



Process integration: process change and batch processes

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PROCESS INTEGRATION: PROCESS CHANGE AND BATCH PROCESSES

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A	heat exchanger surface area	m^2	ft^2
C_{PL}	specific heat capacity of a liquid	kJ/kg K	$\text{Btu/lb } ^\circ\text{F}$
CP	heat capacity flowrate of a stream	kW/K	$\text{Btu/h } ^\circ\text{F}$
DT_{min}	minimum allowable temperature difference for a match	$^\circ\text{C}$	$^\circ\text{F}$
h_C	heat transfer coefficient from stream C	$\text{kW/m}^2 \text{ K}$	$\text{Btu/ft}^2 \text{ h } ^\circ\text{F}$
h_X	heat transfer coefficient from stream X	$\text{kW/m}^2 \text{ K}$	$\text{Btu/ft}^2 \text{ h } ^\circ\text{F}$
$LMTD$	log mean temperature difference between two streams	$^\circ\text{C}$	$^\circ\text{F}$
L/V	liquid-to-vapour mass flow ratio in a distillation column	—	—
m_L	mass of liquid in vessel	kg	lb
Q	heat transfer rate	kW	Btu/h
Q_{inst}	heat transfer rate by direct heat exchange for a match	kW	Btu/h
S	heat transferred from hot to cold streams via storage	$^\circ\text{C}$	$^\circ\text{F}$
T_1, T_2	initial and final temperatures of stream	$^\circ\text{C}$	$^\circ\text{F}$
T_c	temperature of cold stream	$^\circ\text{C}$	$^\circ\text{F}$
T_h	final temperature of cold stream	$^\circ\text{C}$	$^\circ\text{F}$
T_J	temperature of steam of thermal fluid in jacket	$^\circ\text{C}$	$^\circ\text{F}$
T_L	temperature of liquid in vessel	$^\circ\text{C}$	$^\circ\text{F}$
TI	interval temperature	$^\circ\text{C}$	$^\circ\text{F}$
t_1, t_2	start and finish times of stream	h	h
U	heat transfer coefficient	$\text{kW/m}^2 \text{ K}$	$\text{Btu/ft}^2 \text{ h } ^\circ\text{F}$
X	heat directly exchanged between hot and cold streams	kJ	Btu
ΔH	heat load on a hot or cold utility stream	kW	Btu/h

2. PURPOSE AND SCOPE OF THIS DATA ITEM

This is the last in a series of three Data Items on Process Integration, otherwise known as pinch technology. The stages in a Process Integration study are as follows.

- (i) Obtain stream data from the process flowsheet and calculate energy targets and the pinch temperature.
- (ii) Examine opportunities for process change and modify the stream data accordingly.
- (iii) Analyse the site power needs and identify opportunities for using combined heat and power (CHP).
- (iv) Design a heat exchanger network to recover heat within the process.
- (v) Design the utility systems to supply the remaining heating and cooling requirements, modifying the heat exchanger network as necessary.

Item No. 87030 introduced the concepts and covered stages (i) and (iv) for targeting and heat recovery in continuous processes. Item No. 89001 covered stages (iii) and (v), giving calculation methods for utility (site heating and cooling) systems, including CHP and heat pumping. This Data Item covers stage (ii) (process change) and shows how to apply all the stages to batch processes. These techniques have been developed within the last five years.

Process change is defined as altering operating conditions or otherwise changing the process flowsheet to change the stream data and the targets, thus giving more opportunities for heat recovery. Examples would include:

- changing the temperature of a distillation column,
- adding a pumparound, intermediate reboiler or intermediate condenser,
- changing the number of effects (stages) in an evaporator or flash system,
- modifying a dryer to use low-temperature heat or a different drying gas,
- changing a reaction temperature slightly.

Application to batch systems is much more difficult than for continuous processes because of the presence of intermittent streams, vessels which gradually change in temperature, and restrictions on heat exchange. Often products of high value at low production rates are involved so that energy use is neglected as unimportant. In fact, substantial savings are possible on many plants, but the project giving an optimal rate of economic return can be very different from the “theoretical best” project. This Data Item concentrates on methods to achieve practical and economic systems. These include:

- finding targets for maximum heat exchange within a batch,
- identifying possibilities for heat storage within and between batches,
- rescheduling process operations to increase heat exchange,
- designing heat exchanger networks to achieve targets,
- identifying “principal matches” that achieve most heat recovery,
- modelling vessels which gradually heat or cool,
- analysing utility systems, for example heating/cooling jackets for tanks.

The analysis method used, the time-dependent heat cascade, can be extended to handle other situations where the flowsheet is not the same at all times. Examples include:

- start-up and shut-down of continuous or batch processes,
- buildings and other non-process operations,
- multi-plant sites where different sections operate at different times.

3. HOW TO USE THIS DATA ITEM

This Data Item will help its user to understand the methods by which Process Integration (pinch technology) is applied to process changes, batch processes and start-up and shut-down of continuous processes. He or she will then be able to use these techniques to study process plants and other systems, including buildings and multi-process sites, where heating and cooling are required. Alternatively, if it is decided to employ a consultant, it will be possible to make the best use of the information provided.

It is assumed that the user is already familiar with the basic concepts of Process Integration. If not, Item Nos 87030 and 89001 should be read before studying this Item. Even if batch processes are the only interest, Sections 4 to 8 of Item No. 87030 should be consulted as they explain what a stream is, what process data are required, the meaning of the pinch, and basic targeting and heat exchanger network design methods.

In this Data Item, Section 4 covers process change, where operating conditions of certain parts of the system are changed to give a more energy-efficient overall system. In several studies, savings from process changes have exceeded those from conventional heat recovery, especially on smaller plants.

Section 5 describes how to obtain energy targets for batch processes. Heat recovery is possible both by direct heat exchange and also indirectly via heat storage. Both of these methods can be evaluated. The variation of hot and cold utility requirements during a batch cycle can also be found.

Section 6 shows how to design a heat recovery network to achieve or approach the targets found from Section 5 and notes suitable equipment for heat exchange and heat storage on batch plants.

Section 7 shows how the scheduling of the batch process can be altered so that heat recovery which previously required a heat storage system can be achieved by direct heat exchange. Rescheduling is a form of process change.

Section 8 contains two case studies. The first is on a batch speciality chemicals plant; the second is on a hospital, illustrating that the techniques are also applicable outside the process industries. Brief notes on a third process are also included.

A comprehensive glossary and set of references are provided in Sections 10 and 11 respectively.

The engineer wishing to use this Data Item in performing calculations on a continuous plant should first of all obtain the stream data, targets, composite curves and grand composite curve using the methods outlined in Item No.87030. The opportunities for process change should then be explored (Section 4 of this Item) before going on to network design as described in Item No. 87030. When designing the utility systems and total site systems, use may be made of the time-dependent analysis techniques described in Sections 5 to 7.

For a batch plant, the stream data are collected as described in Item No.87030 and Section 5 of this Item is used to obtain the targets. Process changes (Section 4) and rescheduling (Section 7) may be considered before the final network design (Section 6) is carried out. In the later stages the engineer should make use of the information on utility system design from Item No. 89001.

4. PROCESS CHANGE

4.1 The Basic Idea of a Process Change

The two previous Data Items have covered heat exchanger networks and utility systems. However, these are only part of the overall process. A process plant generally consists of all or some of the following sections.

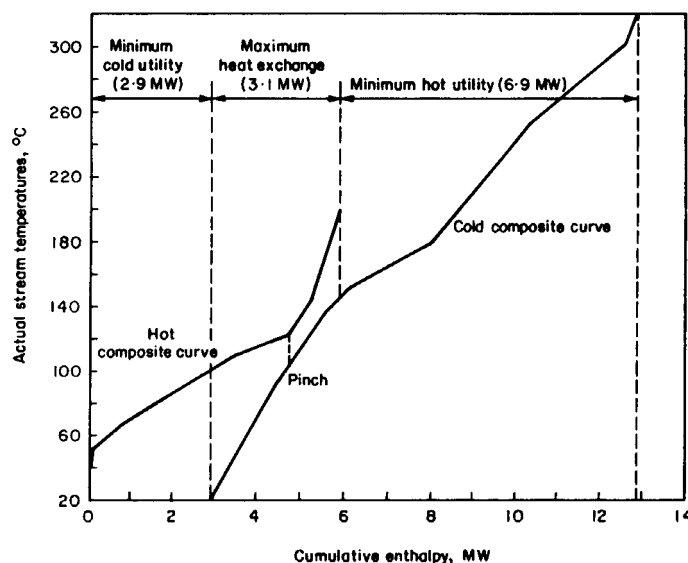
- A reactor, where the main chemical processes take place and impure product is formed from the raw materials.
- A separation system, that divides up the mixture of products, waste and unreacted raw materials emerging from the reactor using some separating agent, such as heat or a solvent.
- A heat exchanger network, that recovers heat from hot product streams to heat the cold feed streams.
- Site utility systems, supplying the external heating and cooling requirements of the plant by fuel, steam, cooling water, refrigeration, *etc.*

Conventional design methods start by designing the reactor, then the separation system, then the heat exchanger network, and finally finish by using utilities to supply the residual needs. This approach, though systematic, does not consider the process as an integral whole.

Process Integration goes a stage further by looking at how the reaction and separation systems fit in with the overall process. Often, changes to the process can be found (usually in the separation system) which increase overall heat recovery and give a better integrated system.

4.2 Composite Curves and the Plus-minus Principle

Sketch 4.1 shows the hot and cold composite curves for the process that has been used as the core example in Item Nos 87030 and 89001. The stream data for this are given in Table 4.1; the data were derived in Item No. 87030, Section 12.1 and allow for all heat losses and inefficiencies. The original process flowsheet is Sketch 4.2.

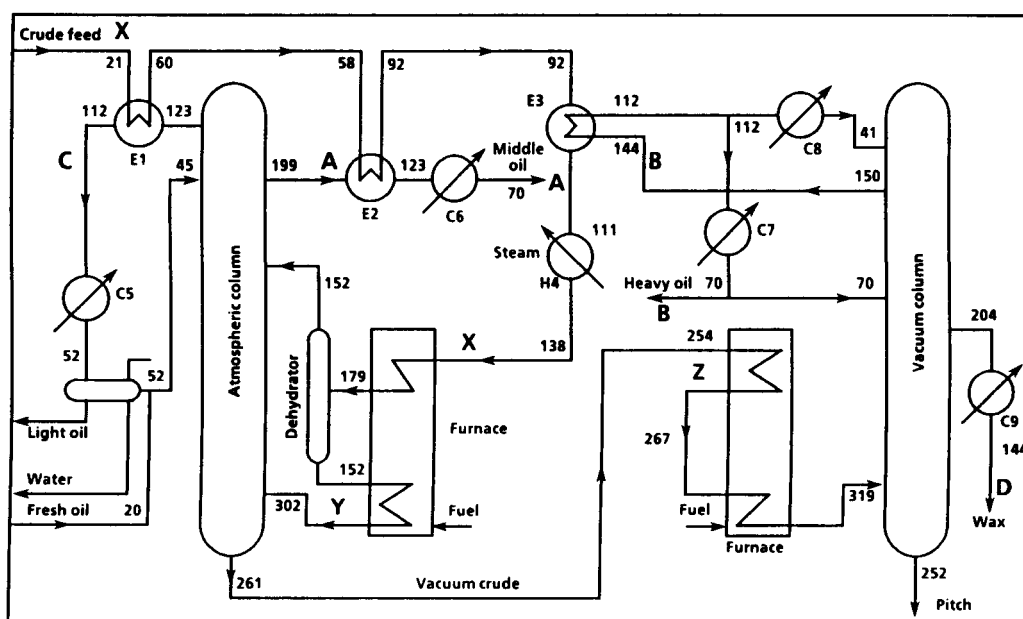


Sketch 4.1 Composite curves for core example

TABLE 4.1 Stream Data For Core Example

	1	2	3	4
Stream	Temperature °C	Enthalpy MW	Heat Capacity Flowrate (CP) MW/K	Interval Temperature °C
HOT STREAM				
A	199	1.35	0.0101 0.0109	189
	123	0.58		113
	70	0		60
B	144	1.51	0.0150 0.0169 0.0110	134
	112	1.03		102
	70	0.32		60
	41	0		31
C	123	3.02	0.0773 0.0362	113
	112	2.17		102
	52	0		42
D	204	0.12	0.0020	194
	144	0		134
COLD STREAM				
X	21	0	0.0218 0.0241 0.0253 0.0263 0.0376	31
	60	0.85		70
	92	1.62		102
	111	2.10		121
	138	2.81		148
	179	4.35		189
Y	152	0	0.0313	162
	302	4.70		312
Z	254	0	0.0146	264
	319	0.95		329

Note: $DT_{min} = 20 \text{ }^{\circ}\text{C}$
Interval Temperatures are defined as follows:
for Hot Stream, $TI = T - DT_{min}/2 = T - 10$,
for Cold Stream, $TI = T + DT_{min}/2 = T + 10$.



Sketch 4.2 Process flowsheet for core example

The hot composite curve plots all the heat available from hot streams while the cold composite curve shows all that required by cold streams. The process is divided in two by the pinch. Suppose a hot stream which is below the pinch could be made to give up its heat at a higher temperature, above the pinch. Then the amount of overlap between the curves in Sketch 4.1, the maximum heat exchange, will be increased, while the hot and cold utility requirements at either end will be reduced.

To find whether a change in operating conditions will save energy, the plus-minus principle can be used. This states that a process change will reduce the utility targets if it:

- (a) increases the total hot stream heat load above the pinch,
- (b) decreases the total cold stream load above the pinch,
- (c) decreases the total hot stream load below the pinch,
- (d) increases the total cold stream load below the pinch.

Changes (a) and (b) will reduce the hot utility requirement. Changes (c) and (d) will reduce the cold utility requirement.

A more concise statement of the principle is that energy will be saved by a process change which

- increases the proportion of the hot composite curve above the pinch, or
- decreases the proportion of the cold composite curve above the pinch.

It is possible to determine by inspection of the stream data which streams could be moved to save energy. Look at the data in Table 4.1. The pinch is at 113°C interval temperature, which corresponds to a temperature of 123°C for hot streams and 103°C for cold streams. It appears that if the temperature of streams A, B or C could be increased or that of X decreased, the proportion above the pinch will change and energy will be saved. The effect will be greatest if the conditions of stream C change; it has the highest heat capacity flowrate CP , so will cause the biggest change in the shape of the composite curves.

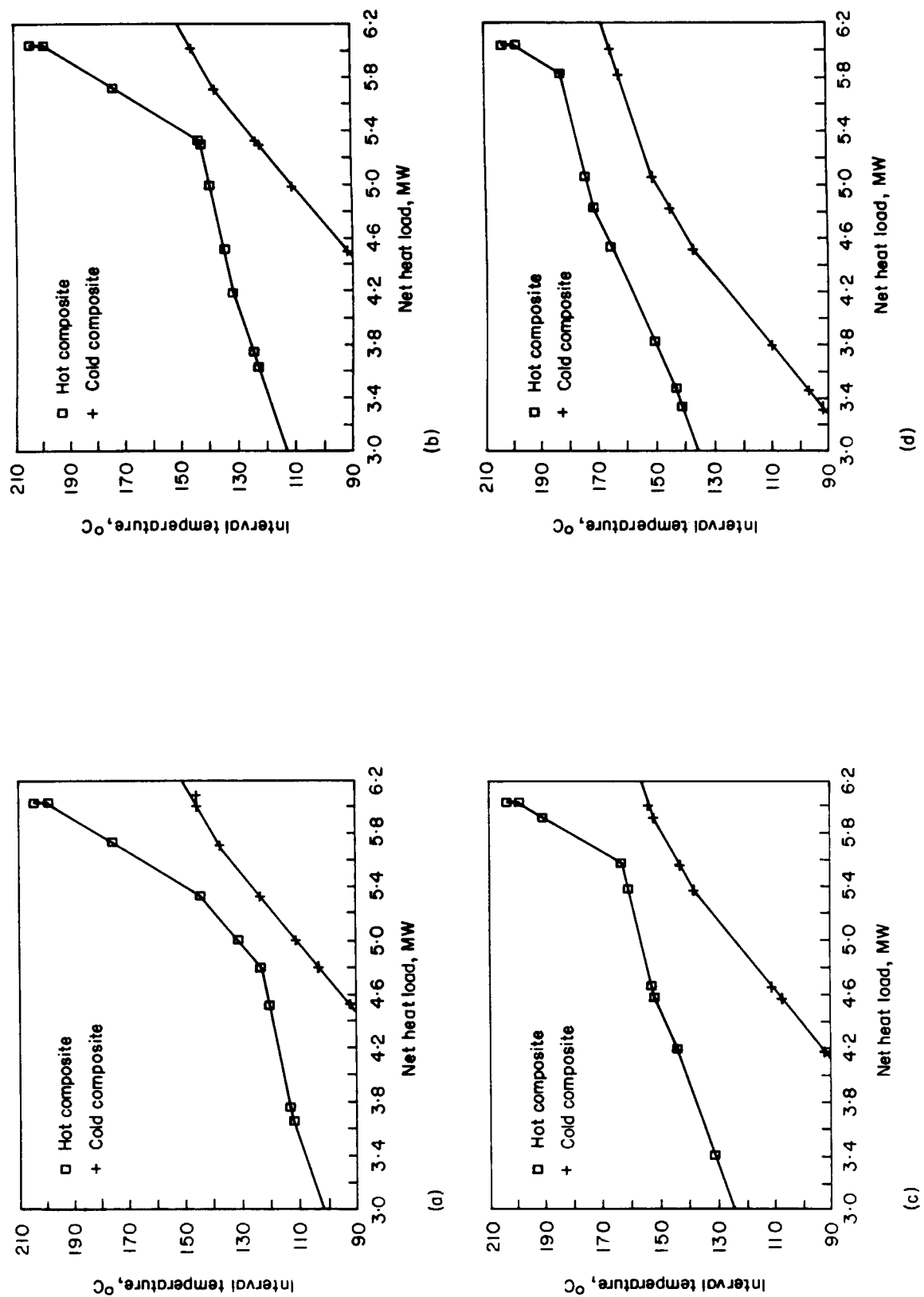
Consider, now, what would happen if the temperature of C were changed (ignoring processing considerations for the time being). Table 4.2 shows the results of increasing the temperature of stream C by 20°C, 40°C and 60°C. In each case, a modified set of stream data has been produced and the energy targets have been recalculated by the Problem Table method. The target heat exchange area has also been calculated, using the methods in Item No. 87030.

TABLE 4.2 Targets With a Process Change On Stream C

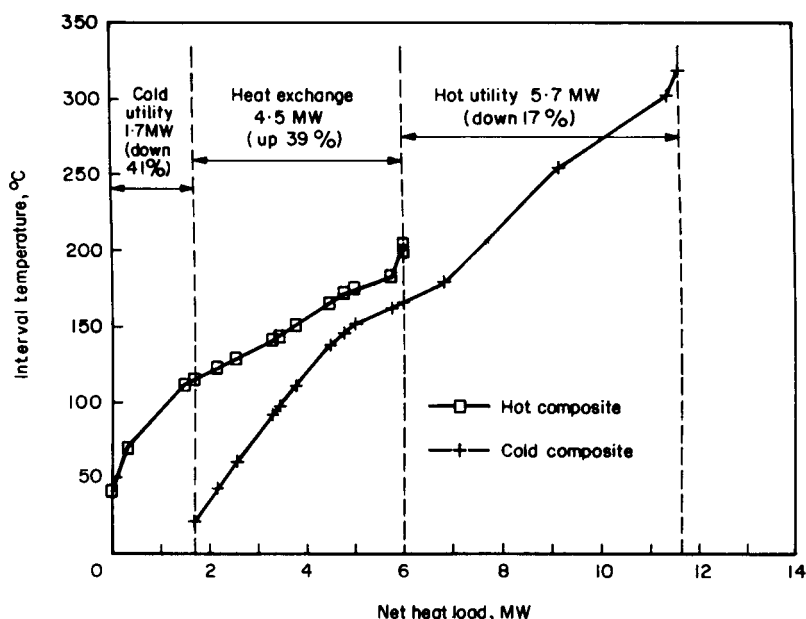
Temperature Range °C	Hot Utility Target MW	Energy Saved MW	Saving %	Area Target m ²
(a) 123 – 52	6.90	0.0		604
(b) 143 – 72	6.88	0.02	0.3	481
(c) 163 – 92	6.55	0.35	5.1	497
(d) 183 – 112	5.70	1.20	17.4	714

Surprisingly, the target does not drop significantly when the temperature of stream C is moved by 20°C, but falls significantly when it is moved by 40°C and even more sharply for a 60°C change. On the other hand, the target for the heat exchanger area falls for case (b) but then rises again. This shows that the plus-minus principle is only a guide; the targets should always be recalculated with the new conditions to find what effect a process change really has.

Sketch 4.3 shows the reason why. It is an exploded view of the pinch region for the four cases. For the original flowsheet (a), the pinch is at 123°C but there is an extensive near-pinch region above it. In (b) the pinch has moved to the other end of this near-pinch region; the relative locations of the composite curves have barely changed but they have been separated considerably, so temperature driving forces are higher and the area target falls. In (c) and (d) the overlap between the composite curves has increased and so has the region where temperature driving forces are small. The energy target has dropped and the area target has risen. This is illustrated more clearly in Sketch 4.4 which shows the whole of the composite curves for case (d). Heat exchange has risen and hot and cold utility usage have fallen compared with Sketch 4.1.



Sketch 4.3 Composite curves in the pinch region for cases (a) – (d)



Sketch 4.4 Composite curves with process change for case (d)

It must also be recognised that there is a two-way tradeoff; a process change affects both the energy use and the capital cost. The benefits must be weighed against any potential problems due to the change in operating conditions.

A limitation of the plus-minus principle is that it only deals with streams in isolation. It does not show whether the proposed change is practicable. For that it is necessary to refer back to the original flowsheet shown in Sketch 4.2. It is apparent that stream C is the column overheads. If the temperature of this were increased, the operation of the whole column would be affected. Changes could occur in reflux ratio, purity and flowrate of products, and column pressure.

So using the simple plus-minus principle on its own cannot identify process changes with certainty. However, it can point the way to potential savings. It shows here that there is potential for saving energy by changing the conditions of hot stream C, provided a practical way of achieving that can be found.

Note that process changes can include many simple energy-saving methods as well as complex plant modifications. For example, on the flowsheet in Sketch 4.2, the heavy oil B falls from 150°C to 144°C on leaving the vacuum column due to heat losses from poorly insulated pipework. If these heat losses are reduced by better insulation, the heat load of stream B will increase. This is a process change because it alters the stream data. Since B is a hot stream above the pinch, by statement (a) of the plus-minus principle, heat recovery will increase and the hot utility target will fall.

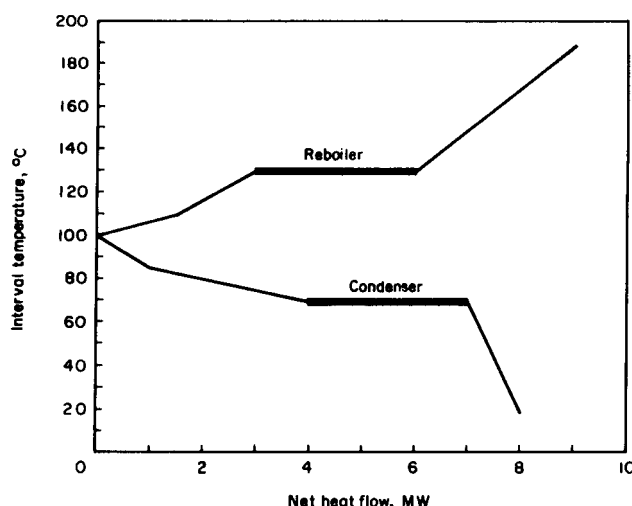
4.3 Splitting the Grand Composite Curve

The conditions of certain streams in a plant are linked. For example, the temperature of a stream discharging from a vessel depends on the vessel temperature and hence on the temperatures of the streams entering it. It would be useful to see how the conditions of a group of linked streams, rather than a single stream, affect the process efficiency.

This can be investigated by **splitting the grand composite curve**. The group of linked streams are taken out of the stream data set and are called the **extracted streams**; the remaining streams are called the **background process**. The grand composite curve (G.C.C.) of the background process is plotted on the same graph as the heat loads of the linked streams, which gives a visual indication of how they affect each

other.

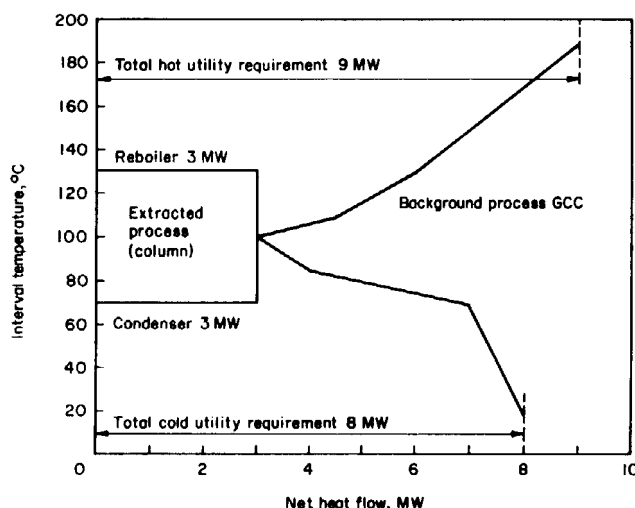
The technique is particularly useful for optimising the conditions of separation systems. Sketch 4.5 shows the G.C.C. for a process containing a distillation column. The column reboiler and condenser are shown as thick-lines; they are at constant temperature because they are latent heat loads.



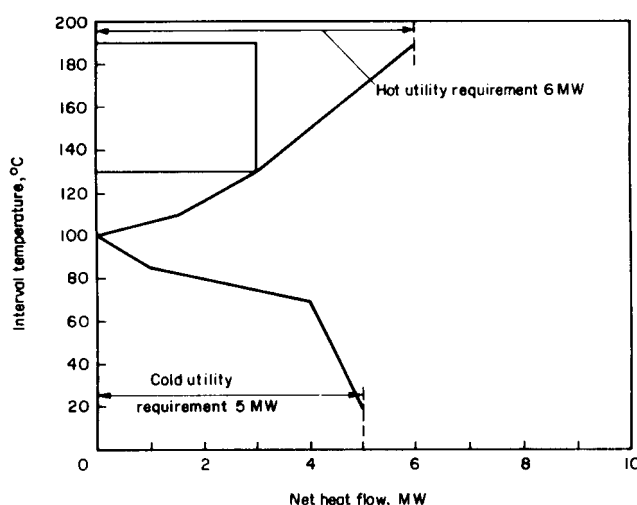
Sketch 4.5 Grand composite curve for process including distillation column

The reboiler and condenser loads are now taken out of the stream data set and plotted as a “box” on the G.C.C. of the background process. The distillation has therefore become the **extracted process**. The result is shown in Sketch 4.6.

Sketches 4.5 and 4.6 show that the reboiler requires heat above the pinch and the condenser releases heat below the pinch. In other words, the column is transferring heat across the pinch, like a wrongly placed heat exchanger. The background process G.C.C. lies on the right-hand side of the column and the total utility requirement is large.



Sketch 4.6 Split grand composite curve with column plotted separately



Sketch 4.7 Split grand composite curve with column pressure increased

Ideally, the extracted process “box” should lie above or below the background process pinch and grand composite curve, so that no heat is transferred across the pinch. This is known as the appropriate **placement principle**.

To achieve this, the operating pressure of the column could be increased. Both reboiler and condenser temperatures will then rise, implying an increase in column pressure. The temperature change necessary to make the box fit above the G.C.C. can be easily found from Sketch 4.6 and the result is shown in Sketch 4.7. An energy saving of 3 MW, equal to the reboiler and condenser load, has resulted.

Alternatively, the column pressure could be decreased so that the column fits below the background process G.C.C. This can be a cheaper option unless the column has to be operated under vacuum.

In practice, it is often impossible to change column pressures for reasons of product quality, safety or other processing reasons. However, it may still be possible to reduce the heat transferred across the pinch by adding pumparounds, intermediate condensers or reboilers. These are defined as follows.

A **pumparound** is a large flow of liquid drawn off from a distillation column that releases sensible heat above the condenser temperature and is returned to a higher tray in the column. They are most commonly used in oil refineries.

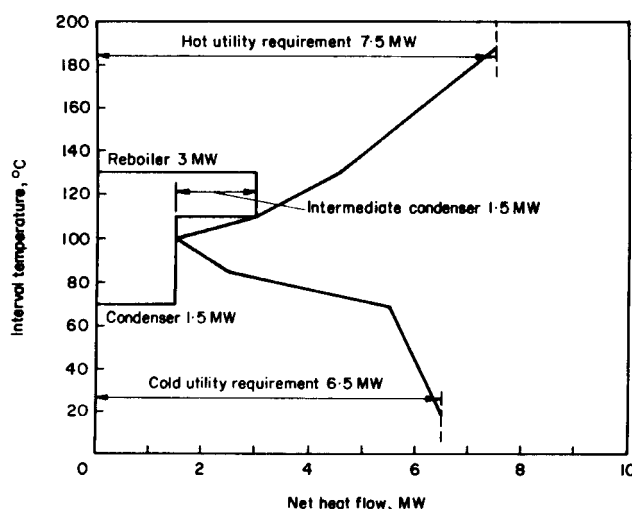
An **intermediate condenser** recovers heat above the condenser temperature by condensing some vapour on an intermediate tray in the column.

An **intermediate reboiler** supplies heat below the reboiler temperature to evaporate liquid on an intermediate tray in the column.

All of these measures can be seen as minimising the temperature at which heat is supplied, or maximising the temperature at which it is removed. This will bring benefits if there is a heat source or sink near the new temperature (for example a process stream or a cheap low-grade utility), and Process Integration shows whether such streams exist. All of them tend to reduce the liquid-to-vapour ratio, L/V , in the top part of the column (the stripping section) and increase L/V in the bottom part (the extractive section).

Clearly, for appropriate placement, pumparounds and intermediate condensers should be placed above the background process pinch and G.C.C., while intermediate reboilers should be placed below the background process pinch and G.C.C. The temperature of the feed tray is an important factor. If it is above the pinch, some of the stripping section of the column will be above the pinch and an intermediate condenser is possible. Conversely, if it is below the pinch, an intermediate reboiler below the feed tray can also be below the pinch. If the feed tray is close to pinch temperature, little can be done unless the feed tray temperature itself is altered.

Sketch 4.8 shows the effect of adding an intermediate condenser to the column. Some useful heat (1.5 MW) is now being recovered and the column pressure has not had to be altered.



Sketch 4.8 Split grand composite curve with intermediate condenser installed

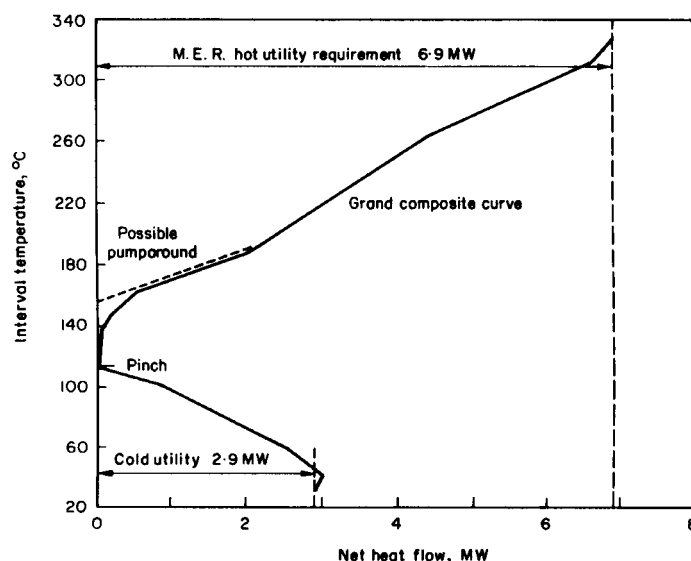
A process change can be defined as an alteration in the temperature of a set of streams. A beneficial process change will increase the amount of heat these streams can exchange with the rest of the process.

4.4 Case Study – Core Example

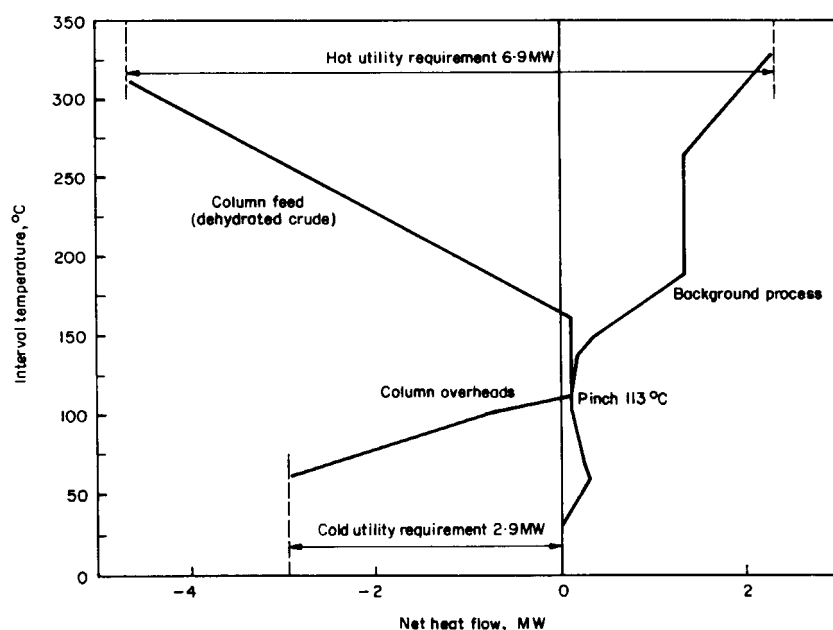
The example of Section 4.3 was a very simple one. The reboiler and condenser loads were equal and were at constant temperature. This is often not the case in practice, but the method of splitting the grand composite curve still applies. Consider the core example.

Nearly every stream is linked in some way with either the atmospheric or vacuum distillation column, as can be seen from the flowsheet in Sketch 4.2. However, it is possible to deduce an approximate best placement of the distillation columns by considering the main streams involving latent heat.

For the atmospheric column, the relevant streams are the column overheads C and the dehydrated crude Y (which partially flashes on entering the column to give additional vapour flow). These streams have unequal loads and have a range of temperatures. Nevertheless they can both be removed from the stream data. The grand composite curve in Sketch 4.9 can be divided into the background process on the right-hand side of Sketch 4.10 and the overheads and dehydrated crude that are plotted on its left. The pinch occurs where the two curves touch. The hot and cold utility requirements can be seen to be 6.9 MW and 2.9 MW, as before.



Sketch 4.9 Grand composite curve



Sketch 4.10 Split grand composite curve

It is clear from Sketch 4.10 that the column is working across the pinch, that a temperature rise of 20°C will make virtually no saving and that it has to be shifted at least 40°C for any significant saving to occur. These are the same conclusions as those obtained from changing the temperature of stream C in Section 4.1, but it has not been necessary to do the separate recalculations. Moreover, it is clear from Sketch 4.10 that shifting stream C upwards will also demand an increase in the temperature of stream Y and hence the whole column will have to work at higher pressure. In practice, the temperatures of all the feed and product streams for the column will also change.

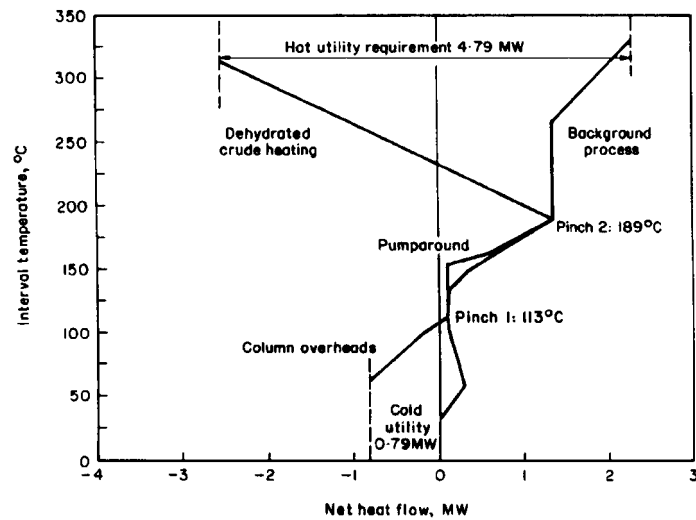
TABLE 4.3 Problem Table for Core Example

Interval Temperature °C	Net Heat Flow MW
329	6.90
312	6.65
264	4.45
194	2.26
189	2.11
162	0.58
148	0.22
134	0.018
121	0.002
113	0.00 Pinch
102	0.86
70	2.13
60	2.56
42	3.01
31	2.90

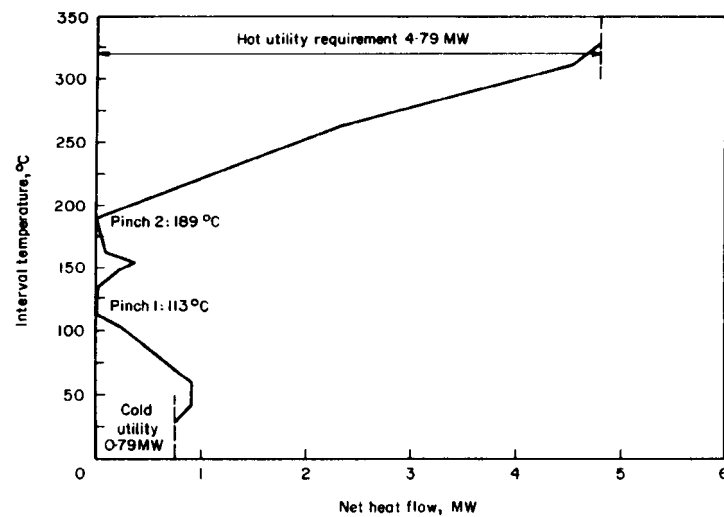
In some columns, condenser pressure and temperature can be increased slightly without changing feed temperature, by reducing the pressure drop through the column with improved trays or better packing. Clearly this is not an option here, as small increases in the temperature of overheads C do not save significant amounts of energy.

Since no easy savings can be found by changing the column pressure, a pumparound should be considered. The flowsheet shows that middle oil is already drawn off above the pinch temperature, at 199°C. This corresponds to an interval temperature of 189°C and the problem table, Table 4.3, shows that the net heat load at that temperature is 2.11 MW. Hence, if this amount of heat is withdrawn from the column by a middle oil pumparound instead of as overheads condensation, an energy saving of 2.11 MW can potentially be made.

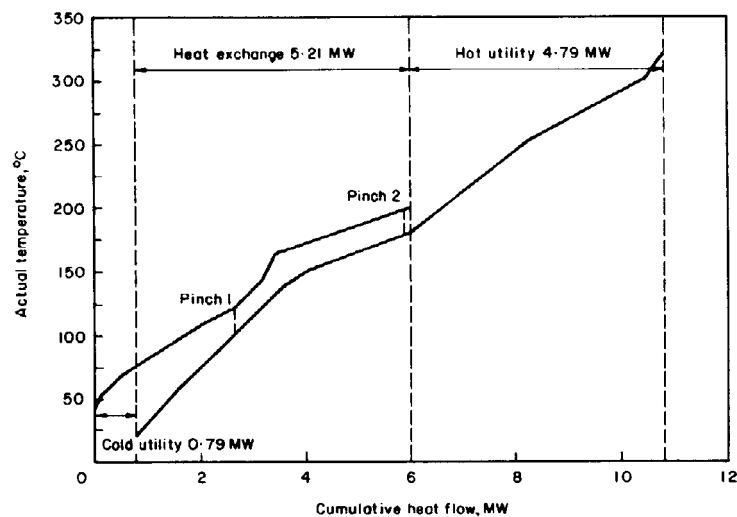
The temperature range of the pumparound must now be deduced. Sketches 4.9 and 4.10 show that the net heat flow falls to very low values below 148°C interval temperature, so the pumparound should not operate below this value. Ideally, the pumparound should match the heat demands of the process in that temperature range; this can be determined by plotting its locus above the full process G.C.C. (broken line in Sketch 4.9). The pumparound will work at a constant flowrate, so it plots as a straight line. The sketch shows that the liquid can be cooled to just over 150°C interval temperature and still remain above the G.C.C. Hence, the temperature range of the pumparound is taken to be 189°C – 154°C interval temperature (199°C – 164°C actual temperature). It removes 2.11 MW of heat, so its *CP* will be 0.0603 MW/K, corresponding to a flowrate nearly six times that of the present middle oil stream A. Sketches 4.11 and 4.12 show the split and overall grand composite curves with the pumparound, and Sketch 4.13 shows the composite curves. Clearly, much more heat is being recovered and the targets have fallen, but there is a much larger region where the composite curves are close together so a large increase in heat exchanger area will be needed. This would be confirmed by designing the heat exchanger network, using the methods in Item No. 87030, Section 8.



Sketch 4.11 Split grand composite curve with pumparound

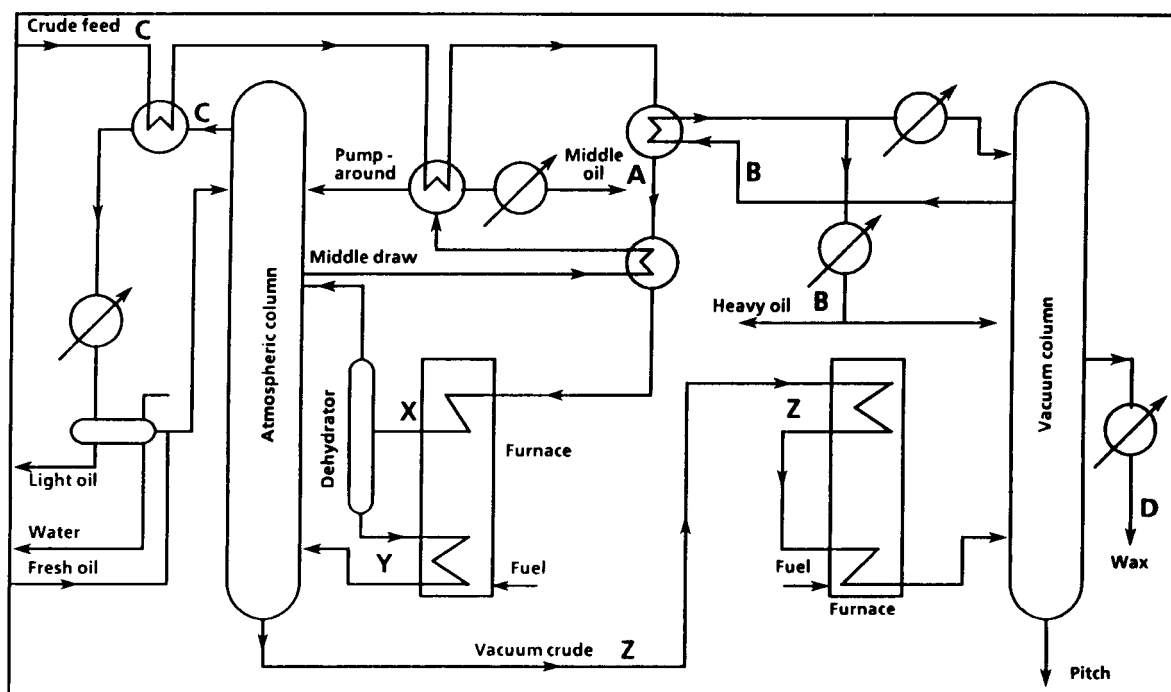


Sketch 4.12 Combined grand composite curve with pumparound



Sketch 4.13 Composite curves with pumparound

Note that the pumparound has saved much more energy than the heat recovery projects identified in Item No. 87030 (2.11 MW as against 0.77 MW). In practice, such a large pumparound may not be feasible. Very large liquid flows and small vapour flows will occur in the column near the pumparound and the separation efficiency will change. The overheads flow falls sharply and its composition changes. Hence, if a pumparound is proposed, it is necessary to check the column performance and compare with current values. If the product deviates too far from specification, the pumparound should be reduced in size. Nevertheless, substantial amounts of energy may still be saved. In general, problems can be reduced by installing pumparounds, intermediate reboilers and condensers in parts of the column where separation driving forces are high and the column is not “pinched” in terms of composition. Sketch 4.14 shows the modified flowsheet with a pumparound installed.

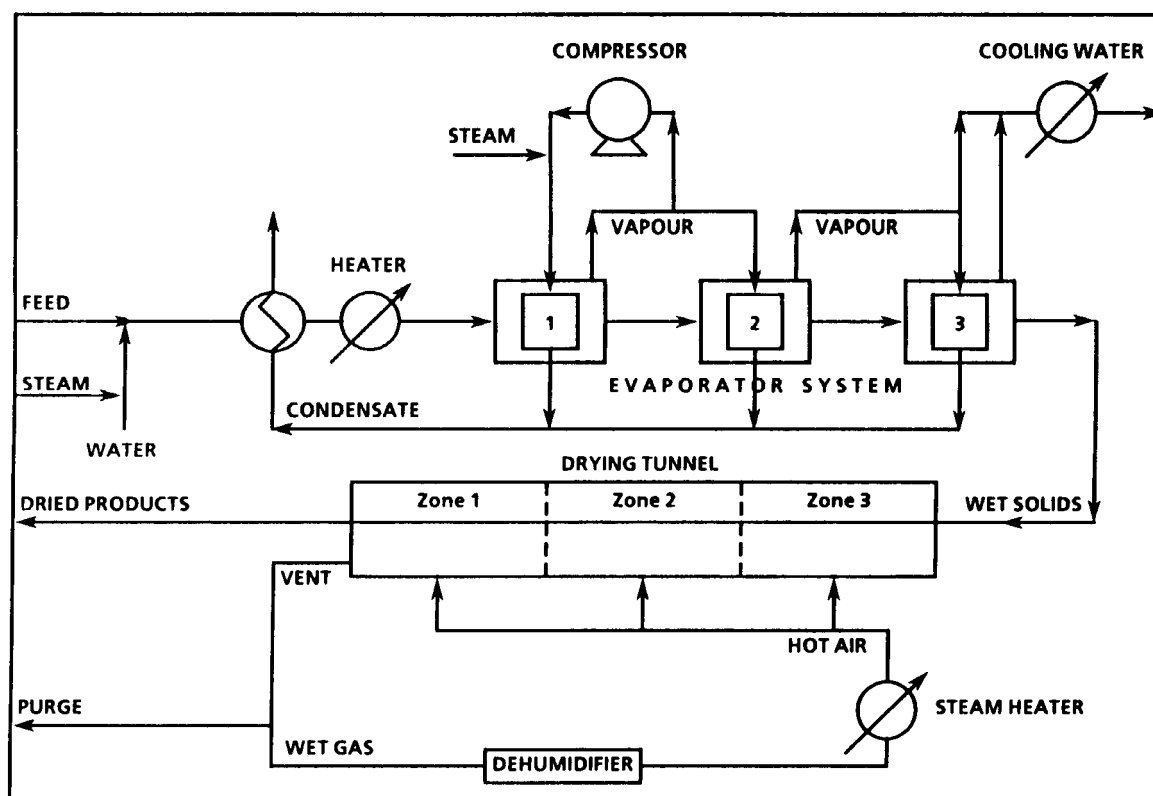


Sketch 4.14 Modified process flowsheet

4.5 Case Study – Food Processing Plant

This example was introduced in Item No. 89001, Section 8.3.

Sketch 4.15 shows the flowsheet and Table 4.4 gives the stream data for an existing food processing plant. The plant contains a triple-effect evaporator, designed to work under vacuum to keep temperatures and energy costs down. The product decomposes above 130°C.



Sketch 4.15 Flowsheet for food processing plant

TABLE 4.4 Stream Data for Food Processing Plant – Existing Process

Stream Name	Hot or Cold	Supply Temp., °C	Target Temp., °C	Heat Load kW	Heat Capacity Flowrate kW/K
Evaporation 1	C	79.4	79.4	1005	
Evaporation 2	C	48.8	48.8	643	
Evaporation 3	C	93.3	93.3	173	
Condensing 1	H	79.4	79.4	1039	
Condensing 2/3	H	43.3	43.3	974	
Condensate 1	H	86.9	10	232	3.017
Condensate 2/3	H	43.3	10	57	1.714
Process Water	C	10	70	183	3.05
Main Feed	C	17.8	87.8	198	3.96
Dryer Vent 1	H	60	13	140	2.979
Dryer Vent 2	H	55	13	189	4.5
Dryer Vent 3	H	41	13	149	5.321
Regenerator	C	55	55	93	
Dryer Zone 1	C	41	41	254	
Dryer Zone 2	C	60	60	124	

TABLE 4.5 Problem Table for Food Processing Plant With $DT_{min} = 14^\circ \text{C}$

Interval Temperature, $^\circ\text{C}$	Net Heat Flow, kW
100.3	1416
100.3	1243
94.8	1243
86.4	1209
86.4	204
79.9	179
77	176
72.4	158
72.4	1197
67	1175
67	1051
62	1031
62	938
55.8	913
55.8	270
53	259
48	254
48	0
44.8	11
36.3	74
36.3	1048
34	1069
17	1316
6	1509
3	1523

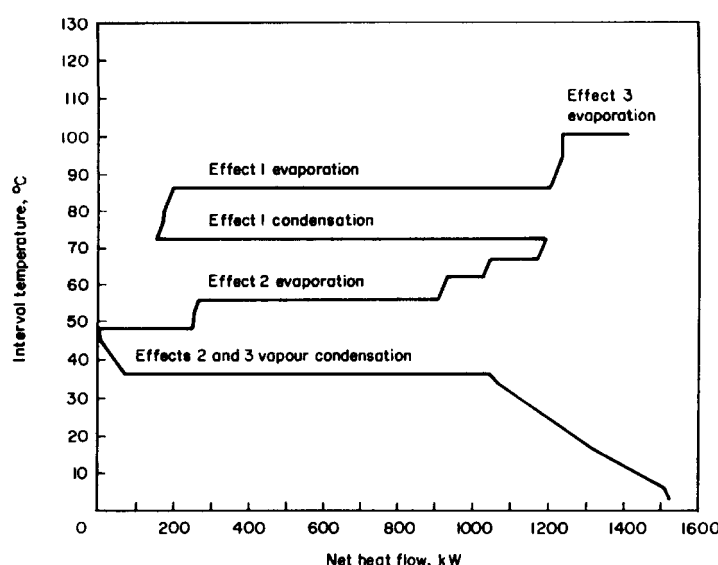
Streams involving latent heat have been taken as evaporating at a single temperature, and therefore have an infinite CP . This emphasises the importance of basing calculations on the heat loads, not the CP values which are often a derived quantity. Some Process Integration software cannot handle infinite CP values and in that case the stream should be considered as evaporating over a small temperature range – say 1°C or 0.1°C ; this method is used in Section 8.1.

Table 4.5 shows the problem table and Sketch 4.16 shows the grand composite curve for the complete plant. The current energy use of the plant is 1530 kW and heat recovery projects identified using network analysis achieve the target of 1416 kW. The minimum temperature difference across heat exchangers, DT_{min} , is 14°C .

At this stage not much can be deduced from the grand composite curve except that an additional effect might be useful.

The first stage is to split the grand composite curve. The streams which should be taken out of the process to do this are the latent heat streams for the evaporator – Evaporation 1, 2 and 3, Condensing 1 and 2/3. The condensate streams would theoretically be removed in a rigorous analysis, but it is far simpler to leave them in the background process.

The condensing and evaporation loads are unequal. The condensing load on effect 1 is 1039 kW and the evaporation load is 1005 kW, so that 34 kW of the condensing load is not balanced. Where more than one evaporator or distillation column is involved, in order to see how they relate, it is simplest to leave them as rectangles on the grand composite curve, that is with equal heat loads, and to incorporate the unbalanced heat loads into the background process. Hence the remaining 34 kW of the Condensing 1 stream should be left in the background process as a hot stream at 79.4°C (72.4°C interval temperature). Likewise $(974 - 643 - 173) = 158$ kW of Condensing 2/3 becomes a hot stream at 43.3°C (36.3°C interval temperature).



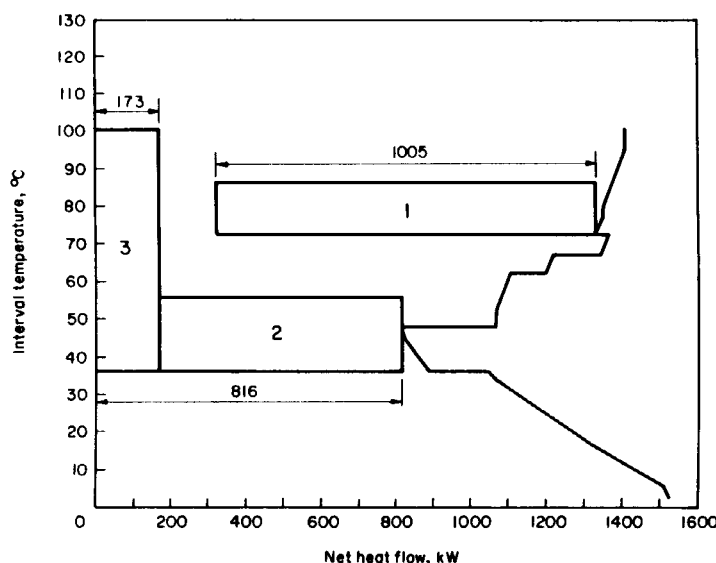
Sketch 4.16 Overall grand composite curve for process

The evaporator effects are now superimposed on the background process and the resulting split grand composite curve is shown in Sketch 4.17. Effects 2 and 3 cross the overall process pinch and waste energy. Effect 1 is wholly above the pinch.

As explained in Item No. 89001, there is an M.V.R. heat pump on effect 1 which upgrades steam with a condensing heat load of 333 kW (at 79.4°C) to give steam at 110°C. Since the heat pump is working across Effect 1, it is wholly above the pinch. It therefore makes no net saving of energy; it merely replaces steam by (more expensive) electricity. The heat recovered from the Condensing 1 stream could equally well have been used to carry out evaporation from Effect 2 at the bottom of the “pocket” below.

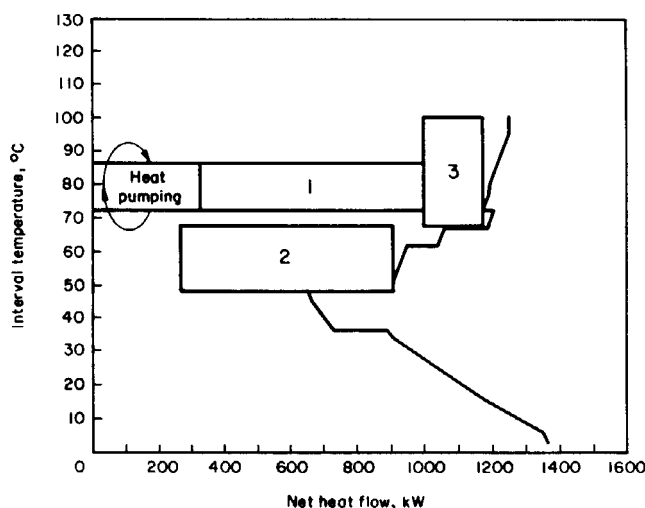
Summarising, two of the evaporator effects are transferring heat across the pinch and the heat pump is misplaced. Possibilities for process change to overcome these problems can now be identified. These include the following.

- (a) Split Effect 2 into two effects in series at different temperatures.
- (b) Shift Effect 3 up in temperature so that its vapour can be used to heat Effect 2 (there is plenty of driving force between the steam and the bulk liquid).



Sketch 4.17 Split grand composite curve of existing process

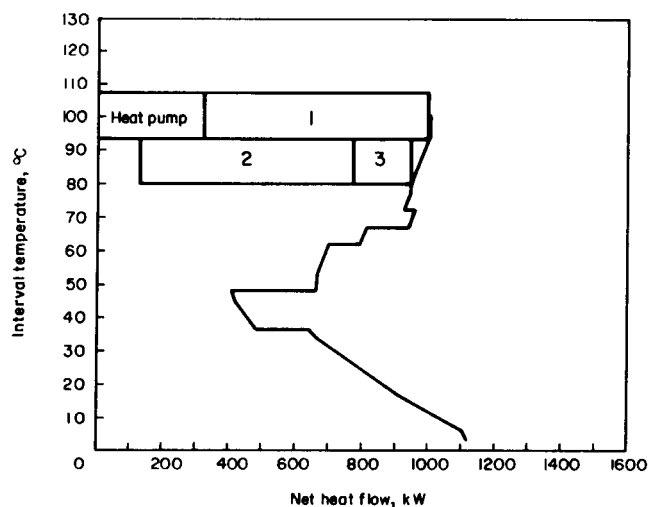
- (c) Put the compressor across Effect 2 instead of Effect 3. This would be a very likely solution in a new plant. In an existing unit like this, moving the equipment (or re-plumbing the effects so that Effect 1 becomes Effect 3) would be costly.
- (d) Move Effect 2 up in temperature so that it comes above dryer zone 1. This is shown in Sketch 4.18, in conjunction with suggestion (b). The heat pump is retained on Effect 1. The heat load is now 1258 kW without heat pumping and 989 kW with heat pumping.



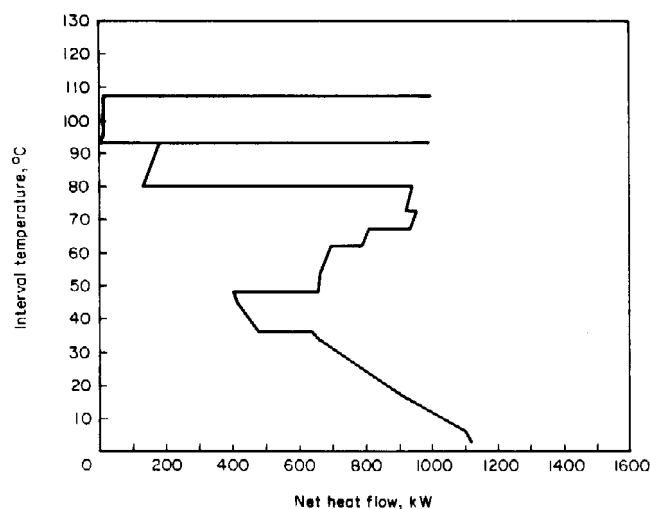
Sketch 4.18 Split G.C.C. with suggestions (b) and (d) implemented

- (e) Sketch 4.18 shows that heat is now recovered between Effects 1 and 2. Without the heat pump, Effects 1 and 3 cause the pinch; with it, Effect 2 causes the pinch. There is an incentive to shift Effect 2 further to the right and to place Effect 3 above or below one of the other effects.

- (f) There is no actual need for the system to be under vacuum. If Effect 1 is run at atmospheric pressure (100°C), the evaporation and condensing streams are at interval temperatures of 107°C and 93°C respectively. The temperature rise of Effect 2 allows it to move further to the right beneath Effect 1. Effects 2 and 3 can be retained in their current configuration with a common vapour discharge (this was desirable for other process reasons). The driving force on Effect 3 is also lowered so that it will fit below Effect 1. The new split grand composite curve is shown in Sketch 4.19 and the corresponding overall grand composite is shown in Sketch 4.20. The hot utility load has fallen to 1012 kW which becomes 875 kW with the heat pump included.
- (g) Effect 3 prevents the heat pump from giving the full potential savings. It is desirable to shift some of the evaporation load from Effects 2 and 3 to Effect 1. The evaporation rate from Effects 2 and 3 will tend to fall anyway because the temperature difference across the calandria is lower than before. Shifting just under 100 kW between effects will allow the heat pump to make the full saving.



Sketch 4.19 Split G.C.C. with suggestion (f) implemented



Sketch 4.20 Modified overall grand composite curve

In implementing a process change possibility, it is essential to correct for the approximations that have been made in the initial assessment and to generate a new set of stream data, and in this case that involves the following.

- (a) The “unbalanced” heat loads from the condensing streams must be moved to their new temperatures.
- (b) The change in evaporator temperature alters the sensible heat requirements of the feed and product streams and the heat balance on each effect so that the stream data change significantly.

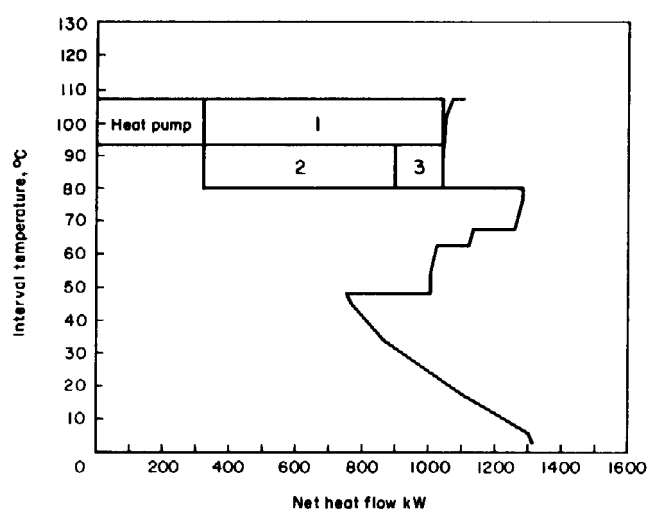
TABLE 4.6 Stream Data for Modified Process

Stream Name	Hot or Cold	Supply Temp., °C	Target Temp., °C	Heat Load kW	Heat Capacity Flowrate kW/K
Evaporation 1	C	100	100	1091	3.34 1.1 3.05 3.96 2.979 4.5 5.321
Evaporation 2	C	86	86	576	
Evaporation 3	C	86	86	139	
Condensing 1	H	100	100	1057	
Condensing 2/3	H	86	86	956	
Condensate 1	H	108.4	10	329	
Condensate 2/3	H	86	10	84	
Process Water	C	10	70	183	
Main Feed	C	37.8	100	248	
Dryer Vent 1	H	60	13	140	
Dryer Vent 2	H	55	13	189	
Dryer Vent 3	H	41	13	149	
Regenerator	C	55	55	93	
Dryer Zone 1	C	41	41	254	
Dryer Zone 2	C	60	60	124	

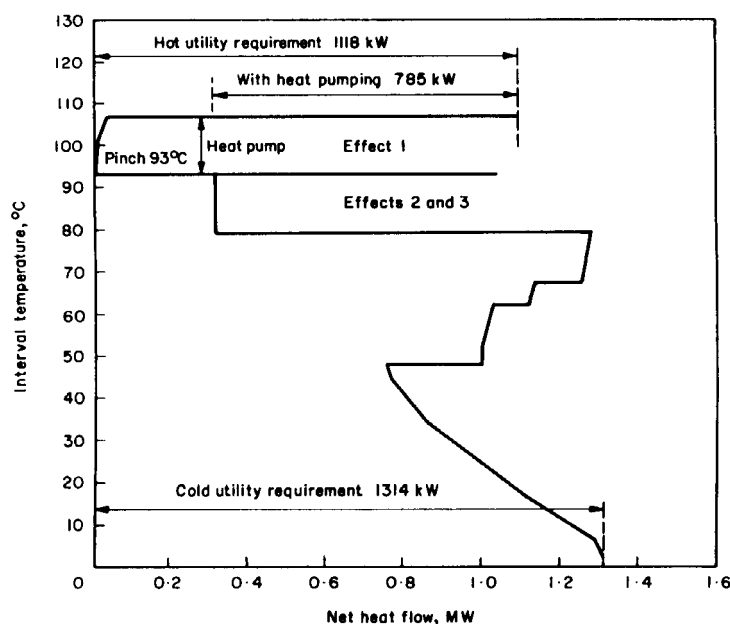
TABLE 4.7 Problem Table For Modified Process With $DT_{min} = 14^{\circ} \text{C}$

Interval Temperature, $^{\circ}\text{C}$	Net Heat Flow, kW
107	118
107	27
101.4	5
93	0
93	1057
93	342
79	333
79	1289
77	1290
67	1264
67	1140
62	1127
62	1034
53	1011
48	1013
48	759
44.8	774
34	870
17	1111
6	1301
3	1314

The final set of stream data allowing for load shifting between the effects is in Table 4.6. Sketch 4.21 shows the corresponding split grand composite curve. The final problem table and overall grand composite curve are Table 4.7 and Sketch 4.22 respectively. Hot utility use is 1118 kW or 785 kW with heat pumping. These are savings of 26.9% and 48.7% respectively over the original energy use of 1530 kW.



Sketch 4.21 Corrected split G.C.C. with repositioned evaporator



Sketch 4.22 Overall grand composite curve

Note that the heat pump now works, correctly, across the pinch. Instead of moving the heat pump to work across the pinch, the saving was achieved by **moving the pinch** to correspond with the heat pump. A side benefit is that Effects 2 and 3 no longer need such a high vacuum, so there is an electricity saving on the vacuum pumps.

Plotting points of the various curves in Sketches 4.16 – 4.22 are given for information in Appendix A.

4.6 Other Separation Systems

The other main types of thermal separation systems are flash evaporators and dryers.

In flash evaporators, a hot liquid stream undergoes a pressure drop and some liquid is flashed off as vapour. The vapour stream is then condensed to recover heat. The same amount of heat could have been recovered at higher temperatures by sensible cooling of the original liquid stream, but the separation would not then have been achieved. The flash vapour, on condensing, should as usual come above the background process G.C.C. possible. If it does not, but the sensibly cooled liquid does, the flash is costing energy. It is often possible to use a two-stage or multi-stage flash to achieve the same separation without costing energy, as described by Kemp². The method for fitting a flash system to a G.C.C. is similar to fitting a pumparound as illustrated in Sketch 4.9.

In dryers, moisture in a solid is evaporated; the latent heat loads often make dryers highly energy-intensive. Most of the waste heat from the dryer is the latent heat of the vapour in the exhaust gas, but this heat cannot usually be recovered by condensation until the exhaust has been cooled close to ambient temperature, which is below the pinch of virtually all processes. Thus, dryers usually cross the pinch and the latent heat of the water vapour cannot be recovered. Waste heat from a process with a high pinch temperature can sometimes be used to heat the dryer, so that it is working below the pinch; however, temperature driving forces are generally lower and size and capital cost higher than for conventional dryers. A promising alternative is to use as the drying gas the superheated form of the solvent being evaporated; the recovered vapour can then be condensed at high temperature, above the pinch.

The commonest case is superheated steam drying, which also has the advantage of a better heat transfer

coefficient between vapour and solids than for air. A heat transformer (see Item No. 89001, Section 7.2) has been used to absorb moisture from the exhaust gas and recover some of its heat.

Other separation systems rely on mass separating agents, for example solvent extraction. Process Integration does not apply directly to the design of these systems. However, if the mass separating agent is regenerated thermally, for example by a solvent recovery system, this can be integrated with the rest of the process.

5. BATCH SYSTEMS: TARGETING

5.1 Types of Stream Encountered

In a continuous process, a stream flows from a constant supply temperature to a constant target temperature at a constant flowrate and heat load, and is present at all times. In batch processes and other time-dependent situations, one or more of these assumptions will generally not hold. Instead, four basic types of stream can be identified as follows.

- (A) A stream which operates between fixed supply and target temperatures and has a fixed heat load, but only exists for a certain time period. Examples would include:
- a feed stream being used to charge a reactor at the beginning of its cycle and being passed through a heater on the way, or a product being discharged and cooled when reaction is complete,
 - a stream flowing over a certain time period from one vessel to another at constant flowrate with the temperature of the supplying vessel being constant.

The main illustrative example in Sections 5.3 – 5.7, 6.1 – 6.4 and 7.3 – 7.4 is based on Type A streams. These may also be called flowing streams to distinguish them from streams (like Types C and D streams) which are heated within a vessel.

- (B) A stream which gradually changes in heat load over a time period although it remains at set temperatures. Examples would be:
- a reflux at constant pressure in a plant at start-up, whose flow gradually increases as the plant heats up to operating temperature (see Section 5.9),
 - a volatile product being boiled off from a batch reaction (see Section 8.3),
 - the exhaust gas from a tray or vacuum batch dryer,
 - a batch distillation product stream, whose composition changes as the lighter fraction boils off – only applies if the draw-off temperature is held constant and reflux ratio changes continuously,
 - certain absorption or desorption processes taking place at fixed pressure and temperature.
- (C) A stream which gradually changes in temperature but whose heat load is constant. Examples would be the heating and cooling of a reaction vessel, where a constant heat input (for example, from electric heating coils) is used; or batch distillation at a constant reflux ratio. This situation is discussed in Sections 5.2 and 5.8.
- (D) A stream which changes in both temperature and heat load with time. This is exemplified by a jacketed reaction vessel heated by steam or cooled by water. The heat transfer depends on the temperature difference between the utility and the vessel contents, so it constantly changes. These are probably the most common type of stream in batch processes, and feature in Sections 5.2 and 5.8 and the case study in Section 8.