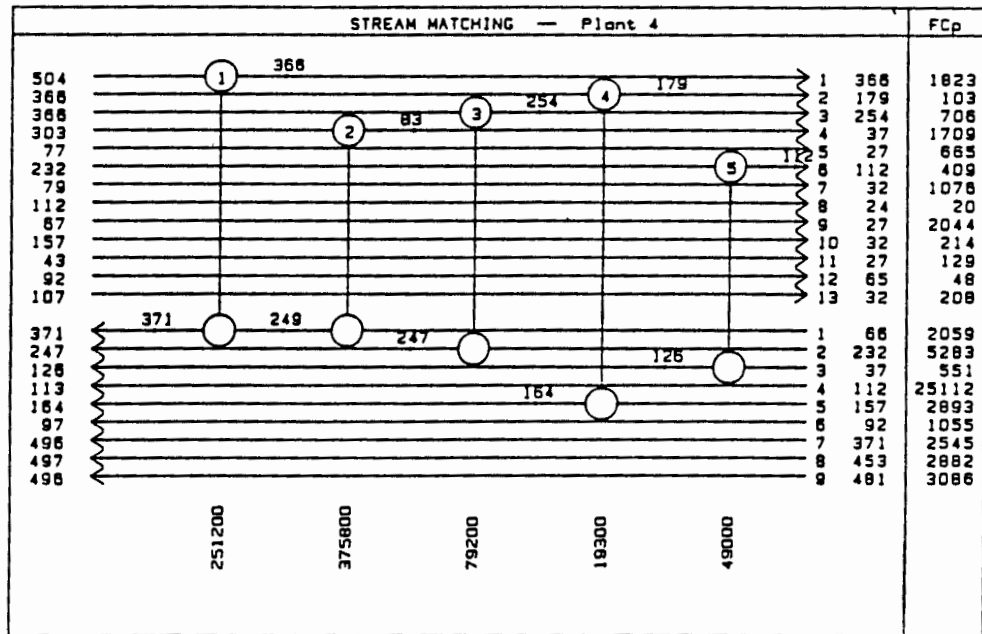


Figure D4 Actual Network for Plant 4

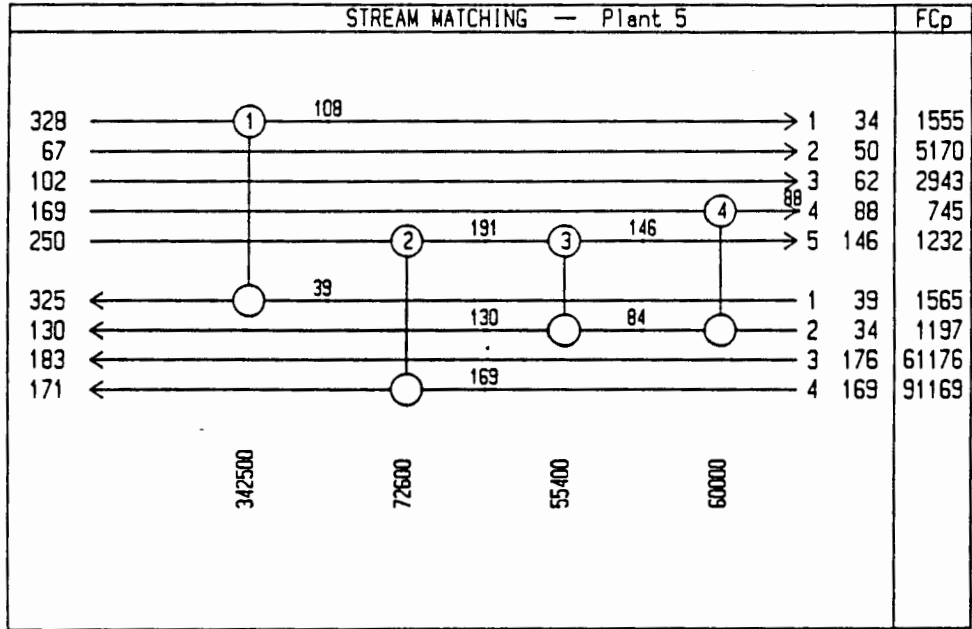


Figure D5 Actual Network for Plant 5

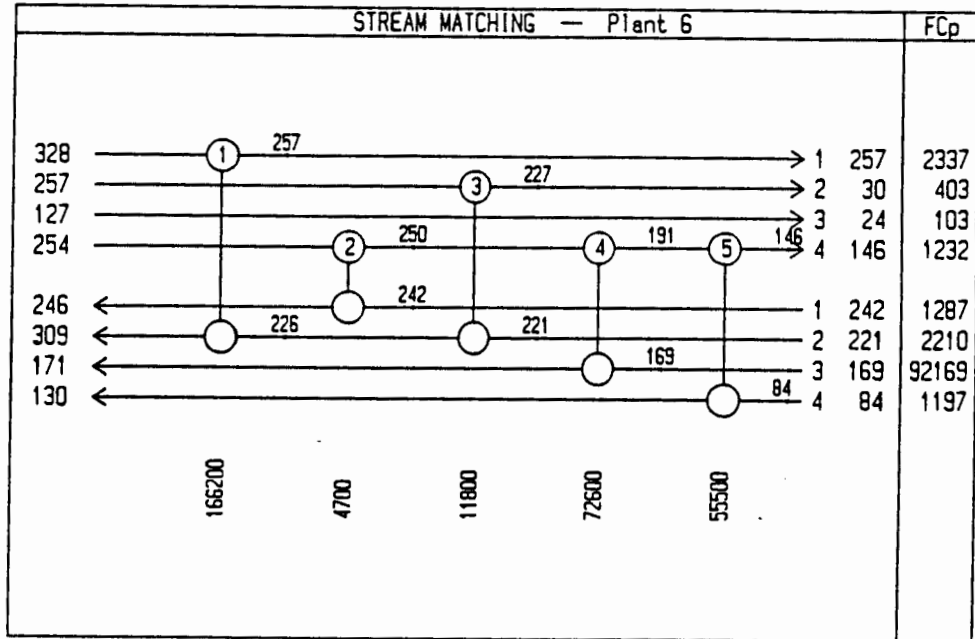


Figure D6 Actual Network for Plant 6

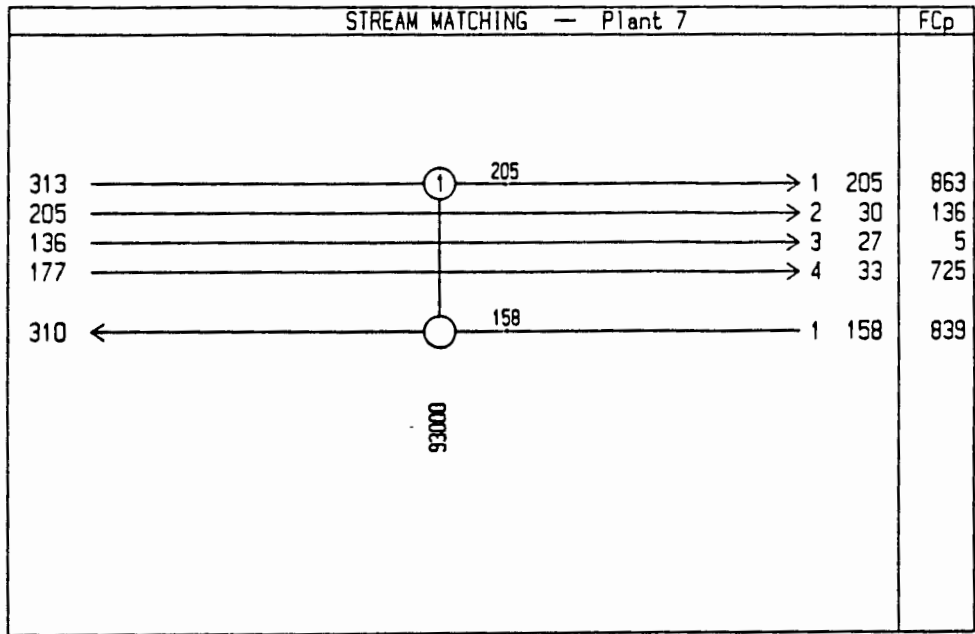


Figure D7 Actual Network for Plant 7

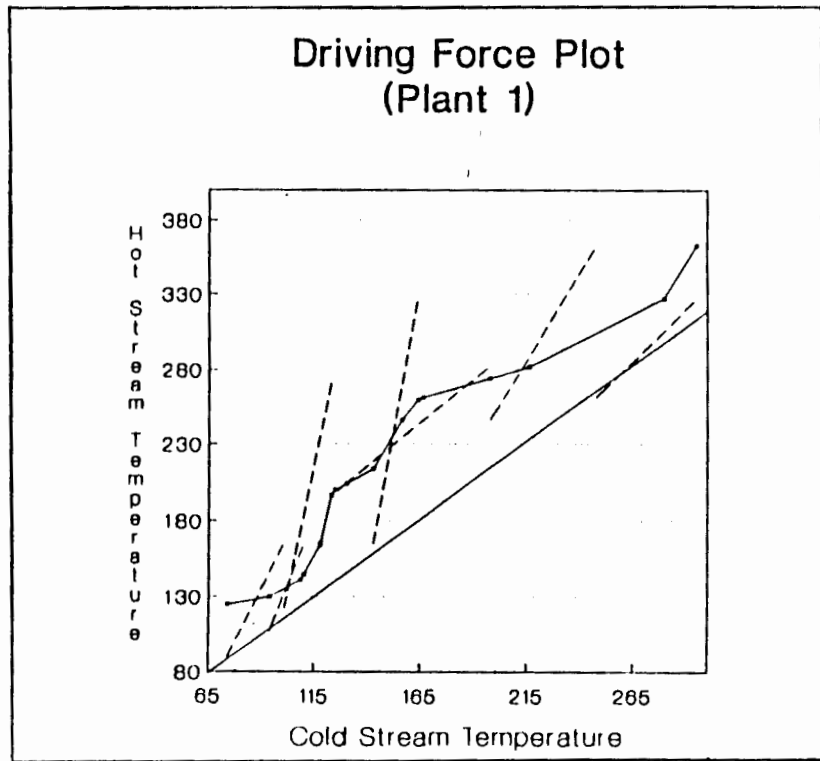


Figure D8 Driving Force Plot for Plant 1

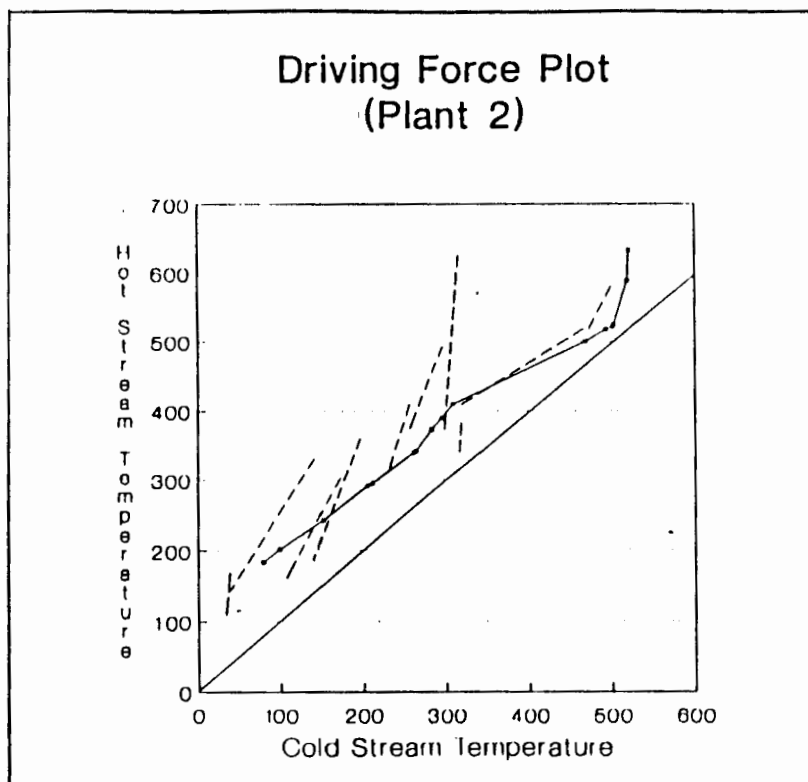


Figure D9 Driving Force Plot for Plant 2

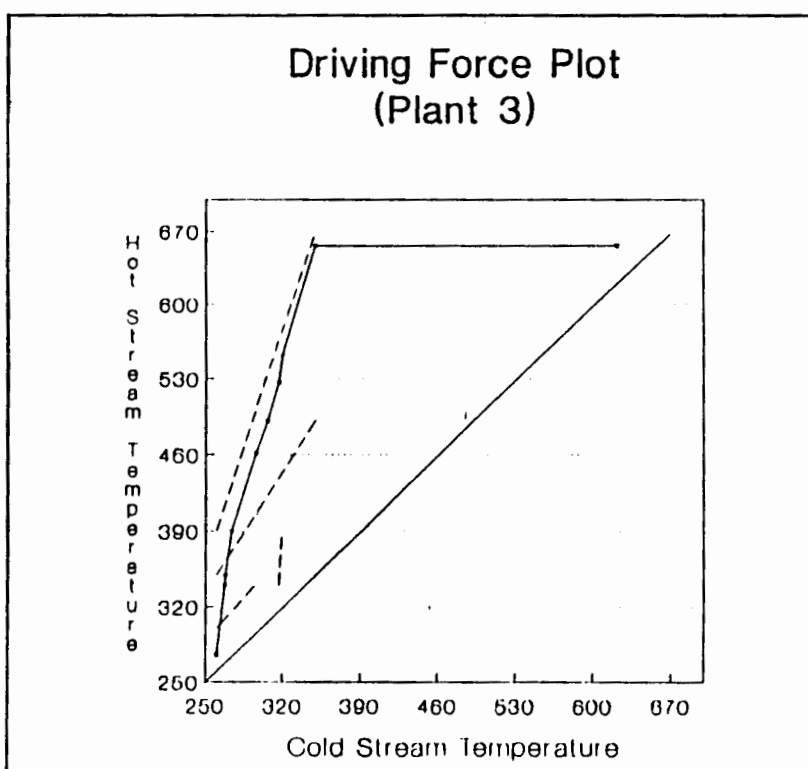


Figure D10 Driving Force Plot for Plant 3

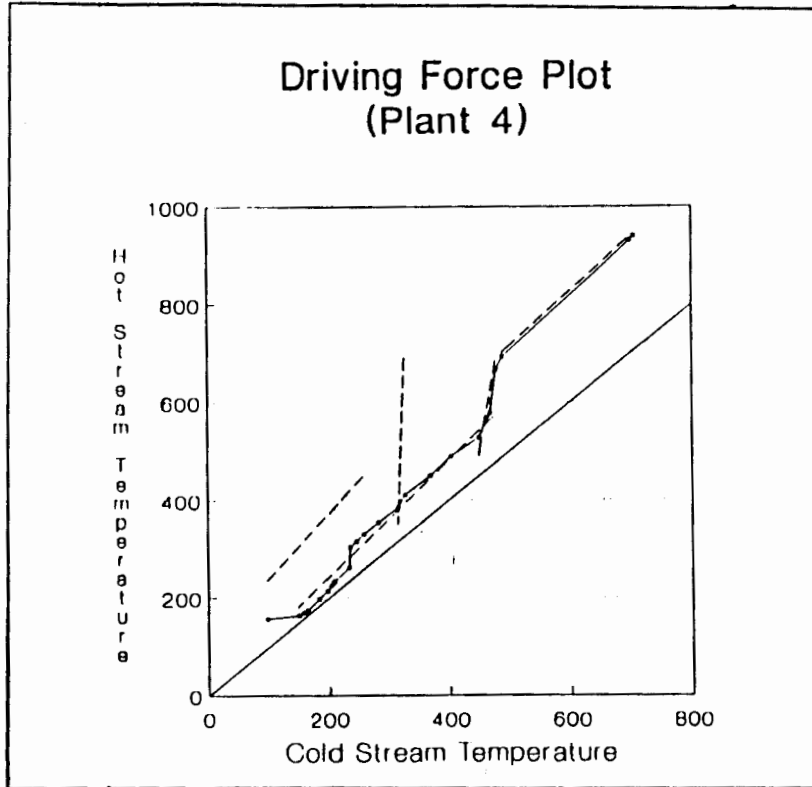


Figure D11 Driving Force Plot for Plant 4

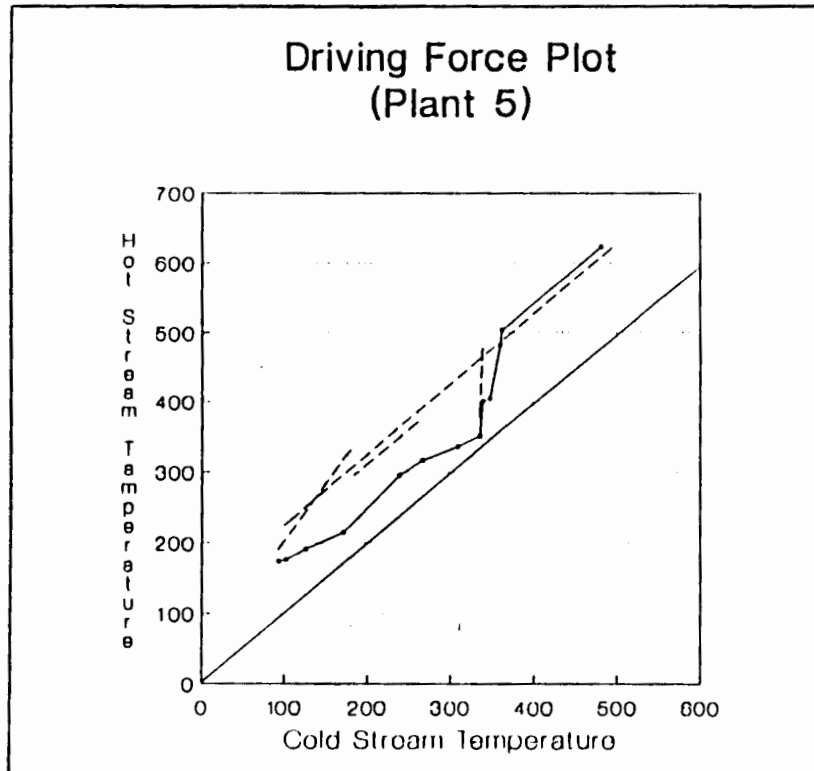


Figure D12 Driving Force Plot for Plant 5

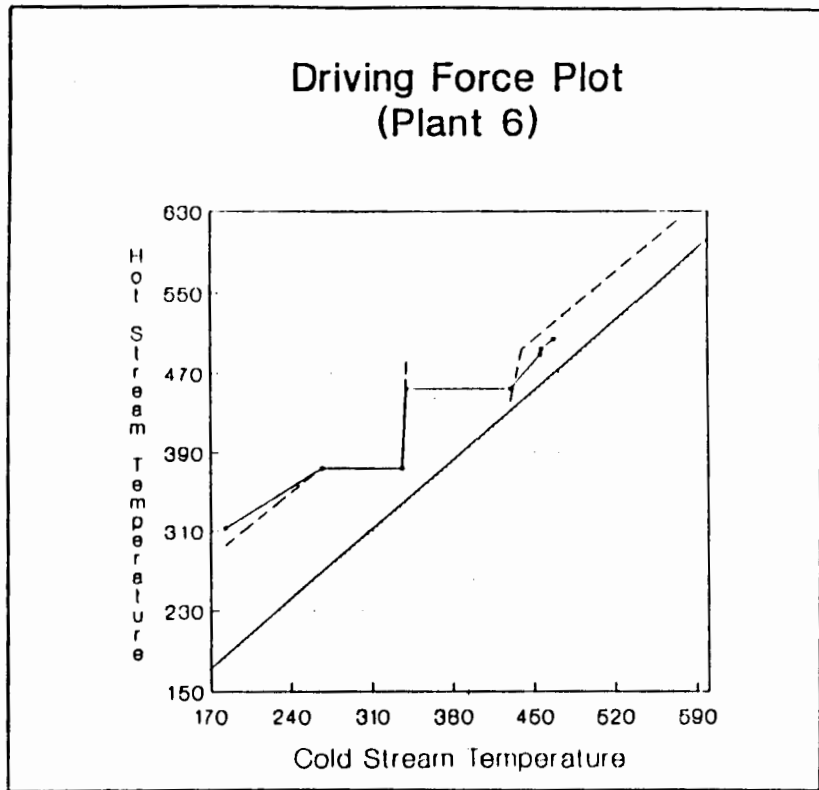


Figure D13 Driving Force Plot for Plant 6

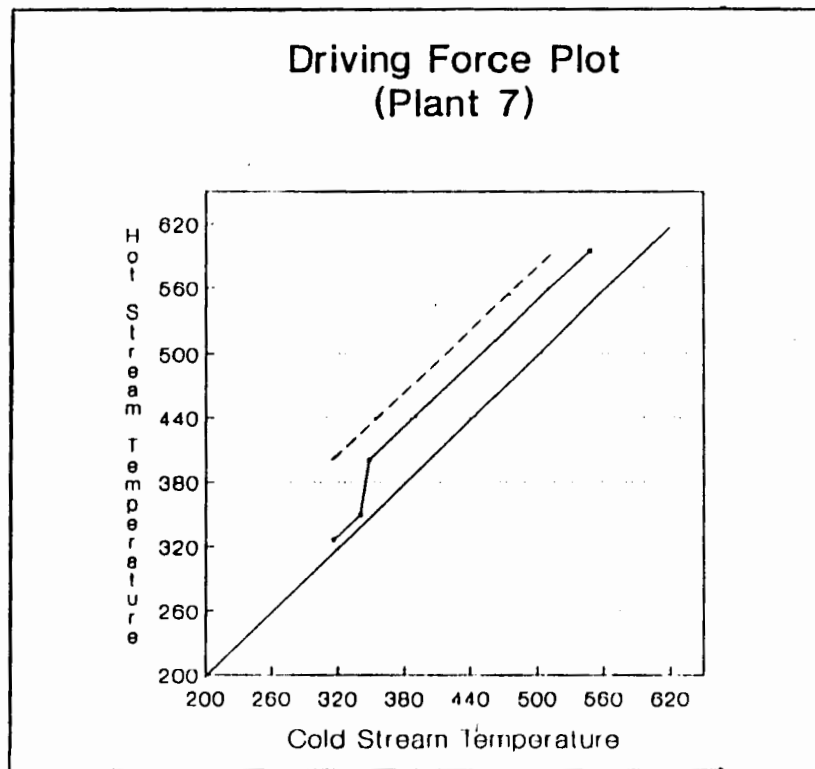


Figure D14 Driving Force Plot for Plant 7

APPENDIX 5

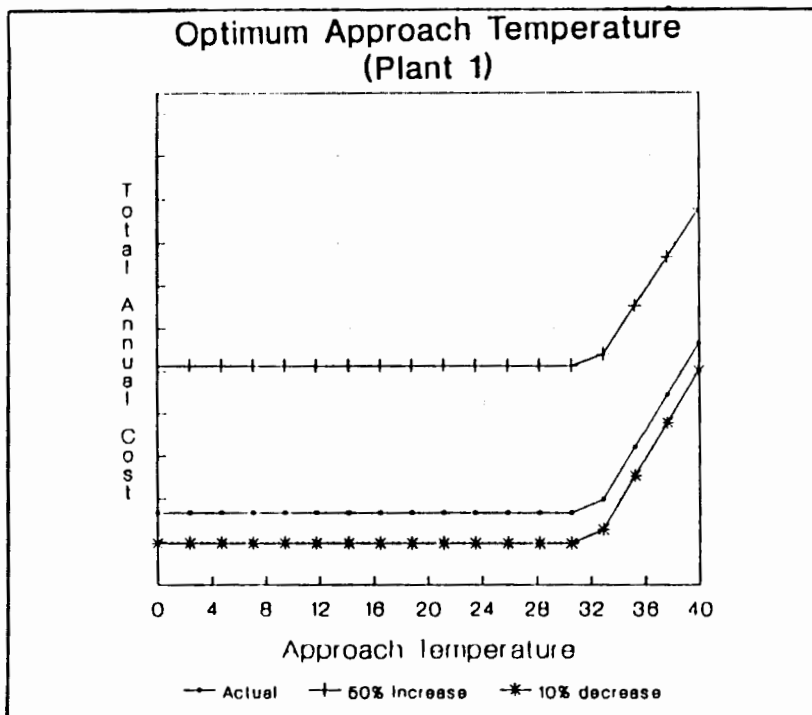


Figure E1 Optimum  $\Delta T_{min}$  for Plant 1

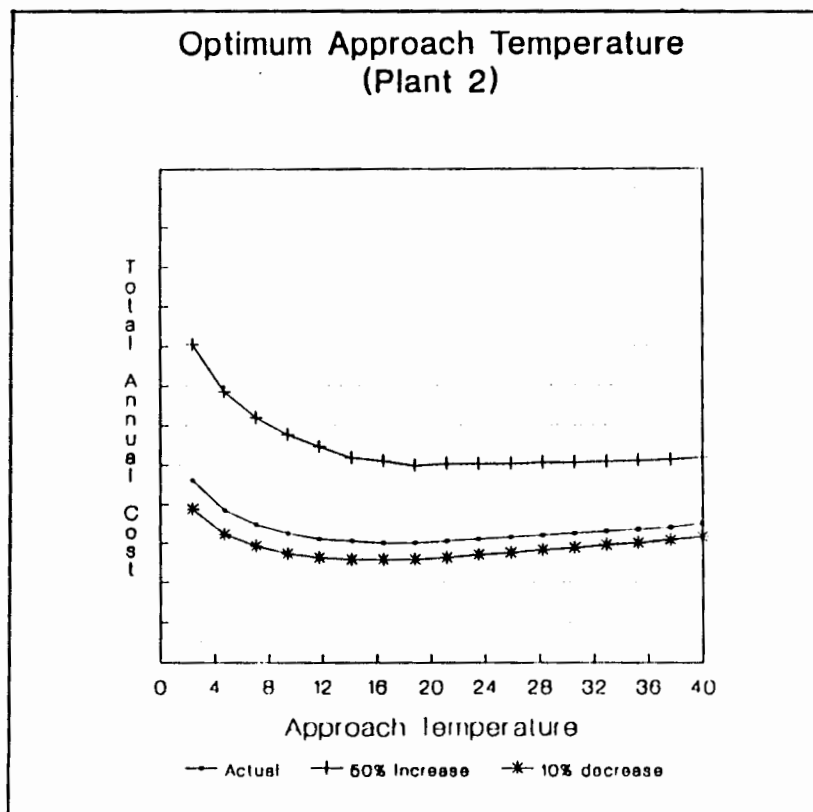


Figure E2 Optimum  $\Delta T_{min}$  for Plant 2

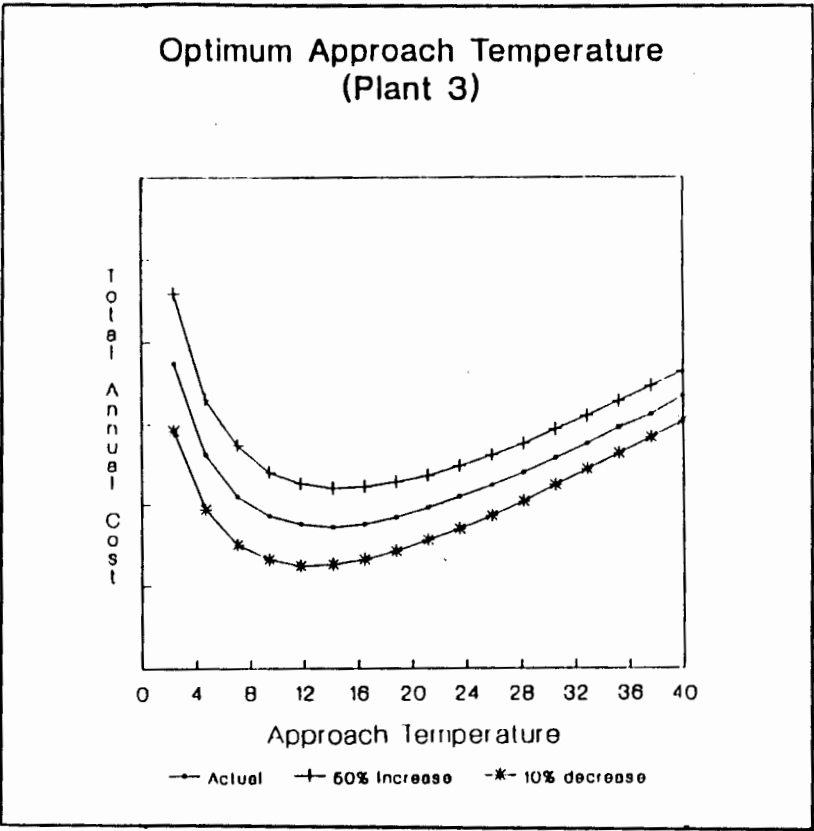


Figure E3 Optimum  $\Delta T_{min}$  for Plant 3

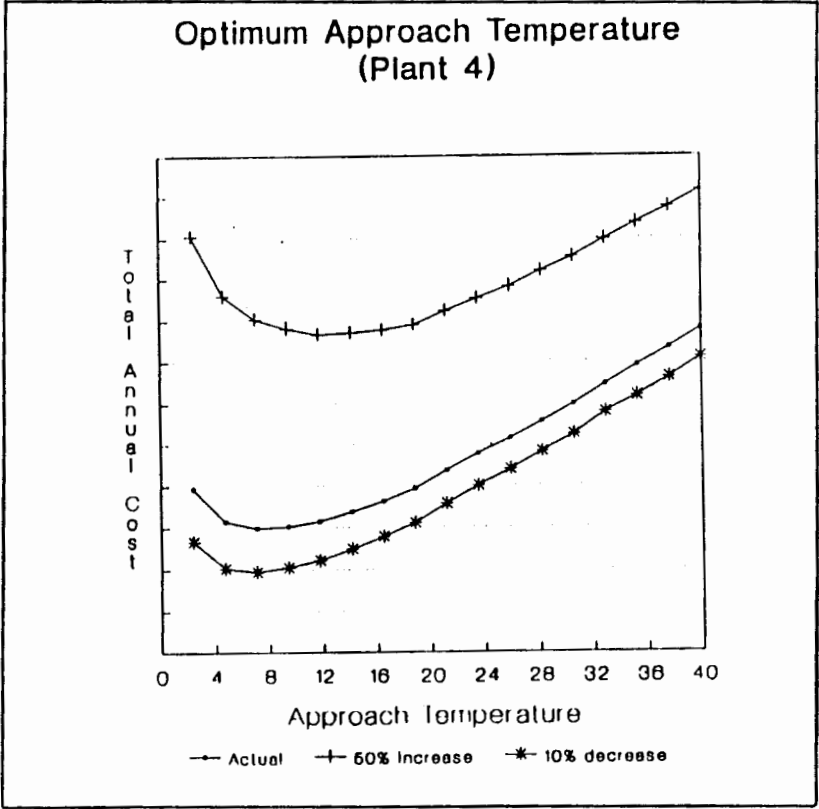


Figure E4 Optimum  $\Delta T_{min}$  for Plant 4

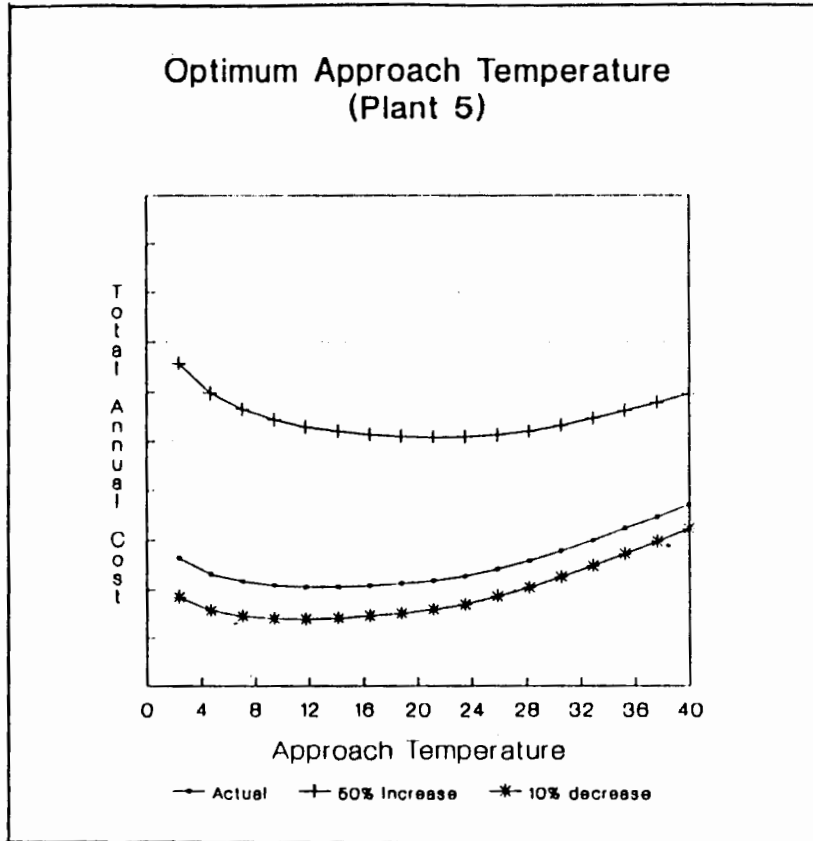


Figure E5 Optimum  $\Delta T_{min}$  for Plant 5

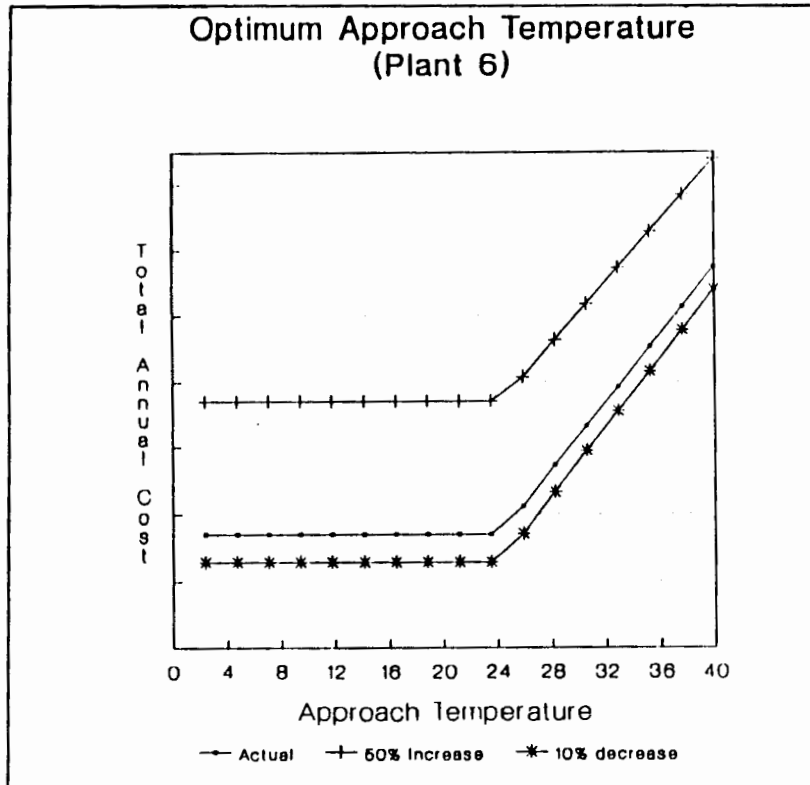


Figure E6 Optimum  $\Delta T_{min}$  for Plant 6

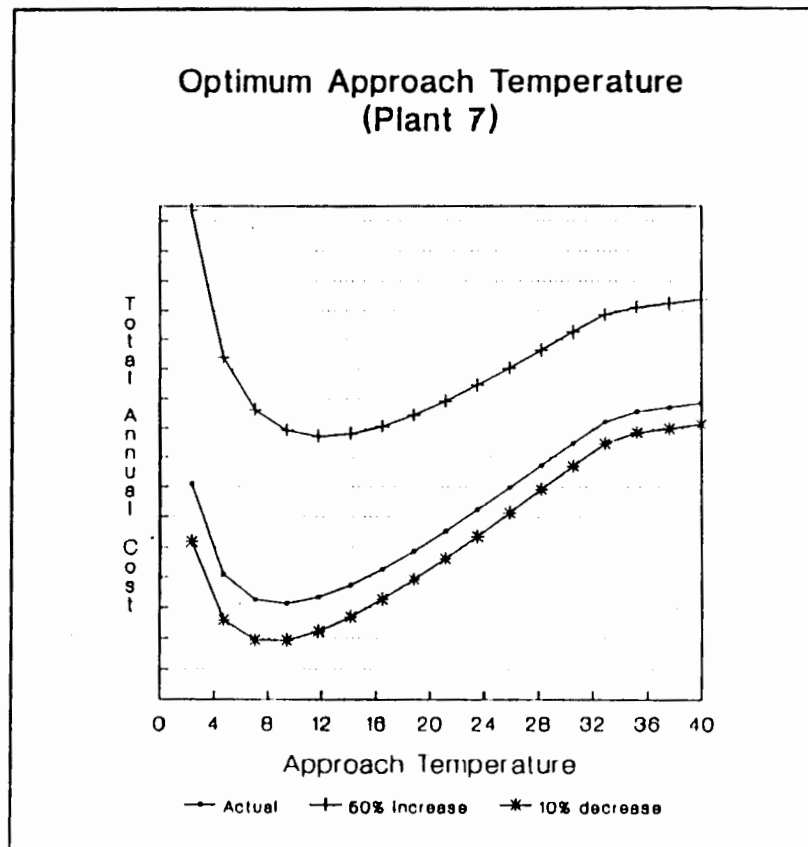


Figure E7 Optimum  $\Delta T_{\min}$  for Plant 7

APPENDIX 6

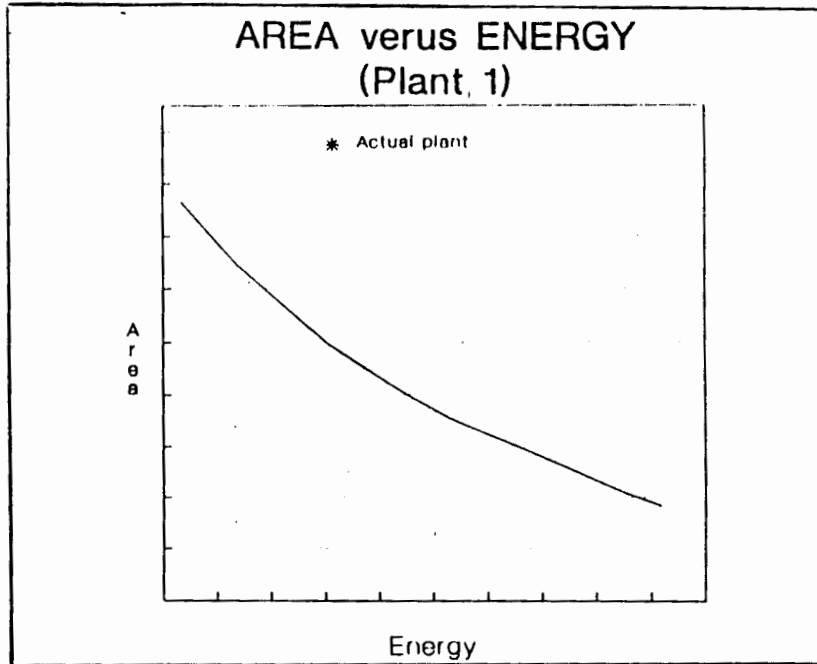


Figure F1 Energy-Area plot for Plant 1

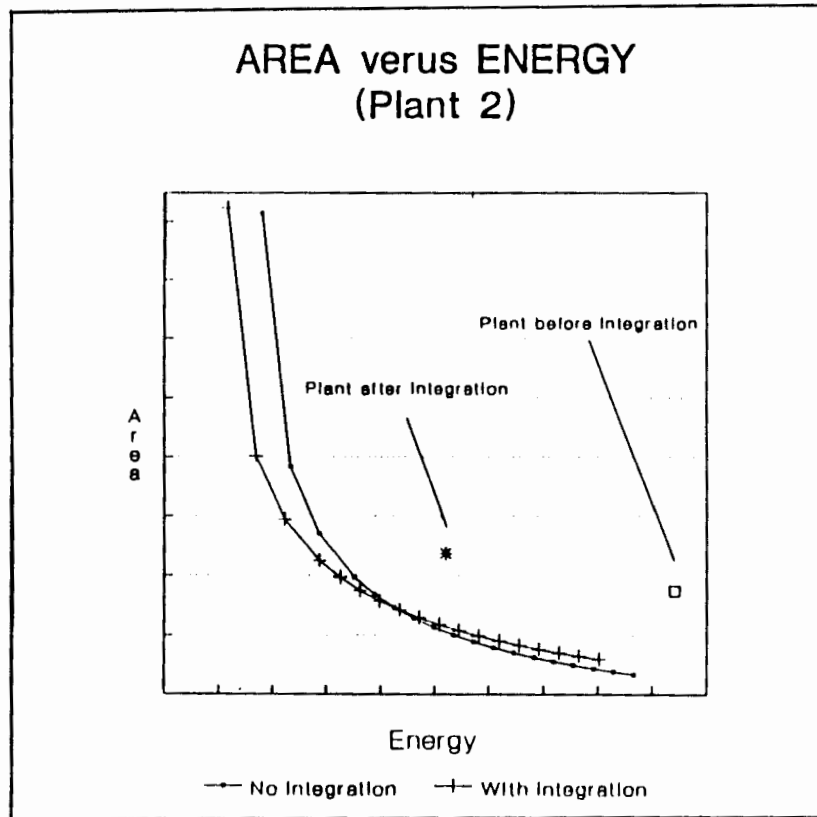


Figure F2 Energy-Area plot for Plant 2

### AREA versus ENERGY (Plant 3)

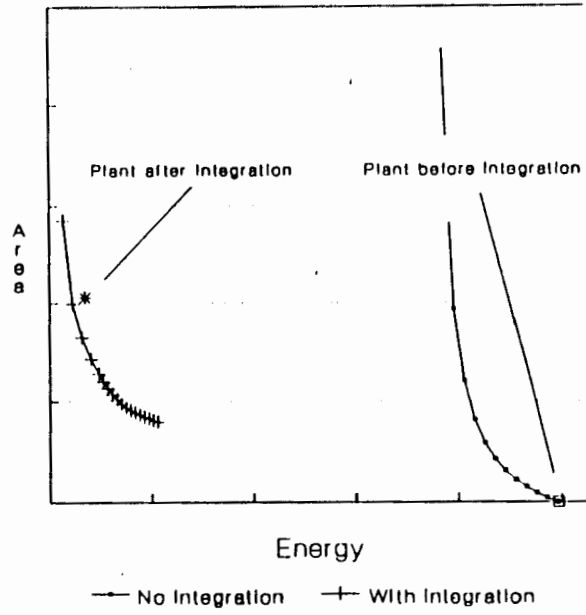


Figure F3 Energy-Area plot for Plant 3

### AREA versus ENERGY (Plant 4)

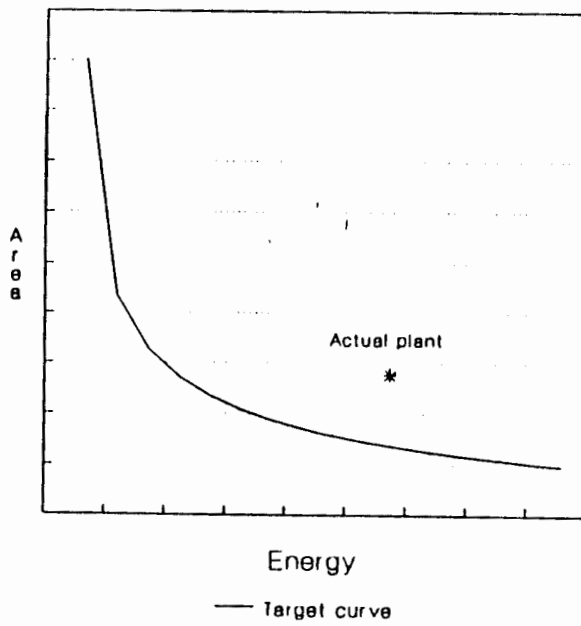


Figure F4 Energy-Area plot for Plant 4

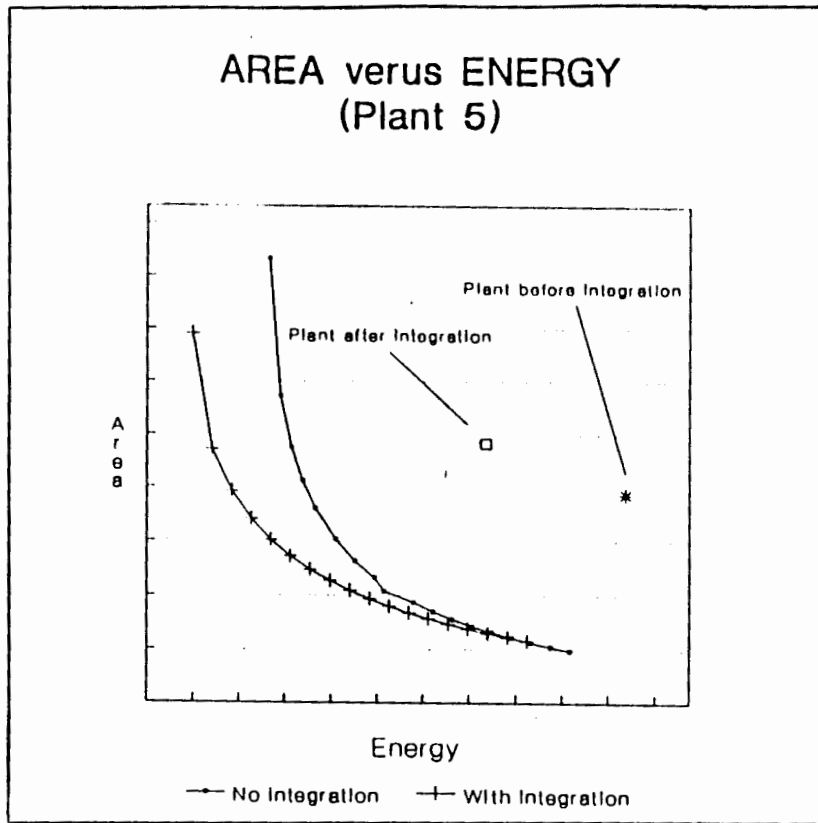


Figure F5 Energy-Area plot for Plant 5

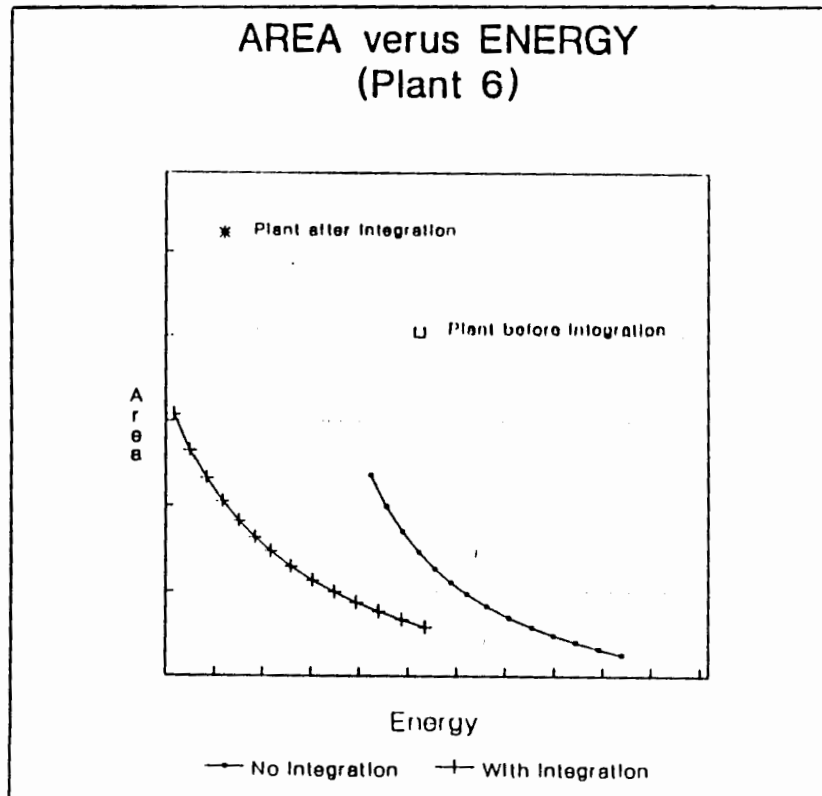


Figure F6 Energy-Area plot for Plant 6

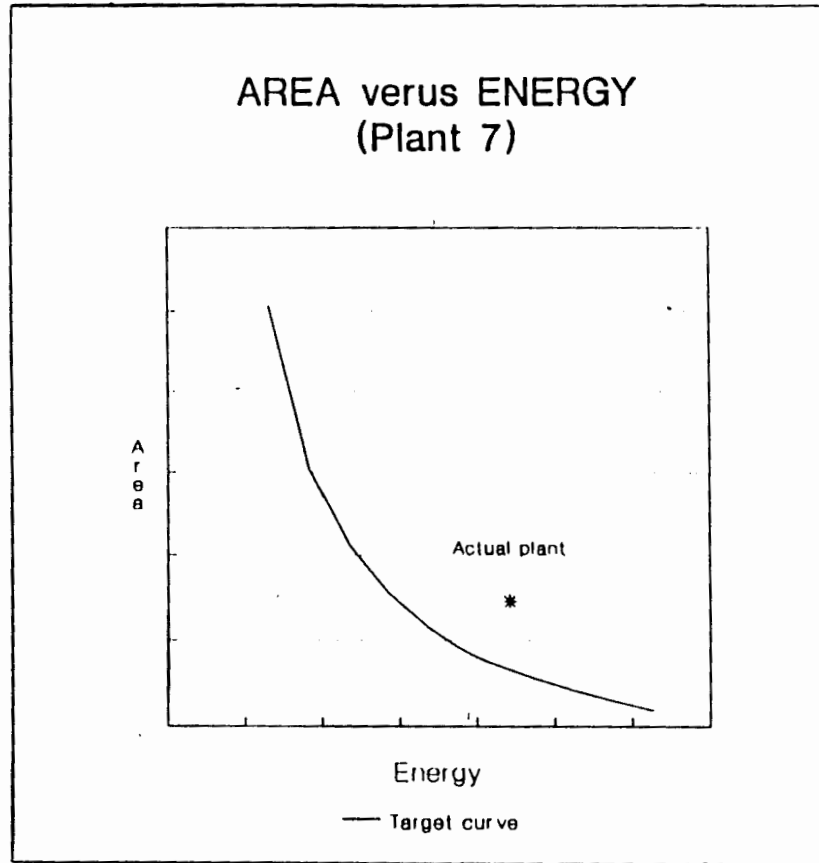


Figure F7 Energy-Area plot for Plant 7



### Grand Composite Curve (Plant 5)

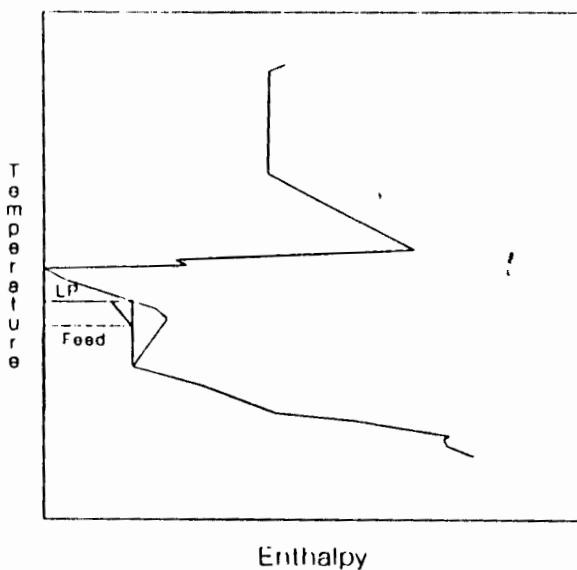


Figure G5 Grand Composite curve for Plant 5

### Grand Composite Curve (Plant 6)

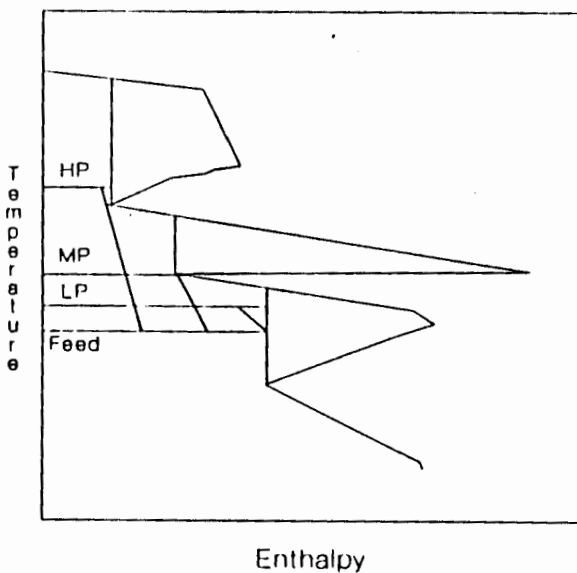


Figure G6 Grand Composite curve for Plant 6

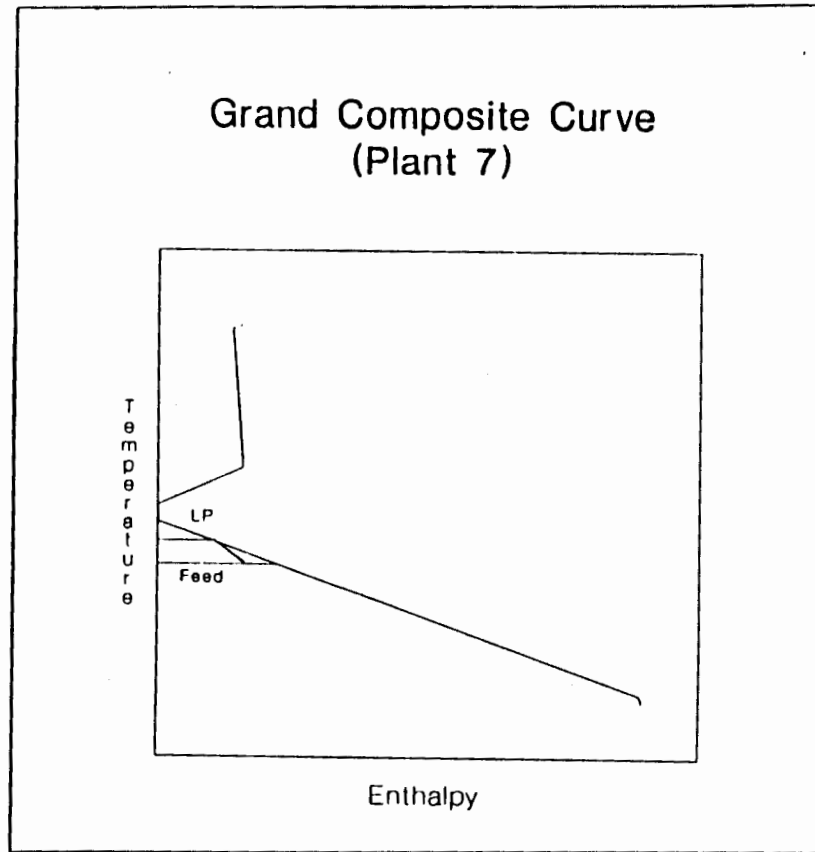


Figure G7 Grand Composite curve for Plant 7

## APPENDIX 8

### 1 Plant 1

The plant is unpinched. The target hot utility consumption is zero while the target cold utility consumption is 15 340 kW. The actual hot utility consumption is 1 400 kW while the actual cold utility consumption is 16 740 kW. The dominant cold stream (stream 1) has a fixed target temperature and thus any modifications leading to an increase in this temperature would not give a saving in hot utility. Instead, modifications involving additional exchange with cold stream 3 would reduce the LP steam requirement.

#### 1.1 Energy Levels

The energy levels for this plant are shown in Figure H1 below.

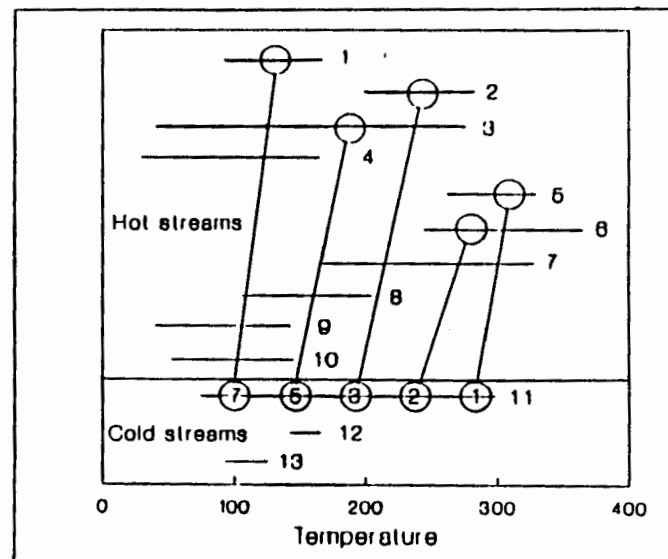


Figure H1 Energy Level plot for Plant 1

Inspection of the stream data for the plant (Table A1 in Appendix 1) shows one major cold stream and several hot

streams. The actual network (Figure D1 in Appendix 4) shows that two of the cold streams are completely matched. An inspection of the matches placed using the energy level plot will show if the hot streams have been matched in the correct order against the major cold stream.

From Figure H1 above, it can be seen that the hot streams are matched in the correct order. It may appear that the two final matches with the cold stream should be reversed. However, if the actual matching arrangement is considered (Figure D1 in Appendix 4), it can be seen that by switching matches 1 and 2, the approach temperature in exchanger 1 would be violated. If a duty of 2.19 (using Table 3.9) was specified in exchanger 2 (instead of the actual 2.35), the cold stream exit temperature would be approximately 246.6°C resulting in the violation ( $\Delta T = 246 - 246.6 = -0.6$ ). However, since the area is already present, the streams could be allowed to exchange as much heat as is thermodynamically possible. This would however, be less than 2.19 or else a temperature cross-over would occur.

The cold stream could also be split after the third match, resulting in the two final matches making better use of the available driving forces. However, since the existing exchangers are to be used, the decreased area requirement would not be utilised and the increased piping costs and controller cost would not make this a viable alternative. For the above reasons it was concluded that the hot streams are matched in the correct order.

## 1.2 Cross-pinch Exchangers

As already stated, the problem is unpinched with the result that no cross pinch exchangers existed.

### 1.3 Badly Placed Matches Observed on the Driving Force Plot

An inspection of Figure D8 in Appendix 4 shows that three matches appear to use excessive driving forces - these being matches 2, 4 and 5. The large approaches are due to the hot stream supply temperatures being much larger than the cold stream target temperatures. Although these matches appear incorrectly placed, they do in fact cross the ideal Driving Force curve. The log mean temperature (LMTD) of the actual exchanger is in fact similar to the LMTD of the ideal exchanger. To reduce the approach temperatures, additional exchangers would have to be installed and a different matching arrangement considered. This would be an impractical solution.

### 1.4 General Plant Modifications

The only cold stream not completely matched, is cold stream 3 (a reboiler stream). Hot streams which could be matched against it, are streams 9 and 10, However, these are overhead streams which undergo condensation. Matches with these streams were not be considered due to the imposed physical constraints.

Due to the unpinched nature of the problem, no columns straddled the pinch and no pump-around streams transferred energy across the pinch.

A possible modification considered involved matching different streams by varying the stream flowrates. The new proposed network is shown in Figure H2 below.

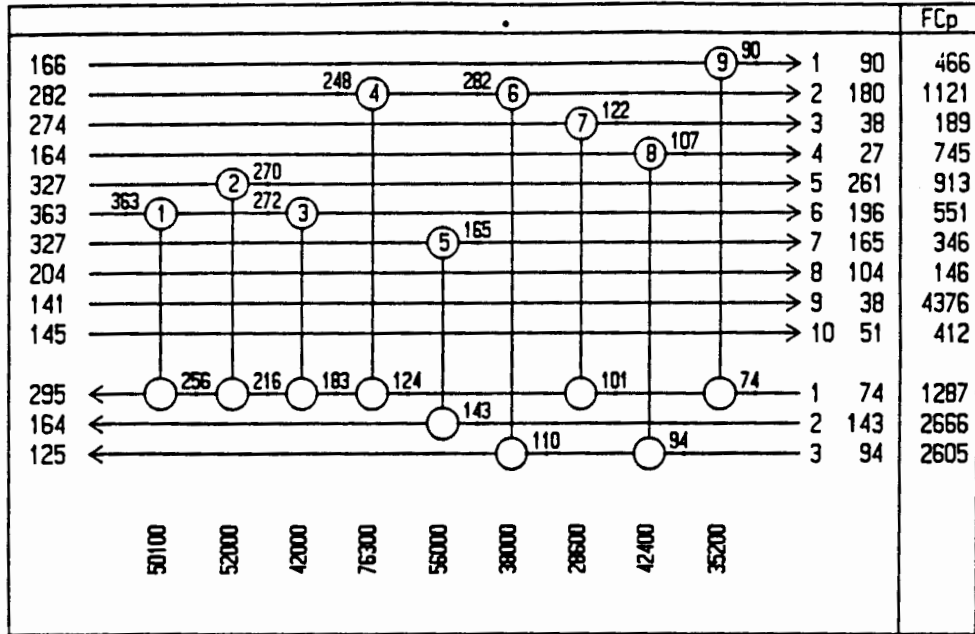


Figure H2 New Network for Plant 1

Instead of matching hot stream 7 with cold stream 2 (match 4), it was decided to match the hot stream against cold stream 3. This however required a larger hot stream flowrate (stream 7 heat capacity flowrate would have to be increased by 144%) since the duty in the new cold stream was larger than the original value. The effect of increasing the hot stream flowrate resulted in a simultaneous decrease in the flowrate of hot stream 5 (since the two streams are split). The decreased flowrate of hot stream 5 would result in cold stream 1 not being heated to its target temperature. This would in turn increase the hot utility consumption. An additional drawback of the new matching arrangement was the fact that hot stream 4 would be unmatched. Thus the net effect of the proposed matching arrangement was an increase in the overall utility consumption as opposed to a decrease.

The final modification considered was to use the available area more effectively by utilising a greater duty in two pump-around streams. This network is shown in Figure H3 below.

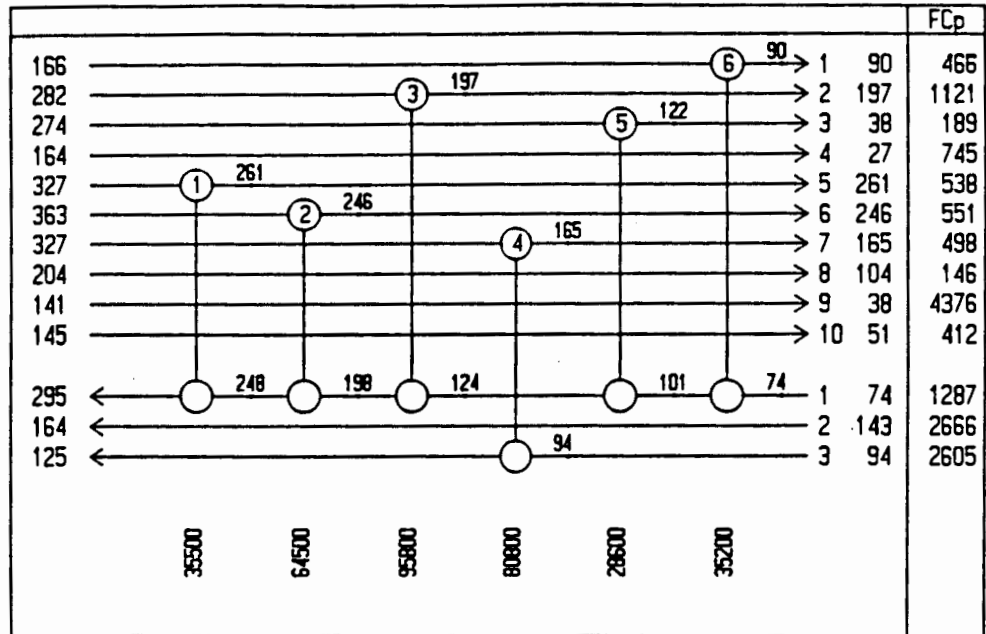


Figure H3 New Network for Plant 1

Hot stream 2 has sufficient duty to complete the match with cold stream 3 if it is not first matched against cold stream 1 (match 3). Once the new match has been completed, a new arrangement must be considered to take cold stream 1 to its target temperature. This may be achieved as follows:

- 1) The target temperature of hot stream 2 may be decreased since it is a pump-around stream. The additional heating so obtained may then be used to heat cold stream 1 to a slightly lower temperature than that achieved in match 3.
- 2) Match 1 makes use of an exchanger consisting of two shells. If matches 1 and 2 are reversed such that cold stream 1 is first passed through the first shell of exchanger 2, then through exchanger 1 (match 1) and finally through the second shell of exchanger 2, and if the target temperature of hot stream 6 is decreased, the cold stream could still be heated to the correct target temperature. It was calculated that the present

area of each exchanger would be sufficient to meet the new duty of the proposed arrangement.

As is immediately obvious, this arrangement would have the following drawbacks:

- 1) Additional pipework and controllers would be required.
- 2) The column operating conditions would change due to decreased pump-around target temperatures.

However, the advantage of this modification would be a saving of 1400 kW in LP steam resulting in a financial saving of approximately \$72 700 per annum. As stated, the area already installed will be sufficient to meet the required duty. Thus the only capital expenditure will involve the additional pipework and controllers. In addition, the effect of the changed pump-around rates on the column operation would have to be investigated.

#### 1.5 Targets without the Overhead Streams

As discussed in Chapter 6, there are constraints in matching a cold stream against an overhead stream. For this reason, the duties associated with these streams were removed and the problem re-analysed. The new targets using the stream data remaining would provide a better insight to the actual savings possible. The targets (as presented in Table 6.3) may be summarized as below:

	Without overhead streams	Fin fan Duty	With all streams
Hot utility (kW)	190		0
Cold utility (kW)	1 950	13 580	15 340
Hot pinch T (°C)	106		(363)*
Cold pinch T (°C)	94		(351)*

Note: \* refers to point of closest approach

From this table, it can be seen that the combined energy savings possible, ignoring the overhead streams, is approximately 380 kW (190 kW in hot utility and 190 kW in cold utility) less than with the streams included. This represents a combined reduced saving of approximately \$15 000 per annum which is approximately 16% less than that for the whole problem.

## 2 Plant 2

The plant is pinched with a hot pinch temperature of 272°C and a cold pinch temperature of 261°C. The target hot utility consumption is 41 200 kW while the target cold utility consumption is 24 760 kW. The actual hot utility consumption is 44 400 kW while the actual cold utility consumption is 21 150 kW. A feature of this plant is dominant cold stream 1 (in terms of its duty). The pinch is caused by hot stream 7 which is a pump-around stream.

### 2.1 Energy Levels

The stream data for the problem (Table A2 in Appendix 1) shows that there are only four cold streams compared to the eleven hot streams. As was the case in the plant 1, there

streams can be matched. The order in which these matches have been placed is best illustrated using the energy level plot in Figure H4 below.

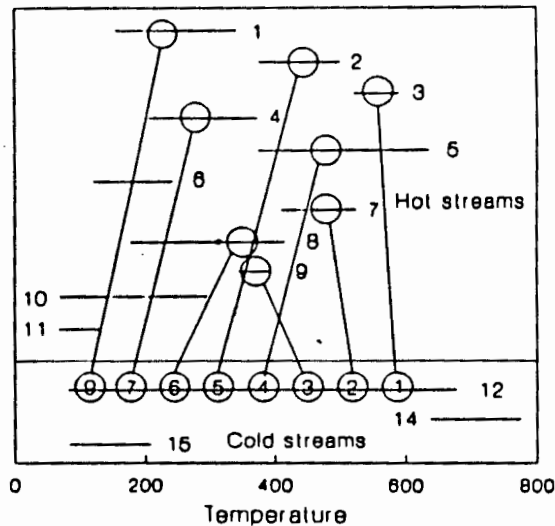


Figure H4 Energy Level plot for Plant 2

As was the case in the previous plant, all matches (with the exception of one) corresponded to increasing temperature levels. Although this is not immediately obvious from Figure H4, consideration should be given to the target temperatures of each hot level. It is clear that these values are ordered from lowest to highest (with the exception of the one match). The supply temperatures of each level merely fix the duty associated with that level. Since the approach temperature most likely to be affected results from the hot stream target temperature, it is this value which is important in determining the energy level and not the supply temperature.

Match 3 (Figure D2 in Appendix 4) clearly contradicts the matching arrangement on the basis of using increasing temperature levels. This match should have been placed before match 5. However, the duty associated with this match is very small resulting in only a three degree rise in the cold stream temperature (this represents 0.7% of the total cold stream temperature rise).

By moving the match (as suggested above), the area efficiency (after matching only hot streams against cold stream 1) only increased from 1.32 to 1.33. This network is shown in Figure H5 below.

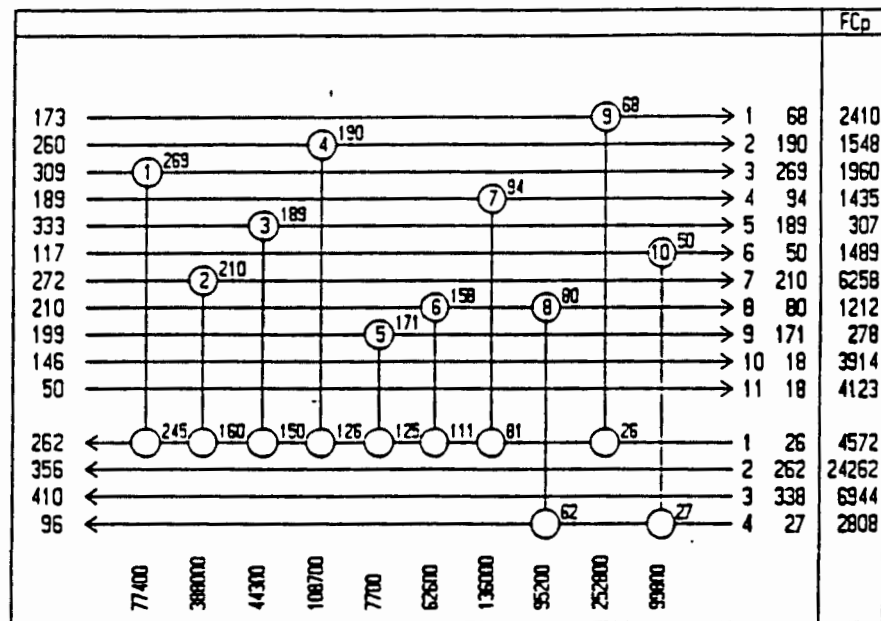


Figure H5 New Network for Plant 2

However, to achieve this small increase in efficiency, additional piping and controllers would be required to re-direct the cold stream. Since only the order of matching the hot streams was changed (the duties in the matches were left the same since they are all fixed), cold stream 1 was still heated to the same target temperature. Thus no energy could be saved resulting in a non-feasible modification due to the capital expense.

As mentioned in Section 5.7 in Chapter 5, both hot and cold streams were added below the pinch. The duty of the cold stream was greater than the combined hot stream duties thus resulting in a reduced cold utility consumption. However, if the inter-unit streams were considered independently (i.e. if they only exchanged heat amongst themselves) and the area target associated with these three streams was

compared to that associated with all streams, the following was noted:

Area target of inter-unit streams only	430 m <sup>2</sup>
Area target of non-integrated problem	5 970 m <sup>2</sup>
Total	6 400 m <sup>2</sup>
Area target of integrated problem	6 589 m <sup>2</sup>

The above analysis shows that integration of the streams into the problem is slightly less efficient (3% increase in the overall area) than if they exchanged heat solely amongst themselves. This efficiency decreases further if actual areas are considered as shown below:

Actual area of matches with inter-unit streams	520 m <sup>2</sup>
Actual area if inter-unit streams exchanged heat amongst themselves	310 m <sup>2</sup>
"wasted" area expressed as a percentage	40%

## 2.2 Cross-pinch Exchangers

Two cross pinch exchangers exist - these being exchangers 1 and 4 (Figure D2 in Appendix 4). Exchanger 1 is transferring 94% (2 646 kW) of its total duty across the pinch (80% of the possible hot utility saving) while exchanger 4 is transferring 43% (687 kW) of its duty across the pinch (20% of the possible hot utility saving). The hot stream in exchanger 1 is a pump-around stream while the stream in exchanger 4 is a liquid stream.

Since the supply temperature on the pump-around stream is 39°C above the hot pinch temperature, the stream cannot be easily moved below the pinch. Thus the exchange must take

place above the pinch. From an inspection of the stream data, the only cold stream above the pinch against which this hot stream could be matched, is cold stream 2 (allowing for an approach of  $10.5^{\circ}\text{C}$  if the hot stream is cooled to the pinch temperature). The heating lost in cold stream 1 would subsequently have to be provided by a different hot stream. From the matching arrangement, the only hot streams with any duty available are streams 10 and 11. However, these are overhead streams thus ruling out any matches with the cold liquid stream. Thus the saving achieved by shifting the match above the pinch is once again offset by the additional heating required below the pinch. The same argument holds true for the second exchanger transferring heat across the pinch.

### **2.3 Badly Placed Matches Observed on the Driving Force Plot**

An inspection of the Driving Force Plot (Figure D9 in Appendix 4) shows three matches which appear to be badly placed, these being matches 3, 4 and 5. Match 4 corresponds to a cross pinch exchanger. However, the other two matches would require different hot streams being matched against the present cold streams or different duties in the exchangers. The former proposal has been partly discussed in that exchanger 3 has already been identified as badly placed. The duty in exchanger 4 could be reduced, but this would result in additional area being required with a different matching arrangement. In addition, exchangers 3 and 4 use hot streams with very low heat capacity flowrates. This in turn results in these streams experiencing large temperature changes. Thus when these matches are located on a driving force plot, they appear to be badly placed.

## 2.4 Change in Operating Conditions

Due to the high pinch temperature (271°C), no columns straddle the pinch and hence there is no need to change their operating pressures or temperatures. As mentioned, there is one pump-around stream extending across the pinch. However, due to the present matching arrangement, integration of this stream entirely above the pinch does not lead to any energy savings (as discussed in Section 2.2 above) since there is a simultaneous decrease in the hot utility consumption below the pinch. It was concluded that the flowrate should not be altered.

## 2.5 General Plant Modifications

The only alternative plant modification considered arose from the poorly placed hot inter-unit stream discussed above. It was decided to exclude the stream from the problem and use the available area to heat cold stream 1 to its correct target temperature. The hot streams considered were streams 5 and 8. However, the flowrate of stream 5 could not be increased due to imposed constraints. Stream 8, on the other hand, was being matched against a cold utility stream once it had been matched against cold stream 1. Thus by increasing the flowrate and using the additional area, the hot stream exit temperature would decrease resulting in a reduced exchange with the utility stream (Boiler feed water). Thus the energy saved is offset by the increased hot utility required to heat the BFW to its target temperature.

A modification involving introducing hot stream 8 into plant 1 at its supply temperature (approximately 200°C) was considered. In plant 1, hot stream 8 (from plant 2) is the dominant cold stream 1. The network involving streams from plants 1 and 2 is shown in Figure H6 below.

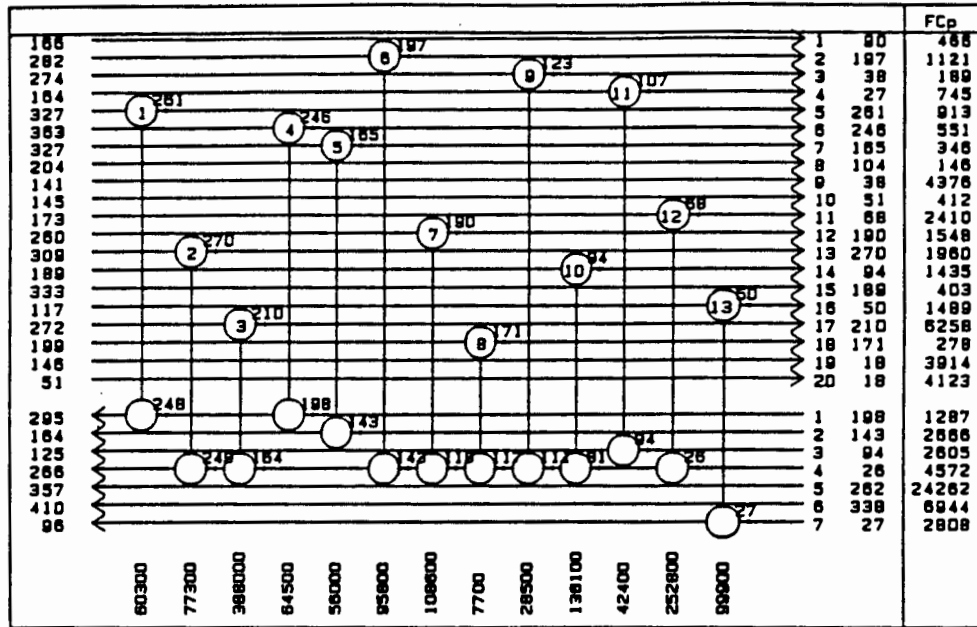


Figure H6 Resulting Network after matching streams from Plants 1 and 2

On plant 1, matches 1 and 2 remained the same, while matches 3, 5 and 7 were removed. This in turn meant that hot streams 1, 2 and 3 were available for heating unmatched cold streams. On plant 2, matches 6 and 8 were removed. This resulted in cold stream 1 no longer being heated to its final target temperature. This additional duty would have to be supplied by the three available hot streams from plant 1. To correctly match hot streams (from plants 1 and 2) against the cold stream from plant 1, the following criteria were considered:

- a) Streams were arranged so that they were matched in order of increasing temperature levels. This also involved matching hot stream 9 (from plant 2) at a lower temperature level.
- b) All streams with fixed duties (pump-around streams) were matched so that these duties remained unchanged.
- c) Streams with a variable target temperature were matched so that the present exchanger area remained unchanged.

Using the above matching criteria, cold stream 1 on plant 2 could be heated to approximately 267°C (previously heated to 262°C). This would represent a fuel oil saving of approximately \$80 000 per annum. However, the steam production in plant 3 would be reduced (since an inter-unit stream from this plant would exchange more heat in plant 2 and would subsequently be returned at a lower temperature) which would result in a loss of approximately \$17 000 per annum. The net savings would be approximately \$63 000 per annum.

## 2.6 Targets without the Overhead Streams

The new targets, using the stream data remaining after removing the overhead streams, may be summarised as below:

	Without overhead streams	Fin fan Duty	With all streams
Hot utility (kW)	44 400		41 200
Cold utility (kW)	0	17 590	14 390
Hot pinch T (°C)	(37.1)*		272.0
Cold pinch T (°C)	(26.0)*		260.9

\* refers to the point of closest approach

From this table it can be seen that the problem becomes unpinched when the overhead streams are removed. Thus the only source of cooling is in the fin fans to cool these overhead streams. More importantly is the fact the new target hot utility and the actual hot utility consumption is the same thus reducing the potential to improve to zero. For this reason, only modifications involving the overhead streams will lead to an energy saving.

### 3 Plant 3

The plant is pinched with a hot pinch temperature of 135°C and a cold pinch temperature of 126.7°C. The pinch is a utility pinch since it is caused by a cold utility stream with a large duty. The target hot utility consumption is 4 780 kW while the target cold utility consumption is 8 260 kW. The actual hot utility consumption is 5 340 kW while the actual cold utility consumption is 2 620 kW.

#### 3.1 Energy Levels

The number of hot and cold streams are equal with no single stream having two or more matches. The energy level plot, as shown in Figure H7 below, does not show any incorrectly placed matches.

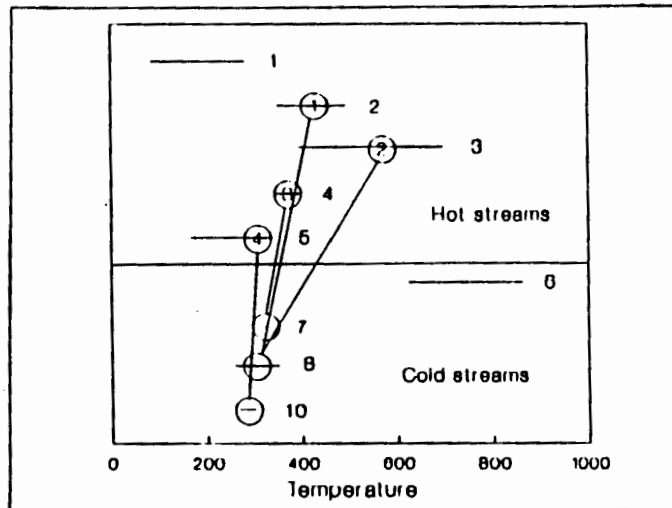


Figure H7 Energy Level plot for Plant 3

#### 3.2 Cross-pinch Exchangers

All matches placed lie above the pinch resulting in no cross-pinch exchangers.

### 3.3 Badly Placed Matches Observed on the Driving Force Plot

The only match which appears misplaced is match 3. This is the result of matching a hot stream with a cold stream at a temperature above its optimum (as predicted by the ideal driving force curve) or a hot stream which is at a temperature below its optimum. However, apart from utility streams, this cold stream is the coldest process stream with the result that no alternative match could be considered.

### 3.4 Change in Operating Conditions

No columns straddled the pinch and no pump-around stream existed with the result that no changes were considered.

### 3.5 General plant modifications

Two unmatched streams (one hot and one cold stream) and one partially matched hot stream exist. The hot unmatched stream is an overhead stream while the temperature level of the cold unmatched stream is too high to be matched against the hot unmatched stream. Thus no further matches could be considered.

### 3.6 Targets without the Overhead Streams

The new targets, using the stream data remaining after removing the overhead streams, may be summarised as below:

	Without overhead streams	Fin fan Duty	With all streams
Hot utility (kW)	5 140		5 140
Cold utility (kW)	870	1 540	2 410
Hot pinch T (°C)	135.0		135.0
Cold pinch T (°C)	126.7		126.7

The actual hot utility consumption (5 340 kW) confirms the scope for improvement, although the target has remained the same since the pinch is still at the same temperature.

#### 4 Plant 4

The plant is pinched with a hot pinch temperature of 79.4°C and a cold pinch temperature of 73.9°C. The target hot utility consumption is 13 480 kW while the target cold utility consumption is 6 290 kW. The actual hot utility consumption is 15 350 kW while the actual cold utility consumption is 8 160 kW. Features of this plant are the number of streams with very small duties and the single dominant hot stream (stream 1) and cold streams (stream 1).

##### 4.1 Energy Levels

This plant is contrasted to the rest in that many hot and cold streams exist (Table A4 in Appendix 1). However, despite the large number of streams, only five process-process matches exist (Figure D4 in Appendix 4). An inspection of the energy level plot in Figure H8 below, gives an indication as to why so few matches are possible.

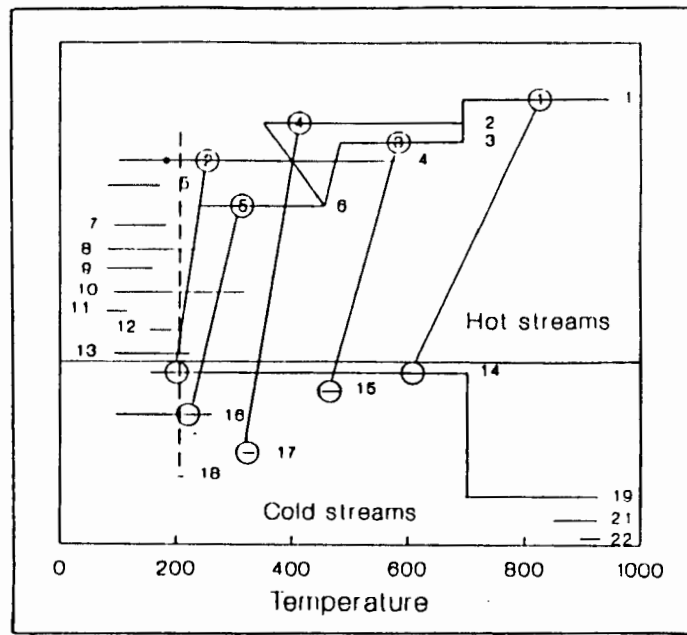


Figure H8 Energy Level plot for Plant 4

Once the five matches have been specified, no cold streams (with the exception of one) with a low enough temperature level exist to be matched against any of the hot streams to the left of the vertical line in the above figure. The single cold stream (stream 6) could only be matched against portions of hot streams 8 or 10. However, the duty associated with hot stream 8 is too small. The match with hot stream 10 will be dealt with later.

The remaining hot streams (to the left of the vertical line) are all cooled by fin fans and hence there is no possibility of reducing this cold utility requirement since there are no cold streams available.

The three hottest cold streams can obviously not be matched against any hot streams (since their temperature levels are higher than that of the hottest hot stream) and they therefore require hot utility.

At present, match 1 heats up cold stream 1 to the furnace inlet temperature. However, if additional area was installed, more heat could be extracted from hot stream 1 so increasing the target temperature on the cold stream. This slightly modified network is shown in Figure H9 below.

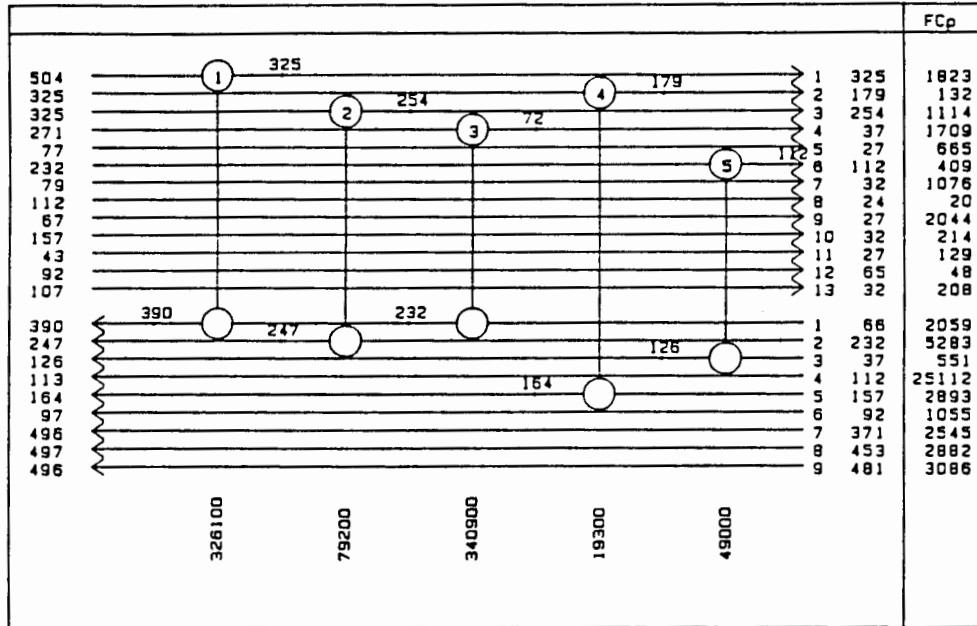


Figure H9 Modified network for Plant 4

It was calculated that if the present area was doubled (i.e. an additional shell of the same size was added), approximately 2000 kW of heating could be saved in the furnace. This would represent a financial saving of approximately \$172 000 per annum. The cost of an installed exchanger would be approximately \$135 000. Since the first four hot streams are all coupled (as shown in Figure H10 below), the new supply temperature of hot streams 2 and 3 would be approximately 325°C (instead of 366°C) after the new match. This would in turn fix the supply temperature of hot stream 4 at approximately 271°C (instead of 303°C) after re-combining hot streams 2 and 3.

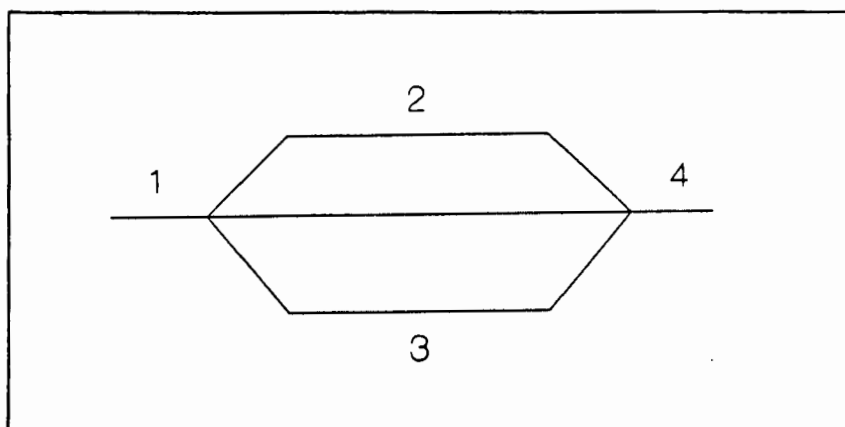


Figure H10 Relation between Hot Streams 1, 2, 3 and 4.

Match 2 would subsequently require less duty to avoid a temperature cross-over in the exchanger. The streams can be allowed to exchange as much heat as is thermodynamically feasible since an existing exchanger is being used with an area larger than that actually required. This however, would be a favorable modification since less power would be required in the fin fan on hot stream 4.

#### 4.2 Cross-pinch Exchangers

The hot pinch temperature is  $79.4^{\circ}\text{C}$  while the cold pinch temperature is  $73.9^{\circ}\text{C}$  resulting in matches 2 and 5 transferring energy across the pinch. The heat transferred in match 2 represents 4% of the total duty exchanged (approximately 400 kW). However, after the modification discussed above, only 50 kW (0.5% of the total match duty) would be transferred across the pinch. For this reason, no additional modification, which would eliminate the energy transferred across the pinch, will be considered. Match 5 has 41% of its total duty (approximately 600 kW) transferred across the pinch. To eliminate this energy transfer, the cold stream should be matched against a hot stream below the pinch. Hot streams to be considered are:

- 4 The colder portion of hot stream 4 would have sufficient duty. The cost of a high pressure exchanger would be approximately \$75 000 while the energy saving would be approximately \$49 000 per annum.
- 8 This stream has too little duty associated with it.
- 10 Only a portion of this stream lying below the pinch could be matched against the cold stream due to a violation of the approach temperature. This match would still leave a portion of cold stream 3 unmatched below the pinch. A further match would have to be considered which would in turn result in a total of two additional exchangers being required.
- 12 This stream is mostly situated above the pinch.
- 13 This stream has too little duty associated with it.

In addition, hot stream 6 would have to be matched against a cold stream above the pinch (since it would no longer be cooled to its correct target temperature). Two cold streams could be used, these being streams 4 and 6. However, the approach would be violated if stream 4 was used, while the duty of stream 6 is insufficient.

Since none of the above matches are feasible, it was decided to leave the cross-pinch exchanger in place.

#### **4.3 Badly Placed Matches Observed on the Driving Force Plot**

An inspection of the Driving Force Plot (Figure D11 in Appendix 4) shows two matches that appear to be badly placed - these being matches 3 and 5. The location of match 5 can be explained in terms of it being a cross-pinch exchanger. Match 3, however, lies entirely above the pinch and appears to be misplaced because the target temperature of the cold stream (stream 15) is 101°C below the hot stream (stream 3) supply temperature. Both hot stream 3

and cold stream 2 are high pressure streams. No other cold stream with a higher target temperature than cold stream 2 can be matched against the hot stream. Thus a different match, which would not result in an energy saving, would have to be considered which in turn would not be an economically feasible solution.

#### 4.4 Change in Operating Conditions

There are several columns in the plant. Each of these columns straddles the pinch. However, in all the condensers, use is made of fin fans and not a process stream. Thus by moving the condenser above the pinch or moving the reboiler below the pinch (by decreasing or increasing the column pressure respectively), no advantage would be gained since there is no transfer of energy across the pinch in terms of process streams. i.e. by integrating the condenser below the pinch, cold utility would still be required. This requirement may be less than the original duty (the inlet temperature to the condenser would have decreased), but since fin fans were being used, the saving would be small thus not warranting the change in pressure.

#### 4.5 General Plant Modifications

Two modifications were considered. The first was varying a mixing point and the second was matching a hot liquid stream against a reboiler stream.

Modification 1: Cold stream 1 consists of two streams which are mixed - the one being a recycle stream and the other being a stream from plant 5. Non-isothermal mixing of the two streams occurs since they are introduced at different temperatures. The stream from plant 5 may be introduced at a higher temperature (as will be explained when dealing

with that plant). By varying the mixing point of the recycle stream and the hotter feed stream, it is possible to vary the approach temperatures in the exchangers resulting in different inlet and exit temperatures. It was found that by introducing the hotter stream after the first exchanger (the exchanger represented in match 2 in fact consisted of two exchangers in series), the cold stream would exit exchanger 1 at a higher temperature thus reducing the hot utility requirement. This reduction in fuel oil would result in a saving of approximately \$93 000 per annum. However, the drawback regarding this arrangement lies in the fact that the hot stream would exit exchanger 2 at a higher temperature thus necessitating an increased fin fan duty - this being approximately 1500 kW. However, the fin fan operation is marginal in summer and would not be able to cope with the increased duty. This modification could be used in winter with the present mode of operation used during summer.

Modification 2: It was proposed to match a portion of hot stream 10 with cold stream 6. The reduced hot utility requirement would result in a saving of approximately \$11 000 per annum. Additional hardware required to achieve this saving would include a flow controller, a block valve and piping. The area already installed is sufficient to meet the required duty (as calculated by a detailed heat exchanger rating procedure).

#### **4.6 Targets without the Overhead Streams**

The new targets, using the stream data remaining after removing the overhead streams, may be summarised as below:

	Without overhead streams	Fin fan Duty	With all streams
Hot utility (kW)	13 570		13 490
Cold utility (kW)	1 710	4 650	6 280
Hot pinch T (°C)	71.7		79.4
Cold pinch T (°C)	66.1		73.9

From the above hot utility targets, it can be seen that the potential to save energy in the form of steam or fuel oil has remained nearly the same.

## 5 Plant 5

The plant is pinched with a hot pinch temperature of 168.9°C and a cold pinch temperature of 160.6°C. The target hot utility consumption is 5 770 kW while the target cold utility consumption is 4 750 kW. The actual hot utility consumption is 6 410 kW while the actual cold utility consumption is 8 940 kW. The findings for this plant are as follows:

## 5.1 Energy Levels

The energy levels are presented in Figure H11 below.

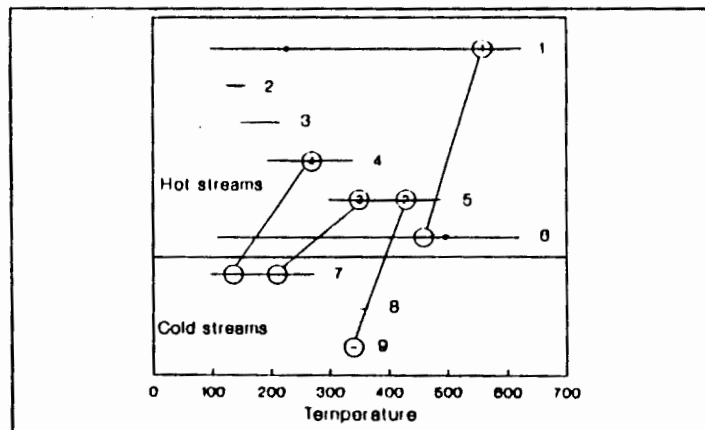


Figure H11 Energy Level plot for Plant 5

From the actual network (Figure D5 in Appendix 4) it can be seen that two hot streams and a single cold stream are unmatched with one hot stream partially matched. From an inspection of Figure H11, it is immediately obvious that no further exchange with these streams can be considered due to their incorrect temperature levels. In addition, hot streams 2 and 3 are overhead streams and cannot thus be matched with any of the reboiler streams. To achieve any savings, the present matches would have to be re-arranged.

## 5.2 Cross-pinch Exchangers

Two cross-pinch exchangers exist - these corresponding to exchangers 1 and 3. Match 1, however, does not transfer all its duty across the pinch since a portion of the streams are matched entirely above the pinch while a portion of the streams are matched entirely below. The duty transferred across the pinch is approximately 2630 kW which represents approximately 27% of the total match duty. However, the approach at each end of the exchanger may be reduced (at present, this approach is much higher than the optimum  $\Delta T$ )

which in turn would result in a decreased cross-pinch exchange. Thus by installing additional area, a greater exchange is possible which in turn would reduce the hot and cold utility requirement. Using the actual heat exchanger data, it was calculated that for a 25% increase in area (the present exchanger consists of four shells and thus the addition of an extra shell was being considered), 59.6% of the additional utility requirement would be saved. This would represent a fuel oil saving of approximately \$135 000 per annum. The additional area required would cost approximately \$200 000. This figure represents the cost for an installed, high pressure exchanger. The payback period is approximately 1.5 years.

Exchanger 3 is transferring approximately 1500 kW (50% of the total match duty) across the pinch. If this match is removed, hot stream 5 will have to be matched against another cold stream (which lies above the pinch). Two cold streams could be used - streams 1 and 3. However, cold stream 1 is too hot while a match with cold stream 3 would only satisfy part of the requirement (to avoid a violation of the approach temperature). The energy saved by matching the colder portion of cold stream 3 against the unmatched portion of hot stream 5 would be approximately 240 kW. The associated fuel oil saving would be approximately \$20 600 per annum. The cost of an installed exchanger would be approximately \$96 000 giving a payback period of approximately 4.7 years. Due to the large payback period associated with this modification, it was not attempted to match the hotter portion of cold stream 7 (previously matched in exchanger 3) with a hot stream.

### **5.3 Badly Placed Matches Observed on the Driving Force Plot**

An inspection of the Driving Force Plot (Figure D12 in Appendix 4) shows two matches that appear to be misplaced - these being matches 1 and 3. Both these matches correspond

to the cross-pinch exchangers already discussed. It was noticed that match 1 showed a close approximation to the ideal driving force at higher temperatures. By increasing the duty of the match, the line representing the match would in fact approach that of the ideal driving force curve since the cold stream inlet temperature and the hot stream exit temperature would both decrease.

#### 5.4 Change in Operating Conditions

A column straddles the pinch, but as in plant 4, use is made of a fin fan to cool the overhead stream. Thus integrating the column below or above the pinch would not lead to any significant energy savings unless the overhead stream could be integrated into the process.

#### 5.5 General Plant Modifications

As mentioned in the discussion of a modification considered in plant 4 (section 4.5 above), the feed stream to that plant could be introduced at a higher temperature. This hot stream (stream 4) first exchanges its heat with cold stream 2 before being fed to plant 4. If this stream was fed at its supply temperature, two penalties would result - these being:

- 1) The fin fan inlet temperature (on plant 4) would increase by approximately 33°C which might cause problems in summer (as discussed in section 4.5 above).
- 2) The hot utility requirement on plant 5 would increase due to the reduced heating associated with hot stream 4. If a solution to problem (1) was found, it could be argued that the unmatched portion of hot stream 1 could be matched against that portion of the cold stream previously heated by the feed stream to plant 4. The cost of fuel oil saved in plant 4 would be approximately \$60 000 per annum while the cost of the

high pressure exchanger required in plant 5 would be approximately \$250 000. The latter value represents the installed exchanger cost. The resulting payback period would be approximately 4 years.

### 5.6 Targets without the Overhead Streams

The new targets, using the stream data remaining after removing the overhead streams, may be summarised as below:

	Without overhead streams	Fin fan Duty	With all streams
Hot utility (kW)	3 620		3 280
Cold utility (kW)	410	5 740	5 810
Hot pinch T (°C)	47.4		168.9
Cold pinch T (°C)	39.1		160.6

Comparing the target hot utility requirement, after removing the overhead streams, to that before removing the streams, shows that it has decreased slightly. This is due to a decrease in the pinch temperature which in turn results in the hot overhead streams being removed above the pinch. Removal of hot streams above the pinch causes a decrease in the hot utility consumption. To achieve this energy saving, additional area would have to be added to match 1 since this match would transfer more energy across the new pinch.

## 6 Plant 6

The plant is unpinched. The target hot utility consumption is zero while the target cold utility consumption is 5 610 kW. The actual hot utility consumption is 450 kW while the actual cold utility consumption is 2 500 kW.

### 6.1 Energy Levels

The energy levels for the plant are shown in Figure H12 below.

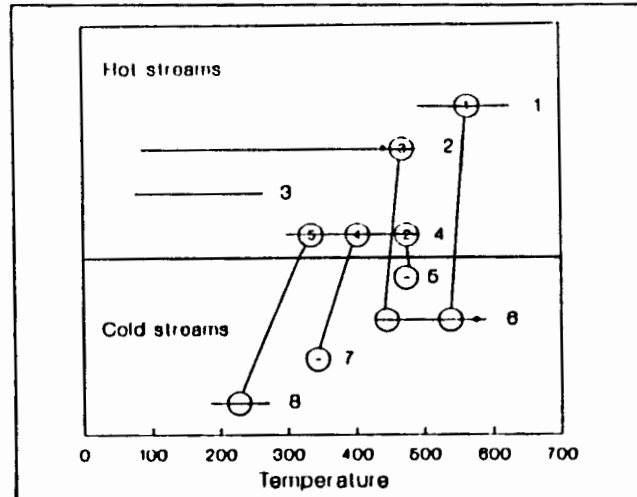


Figure H12 Energy Level plot for Plant 6

An immediate observation is the fact the unmatched hot stream (stream 3) and the partially matched hot stream (stream 2) cannot be matched against the remaining portion of cold stream 2 since their temperature levels are too low.

### 6.2 Cross-pinch Exchangers

The problem is unpinched with the result that no cross pinch exchangers are possible.

### 6.3 Badly Placed Matches Observed on the Driving Force Plot

An inspection of the Driving Force Plot (Figure D13 in Appendix 4) shows that no matches are badly placed.

#### 6.4 Change in Operating Conditions

No pump-around streams exist and all columns lie below the pinch thus not necessitating a change in any of the operating parameters.

#### 6.5 Targets without the Overhead Streams

The new targets, using the stream data remaining after removing the overhead streams, may be summarised as below:

	Without overhead streams	Fin fan Duty	With all streams
Hot utility (kW)	0		0
Cold utility (kW)	1 760	290	2 050
Hot pinch T (°C)	(327.8)*		(327.8)*
Cold pinch T (°C)	(322.2)*		(322.2)*

Note: \* refers to point of closest approach

By removing the overhead streams, the pinch temperature remains unchanged which in turn means that the problem remains unpinched.

### 7 Plant 7

The plant is pinched with a hot pinch temperature of 176.7°C and a cold pinch temperature of 171.1°C. The target hot utility consumption is 540 kW while the target cold utility consumption is 3 140 kW. The actual hot utility consumption is 960 kW while the actual cold utility consumption is 3 560 kW.

## 7.1 Energy Levels

The plant is very small in that only five streams exist - one of these being a cold stream. From an inspection of the energy level plot in Figure H13 below, it can be seen that the unmatched hot streams cannot exchange heat with the remaining portion of the unmatched cold stream.

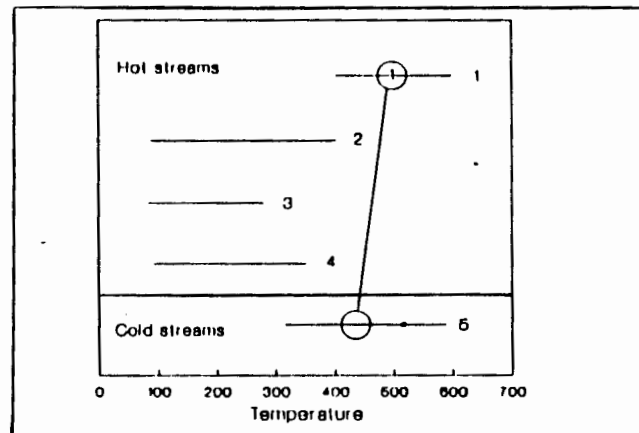


Figure H13 Energy Level plot for Plant 7

## 7.2 Cross-pinch Exchangers

The only exchanger present transfers 230 kW (9% of its total duty) across the pinch. To save this energy, the cold stream would have to be matched against either hot streams 2, 3 or 4. However, the heat capacity flowrates of each of these streams is less than that of the cold stream resulting in the fact that not all the cross-pinch duty can be matched below the pinch.

However, if a portion of hot stream 4 is matched against cold stream 1 below the pinch, 86% of the heat transferred across the pinch can be saved, giving an energy saving of approximately \$23 700 per annum. This network is shown in Figure H14 below.

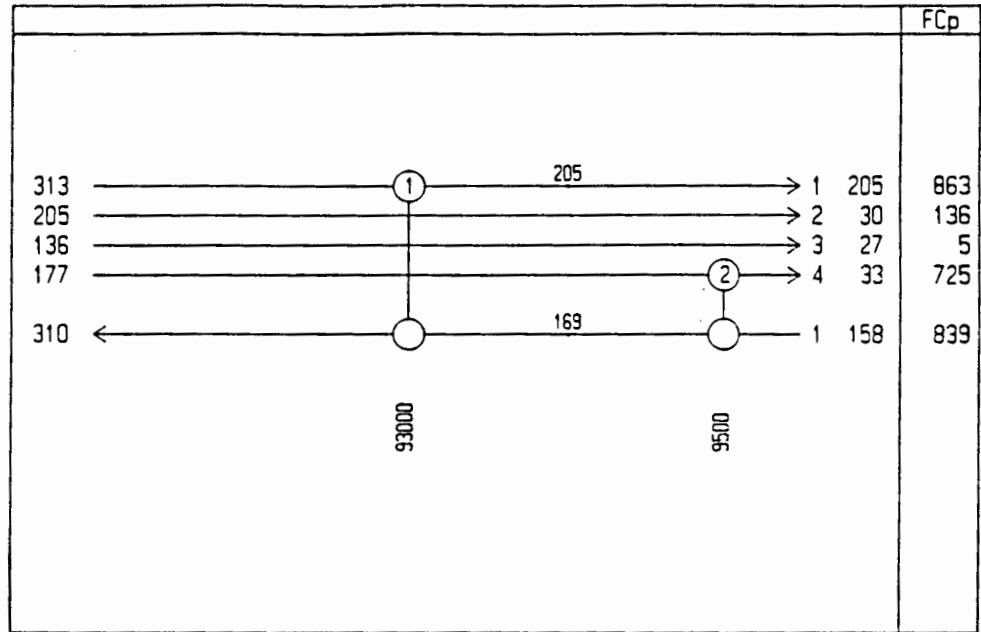


Figure H14 New Network for Plant 7

By utilising the same area (using the existing exchanger), a similar exchange would be achieved (same duty) although less energy would be transferred across the pinch. Hot stream 1, previously supplying the total duty for match 1, would exit at a higher temperature due to the reduced duty exchanged with the cold stream. To ensure that hot stream 1 exits at the correct temperature, additional area will have to be installed. The cost of installing a high pressure exchanger with its associated hardware would be approximately \$132 000. This would result in a payback period of approximately 5.6 years.

**7.3 Badly Placed Matches Observed on the Driving Force Plot**

The single match represented on the Driving Force Plot (Figure D14 in Appendix 4) appears to be misplaced. This is due to the fact that it transfers energy across the pinch.

#### 7.4 Change in Operating Conditions

No pump-around streams exist and no columns straddle the pinch thus making operating changes unnecessary.

#### 7.5 General Plant Modifications

The only modification which would have resulted in an energy saving has been discussed in section 7.2. No other minor modifications would reduce the energy consumption with the result that no further savings were expected.

#### 7.6 Targets without the Overhead Streams

The new targets, using the stream data remaining after removing the overhead streams, may be summarised as below:

	Without overhead streams	Fin fan Duty	With all streams
Hot utility (kW)	550		550
Cold utility (kW)	3 130	10	3 140
Hot pinch T (°C)	176.7		176.6
Cold pinch T (°C)	171.1		171.1

The potential to save hot utility after removing the overhead streams has remained the same. The very small decrease in the cold utility target is due to a very small condensor duty.