



Application of process integration to utilities, combined heat and power and heat pumps

ESDU Copyright material. For current status contact ESDU.

Copyright Engineering Sciences Data Unit

ESDU DATA ITEMS

Data Items provide validated information in engineering design and analysis for use by, or under the supervision of, professionally qualified engineers. The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants. The whole process is subject to independent review for which crucial support is provided by industrial companies, government research laboratories, universities and others from around the world through the participation of some of their leading experts on ESDU Technical Committees. This process ensures that the results of much valuable work (theoretical, experimental and operational), which may not be widely available or in a readily usable form, can be communicated concisely and accurately to the engineering community.

We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the following Working Party on behalf of the Heat Transfer Steering Group:

Mr R.J. Allam	— Air Products Ltd
Prof. P.J. Heggs	— Bradford University
Mr T.J. Loraine	— McLellan and Partners
Mr A.N. Patel	— ICI Chemicals and Polymers Group.

The Heat Transfer Steering Group first met in 1966 and now has the following membership:

Chairman	
Mr D. Butterworth	— HTFS, Atomic Energy Authority, Harwell
Vice-Chairman	
Dr R. Cheesewright	— Queen Mary College, London
Members	
Mr R.J. Allam	— Air Products Ltd
Dr T.R. Bott	— Birmingham University
Prof. P.J. Heggs	— Bradford University
Mr T.J. Loraine	— McLellan and Partners
Dr A.C. Pauls*	— Monsanto Company, USA
Mr A.C. Rapier	— Atomic Energy Authority, Windscale
Prof. R.H. Sabersky*	— California Institute of Technology, USA
Mr E.A.D. Saunders	— Independent
Mr R.A. Smith	— Independent
Dr J. Taborek*	— Independent
Mr M.A. Taylor	— Independent
Mr D.A. Winkworth	— Independent

* Corresponding Members

The technical work involved in the assessment of the available information and the construction and subsequent development of the Data Item was undertaken (under contract to ESDU) by

Mr I.C. Kemp	— Energy and Process Integration Service, Harwell Laboratory
Dr A.W. Deakin	— Energy and Process Integration Service, Harwell Laboratory

APPLICATION OF PROCESS INTEGRATION TO UTILITIES, COMBINED HEAT AND POWER AND HEAT PUMPS

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. PURPOSE AND SCOPE OF THIS DATA ITEM	3
3. HOW TO USE THIS DATA ITEM	4
4. BASIC CONCEPTS OF HEAT AND POWER SYSTEMS	5
4.1 Heat Engines	5
4.2 Heat Pumps	8
4.3 Marginal Cost	10
4.4 Types of Utilities	12
5. MULTIPLE LEVEL UTILITIES	13
5.1 Basic Concepts of Process Integration	13
5.2 Multiple Utility Levels	16
5.3 Calculation of Utility Load at a Given Level	17
5.4 Network Design to Achieve Maximum Low-level Utility Load	18
5.5 New Plants – Selection of Constant Temperature Utility Levels	22
5.6 Variable Temperature Utilities	23
5.7 Network Design for Variable-temperature Utilities	25
5.8 Heat Recovery within the Utility Supply System	28
6. COMBINED HEAT AND POWER	30
6.1 Introduction to CHP	30
6.2 Steam Turbine Systems	32
6.3 Gas Turbine Systems	33
6.4 Combined Cycles	35
6.5 Diesel and Gas Reciprocating Engines	35
6.6 Exotic Cycles	36
6.7 Selection of a CHP System	37
6.8 Case Study – Core Example	38
7. HEAT PUMPS	39
7.1 Introduction: Appropriate Placement	39
7.2 Selection of Heat Pump Type	40
7.3 Thermal Design	42
7.4 Case Studies and Economics	43

8.	CASE STUDIES	45
8.1	Core Example: Organics Distillation Unit	45
8.2	Refrigeration Cycle	45
8.3	Heat Pump – Food Processing Plant	48
8.4	Utilities and CHP – Whisky Distillery	53
9.	GLOSSARY OF TERMS	60
10.	REFERENCES AND DERIVATION	66
	APPENDIX A CALCULATION OF MARGINAL COSTS	69
A1.	MARGINAL COST FOR A STEAM TURBINE CHP SYSTEM	69
A2.	HEAT PUMP CALCULATION	72
	APPENDIX B CALCULATION OF HEAT EXCHANGER NETWORKS	73
B1.	NETWORK DESIGN BETWEEN UTILITY AND PROCESS PINCHES	73
B2.	NETWORK DESIGN ABOVE THE UTILITY PINCH	74
B3.	NETWORK DESIGN BELOW THE PROCESS PINCH	75
	APPENDIX C CALCULATION OF HEAT AVAILABLE FROM EXHAUST OF FLUE GAS	76
C1.	EXHAUST OF FLUE GAS	76
	APPENDIX D ECONOMIC CALCULATIONS OF DISTILLERY HEAT PUMP AND CHP	78
D1.	HEAT PUMP SYSTEM	78
D2.	COMBINED HEAT AND POWER SYSTEM	78

APPLICATION OF PROCESS INTEGRATION TO UTILITIES, COMBINED HEAT AND POWER AND HEAT PUMPS

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
COP_p	coefficient of performance (heat pump)	—	—
COP_r	coefficient of performance (refrigeration)	—	—
C_p	specific heat capacity	J/kg K	Btu/lb °F
CP	heat capacity flowrate	W/K	Btu/h °F
DT_{min}	minimum temperature difference across exchangers	K or °C	°F
h	specific enthalpy	J/kg	Btu/lb
ΔH	heat load on a hot or cold utility stream	W	Btu/h
N	number of stream at pinch	—	—
$^*p$	pressure	bar	lbf/ft ²
Q_p	heat transferred between the process and a heat engine or pump	W	Btu/h
Q_x	extra utility due to heat transfer across pinch	W	Btu/h
Q_1	heat flow to or from upper cycle temperature	W (th)	Btu/h
Q_2	heat flow to or from lower cycle temperature	W (th)	Btu/h
s	specific entropy	J/kg K	Btu/lb °F
T	temperature	°C	°F
T_1	absolute upper working temperature of heat/power cycle	K	°R
T_2	absolute lower working temperature of heat/power cycle	K	°R
TI	interval temperature	°C	°F
T_s	saturation temperature	°C	°F
W	shaft power of a heat engine or heat pump	W (e)	Btu/h
ε	mechanical efficiency	—	—

η	Carnot factor	—	—
--------	---------------	---	---

Subscripts

C	cold stream
-----	-------------

H	hot stream
-----	------------

* All pressures are absolute unless otherwise stated.

2. PURPOSE AND SCOPE OF THIS DATA ITEM

This Data Item describes how Process Integration techniques may be used to design or optimise the heat and power systems of a process plant or site. It covers the heat supply and removal systems of a plant, which are referred to as the hot and cold utility systems respectively. Hot utilities include furnaces and steam systems; cold utilities include cooling water and refrigeration. The discussion of heat and power systems lays particular emphasis on combined heat and power (CHP) and heat pumps. The techniques are an extension of those for energy targeting and heat exchanger network design described in Data Item 87030.

The difference between the two Data Items is that Item 87030 dealt primarily with quantity of heat (*i.e.* how much could be recovered and how to minimise that required from external sources) whereas this Data Item is chiefly concerned with the quality of heat (*i.e.* ensuring that the best use is made of temperature driving forces, maximising use of cheap low-grade utilities and cogeneration, and minimising power consumption for heat pumping and refrigeration).

A Process Integration study requires the following steps.

- (i) Obtain energy targets and the pinch temperature for the existing process flowsheet.
- (ii) Examine opportunities for process change and modify the problem accordingly.
- (iii) Analyse the site power needs and identify opportunities for using the utility systems to generate electrical power or mechanical shaft work at the same time as supplying heat to the process.
- (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.

This Data Item covers Stages (iii) and (v) in the procedure. Stages (i) and (iv) have already been covered by Item 87030 for continuous processes; for batch processes, more advanced techniques are required. Stage (ii) requires specialist methods not covered in these Data Items and, although references to the published papers covering this subject are included, it is advisable to consult an experienced Process Integration analyst. There is also an overlap between the last three stages – heat exchanger network design interacts with utility system design, especially where multiple utilities, heat engines and heat pumps are used. These interactions are covered in this Data Item.

3. HOW TO USE THIS DATA ITEM

Users who are unfamiliar with the concepts of the pinch, energy targeting and the composite and grand composite curves should first refer to Data Item 87030. Sections 4, 6, 7 and 13 of that Item cover the basic concepts, but the user who is planning to use the techniques for detailed design is strongly advised to study the whole of Sections 5 to 10.

In the present Data Item, Section 4 summarises the basic concepts of heat engines and heat pumps and lists the different types of utility system. Section 5 shows how the concepts of targeting, the pinch and exchanger networks, described in Data Item 87030, are applied to utilities. This Section gives the detailed design methods for integrating utility systems, particularly those with multiple levels, into the heat recovery system.

Sections 6 and 7 cover two important alternatives to simple heating and cooling systems. Section 6 describes combined heat and power (CHP) systems, listing the different types and covering the selection and design procedure. Section 7 explains how heat pumps should be integrated with the process.

The techniques have been illustrated throughout by reference to a single 'core example', which is the same process as that used in Data Item 87030. This example is briefly reviewed in Section 8, which also contains three further case studies illustrating the selection and design of all major utility systems.

Process integration is a subject with many specialised terms; also, some apparently familiar terms are used in an unusual or highly specific sense. For this reason, a comprehensive glossary is provided in Section 9. References in the area of heat and power are covered in Section 10. Some recent papers on other areas of process integration that have appeared since the issue of Data Item 87030 are also referenced.

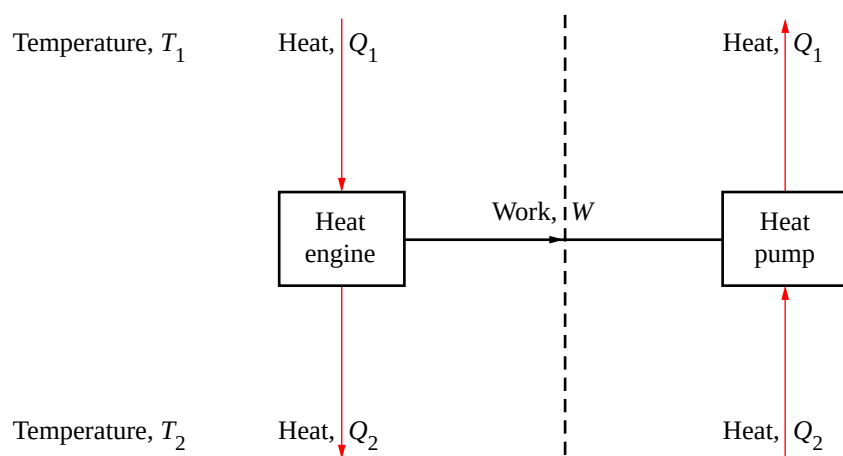
For practical design purposes, the user will need at least the grand composite curve and problem table for the process, obtained using Section 6 of Data Item 87030. Section 4 of the present Data Item lists possible options for the utility systems. Options for integration with the site power systems, using CHP or heat pumps, can be explored by reference to Sections 6 and 7. The best size and layout of the heat and power systems for the site can then be selected using appropriate economic criteria. Finally, Section 5 is used to carry out the detailed network design incorporating the selected utility system and iterating the sizing of the site heat and power systems as necessary.

4. BASIC CONCEPTS OF HEAT AND POWER SYSTEMS

4.1 Heat Engines

A heat engine is a device that takes high-temperature heat, degrades it to a lower temperature and simultaneously produces shaft work. It is not possible to achieve total conversion of heat into work; only a proportion of the high-temperature heat supplied can be converted into work, and this proportion is limited by the second law of thermodynamics.

A typical heat engine is represented in schematic form in the left-hand half of Sketch 4.1. Everyday examples are power stations, where the shaft power is converted to electrical power, and the car internal combustion engine where the shaft power is used directly.



Sketch 4.1 Ideal heat engine and heat pump

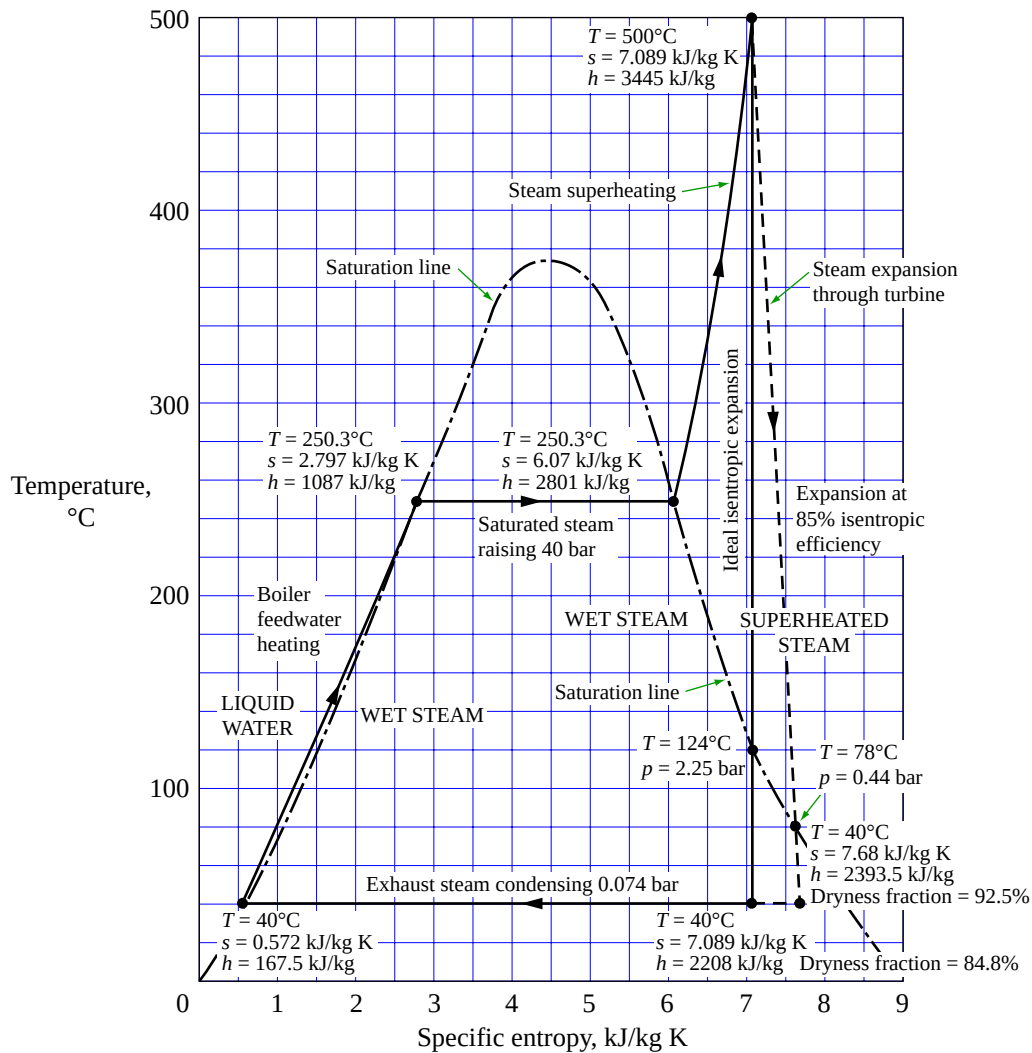
The work produced by a heat engine depends on the temperatures between which it operates. The maximum work is given by the second law of thermodynamics and can be expressed by the Carnot factor, η :

$$\eta = \frac{W}{Q_1} = 1 - \frac{T_2}{T_1}.$$

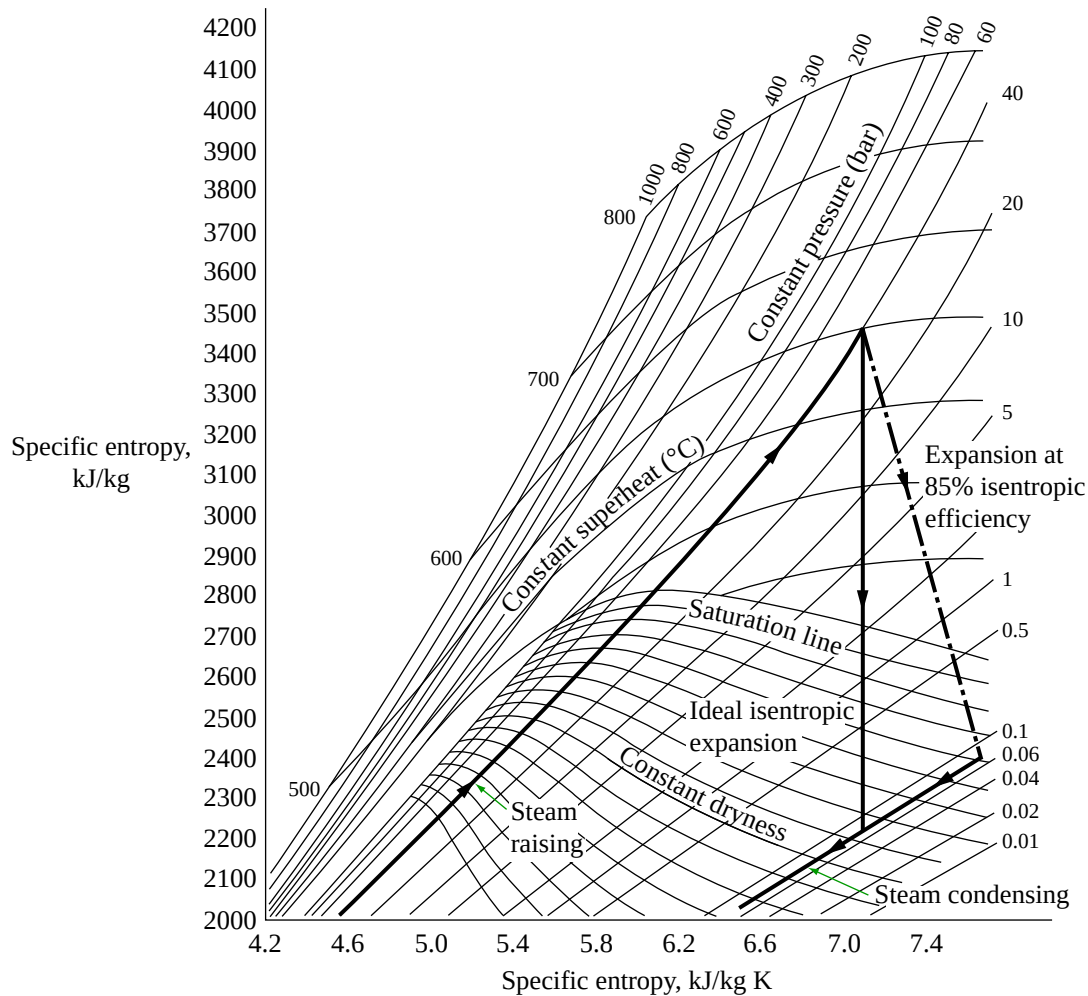
Note that T_1 and T_2 are absolute temperatures.

This is a theoretical, ideal efficiency. For two reasons it cannot be achieved in practice.

Firstly, the Carnot efficiency can be achieved (even with no mechanical losses) only if all the heat is taken in at temperature T_1 and rejected at temperature T_2 . A practical heat engine will take in and reject heat over a range of temperatures; this can be illustrated by plotting a T - S or temperature-entropy diagram. Sketch 4.2 shows a T - S diagram for a simple steam cycle, for which the corresponding Mollier (enthalpy-entropy or H - S) diagram is shown in Sketch 4.3. Heat is required at all temperatures from 40°C (for heating feed water) to 500°C (for superheating steam) and most is required at 250°C (for boiling water to raise steam at 40 bar absolute pressure). So the Carnot factor for most parts of the cycle is much less than that for the maximum and minimum temperatures, 500°C and 40°C respectively. The Carnot factor based on that temperature range is 59.5% (and if based on the actual flame temperature in the furnace - typically 1700°C - the Carnot factor is 84.1%) but the maximum thermal efficiency of this Rankine cycle is only 37.8%.



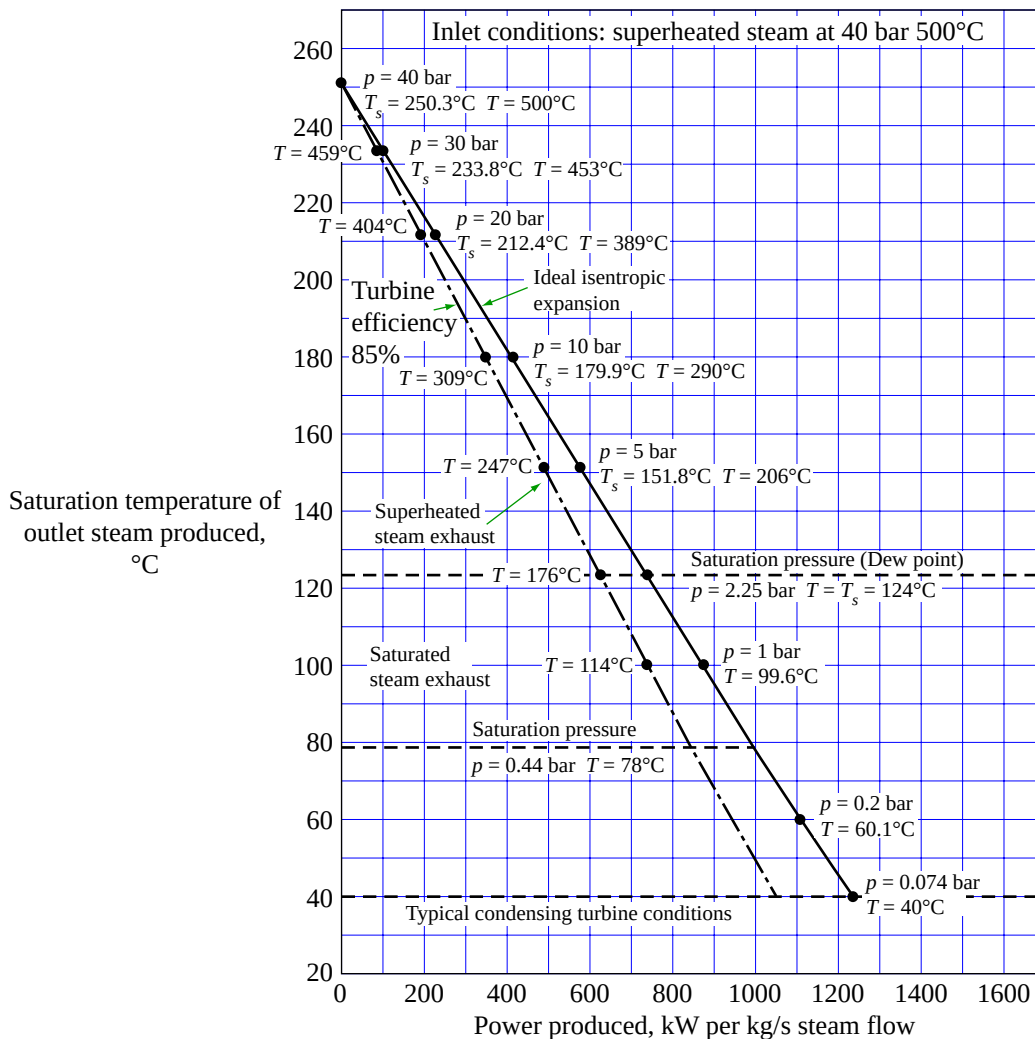
Sketch 4.2 T-S diagram for a 40 bar steam cycle



Sketch 4.3 H-S diagram for a 40 bar steam cycle

Secondly, energy losses in the process equipment must be taken into account. A mechanical efficiency, ε , can be defined, based on losses from friction in machinery such as turbine drives, whilst a 'lost work' or 'energy' factor allows for pumping losses, pressure drops and wall heat losses. These can be multiplied together with the relevant cycle efficiency to give the practical overall efficiency. For example, expansion of steam through a turbine will not be isentropic, and the turbine efficiency relative to isentropic will be about 85% of the ideal value for the Rankine cycle, as shown by the broken line in Sketches 4.2 and 4.3. The overall efficiency of the heat engine is then 85% of 37.8%, i.e. 32.1%.

The Carnot factor calculations show that the work available from a heat engine is dependent on the temperature difference between the heat supply and heat rejection temperatures. For example, the work produced by a steam turbine supplied with high-pressure steam increases considerably as the outlet steam temperature and pressure are reduced. Sketch 4.4 illustrates this point, which is of great relevance in combined heat and power systems. For example, the power generated by a back-pressure turbine producing 10 bar steam at 180°C saturation temperature is barely one-third that produced from a condensing turbine. A system utilising the heat at the temperature of the original furnace where the fuel was burnt, such as a gas turbine, will produce even more work.



Sketch 4.4 Power produced from a steam turbine at different exhaust temperatures and pressures

4.2 Heat Pumps

A heat pump is the reverse of a heat engine. It upgrades heat from a low temperature to a higher temperature, using mechanical work. Its performance is again limited by the second law of thermodynamics.

The right-hand half of Sketch 4.1 represents a simple heat pump, and it is obvious from this that it is a heat engine working backwards. Everyday examples of heat pumps are refrigeration and air-conditioning systems.

The maximum amount of heat that can be pumped between two temperatures for a given work input is given by the ideal coefficient of performance or COP. For a heat pump this is defined as the ratio of the heat released at the upper temperature to the work input:

$$COP_p = \frac{Q_1}{W} = \frac{T_1}{T_1 - T_2}$$

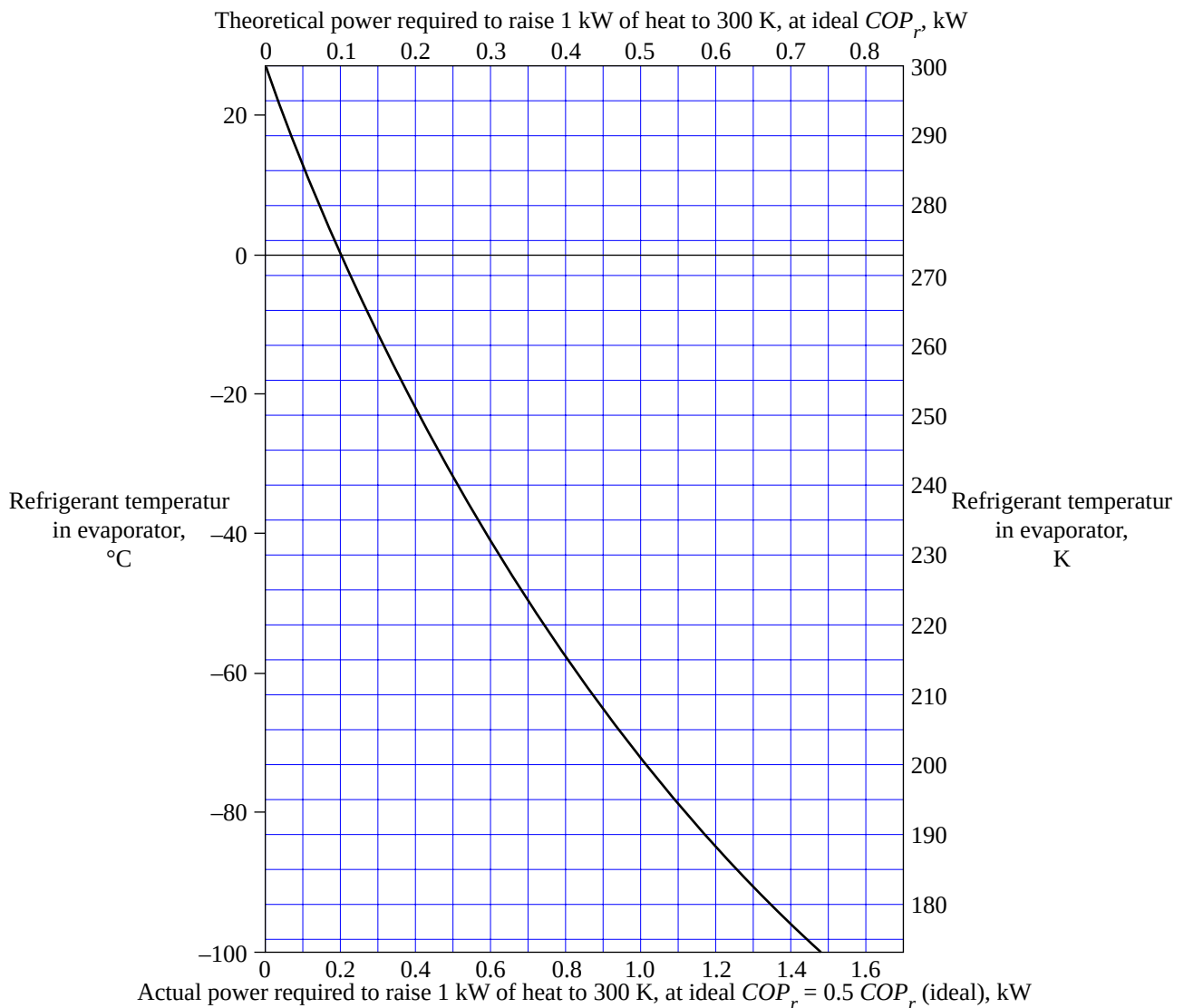
The COP is the reciprocal of the Carnot factor, and is therefore always greater than 1. It is not an efficiency.

COP_p is based on the heat supplied by the heat pump at the upper temperature level. However, in refrigeration systems, the important factor is the heat which can be extracted at the low temperature. An alternative definition of coefficient of performance, COP_r , is therefore used for refrigeration systems:

$$COP_r = \frac{Q_2}{W} = \frac{T_2}{T_1 - T_2}.$$

By definition $COP_r = COP_p - 1$.

In both cases the COP falls rapidly as the temperature difference increases, and this effect is particularly severe at low temperatures. As a result, low levels of refrigeration are much more costly than moderate levels close to ambient. Sketch 4.5 illustrates this by showing the ideal power required to raise 1 unit of heat from different temperatures to 300 K (a reasonable value for heat rejection into a cooling water system).



Sketch 4.5 Power required to carry out refrigeration below ambient temperature

As for heat engines, the combined effect of mechanical losses and non-isothermal heating means that practical efficiencies are much lower than theoretical ones. Typically, practical heat pumps have COPs about 50% of the theoretical value.

4.3 Marginal Cost

Usually, where two or more utilities are available, they will cost different amounts per unit of heat. The difference in price between two utilities is the marginal cost, typically expressed in £/MWh.

The marginal cost is vital when evaluating possibilities for replacing one utility by another, and when optimising the use of different utilities. It is this price difference that gives the main incentive for using multiple utilities at several temperature levels, rather than a single extreme level. It should, however, be remembered that marginal cost depends on fuel and power costs, and the effect of changes in these should be checked when costing projects in detail.

In general, high-grade utilities well above or below ambient temperature (for example, high-pressure steam and refrigeration) are more expensive than low-grade utilities relatively close to ambient temperature such as low-pressure steam and cooling water. However, this is not always the case. A direct-fired furnace may be more efficient and cheaper to run than a steam system, which usually has large distribution and boiler losses. In the steam system itself, if low-pressure (LP) steam is obtained by simple letdown through a pressure reducing valve it will cost the same as high-pressure (HP) steam, but if it is obtained by expanding through a turbine, doing useful work, its net cost can be very much less than high-pressure steam. This is illustrated by Table 4.1, which compares net cost for steam generated by package boilers and by a combined heat and power (CHP) system at various levels. Detailed calculations are shown in Appendix A.

TABLE 4.1 Marginal Cost For Different Steam Levels

Steam pressure bar	Saturation Temperature °C	Shaft Work Produced MWh/tonne	Cost of Steam per Unit Heat	
			From Letdown £/MWh	From CHP £/MWh
40	250	0.000	15.65	15.65
30	234	0.023	15.14	14.41
20	212	0.053	14.55	12.82
10	180	0.098	13.76	10.39
5	152	0.136	13.16	8.32
2.25	124	0.173	12.62	6.30
1	100	0.206	12.19	4.47
0.44	78	0.236	11.83	2.81
0.2	60	0.263	11.55	1.26
0.074	40	0.292	11.26	-0.42

For cold utility, the situation is even more clear-cut; lower temperature levels of refrigeration will always be more costly because of the power required to achieve the larger temperature lift to ambient. Table 4.2 details the cost of achieving 1 MWh refrigeration at various levels. The calculation is again shown in Appendix A and is the same as the one used to generate Sketch 4.5.

TABLE 4.2 Cost of Refrigeration at Different Temperature Levels

Refrigerant Temperature in Evaporator		Ideal COP_r	Practical COP_r	Power Use per Unit Cooling	Power Cost per Unit Cooling
°C	K			MW (e)/Mw (th)	£ /Mwh (th)
27	300			0.000	0.00
17	290	29	14.5	0.069	2.48
7	280	14	7	0.143	5.14
-3	270	9	4.5	0.222	8.00
-13	260	6.5	3.25	0.308	11.08
-23	250	5	2.5	0.400	14.40
-33	240	4	2	0.500	18.00
-43	230	3.286	1.643	0.609	21.91
-53	220	2.750	1.375	0.727	26.18
-63	210	2.333	1.167	0.857	30.86
-73	200	2	1	1.000	36.00
-83	190	1.727	0.864	1.157	41.68
-93	180	1.5	0.75	1.333	48.00
-103	170	1.308	0.654	1.529	55.06

Marginal costs are operating costs, but there are capital costs associated with utility systems that must also be taken into account. A HP steam system will be more expensive than a LP one because much heavier vessels and pipework are required. For this reason the steam distribution system for large sites is generally run at the minimum practical pressure. Conversely, refrigeration systems become increasingly expensive as the temperature falls; improved insulation, multistage compressors, special materials (especially below -50°C) and other specialist cryogenic equipment are required.

4.4 Types of Utilities

Apart from the obvious distinction between hot and cold utilities, it is sometimes useful to distinguish between utilities that work at effectively constant temperature (usually phase-change systems such as condensing steam) and those that operate over a significant temperature range (based on sensible heating and cooling, such as flue gases or cooling water). Typical hot and cold utilities are listed below.

Hot utilities - constant temperature:

- condensing steam from a site distribution network,
- radiant-type furnaces that can effectively be treated as being at constant temperature,
- heat pump or refrigerant condensers,
- electric local or trace heating.

Hot utilities - variable temperature:

- flue gas from a furnace,
- exhaust gas from a gas turbine or reciprocating engine,
- hot compressor jacket water,
- desuperheating steam,
- subcooling condensate,
- warm drain water or effluent,
- hot water, thermal fluid and hot oil systems,
- furnaces with large internal temperature variations.

Cold utilities - constant temperature:

- evaporating water or other liquids (including steam raising),
- heat pump or refrigerant evaporators,
- melting solids,
- space heating (effectively at ambient temperature),
- direct discharge to atmosphere or river (again ambient temperature).

Cold utilities - variable temperature:

- cooling water,
- air cooling,
- boiler feedwater,
- inlet air to furnaces,
- superheating vapours.

5. MULTIPLE LEVEL UTILITIES

5.1 Basic Concepts of Process Integration

The key initial stages in a process integration analysis were stated in Data Item 87030. For the core example, the essential information obtained is the set of stream data (Table 5.1), the hot and cold composite curves (Sketch 5.1), the problem table and hence the energy targets (Table 5.2), and the grand composite curve or G.C.C. (Sketch 5.2).

TABLE 5.1 Stream Data For Core Example Problem

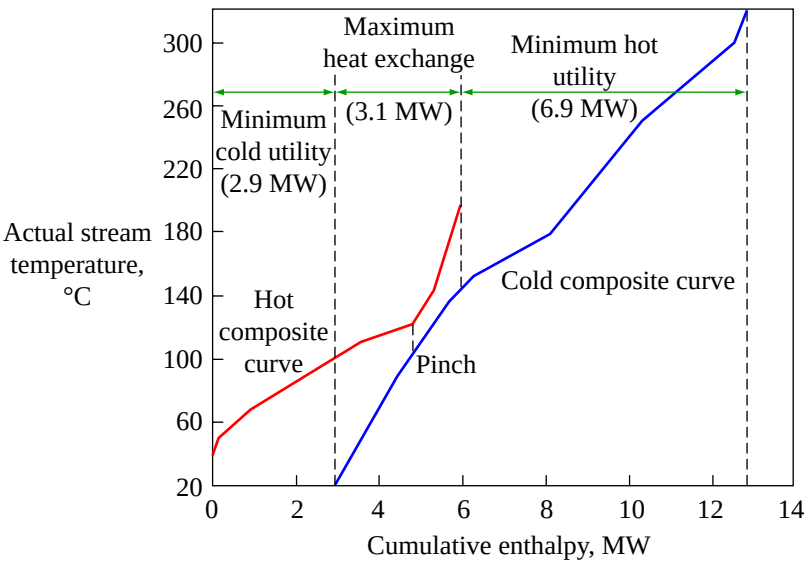
	1	2	3	4
Stream	Temperature °C	Enthalpy MW	Heat Capacity Flowrate (CP) MW/K	Interval Temperature °C
HOT STREAM				
A	199 123 70	1.35 0.58 0	0.0101 0.0109	189 113 60
B	144 112 70 41	1.51 1.03 0.32 0	0.0150 0.0169 0.0110	134 102 60 31
C	123 112 52	3.02 2.17 0	0.0773 0.0362	113 102 42
D	204 144	0.12 0	0.0020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

Note: $DT_{min} = 20^{\circ}\text{C}$.

Interval Temperatures, TI , are defined as follows:

for Hot Stream, $TI = T - DT_{min}/2 = T - 10$,

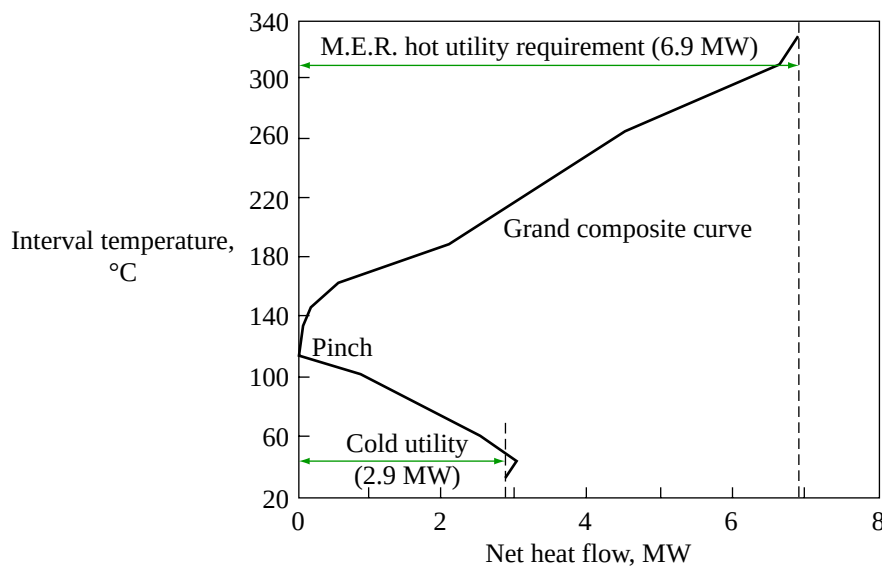
for Cold Stream, $TI = T + DT_{min}/2 = T + 10$.



Sketch 5.1 Composite curves

TABLE 5.2 Heat Cascade or Problem Table

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



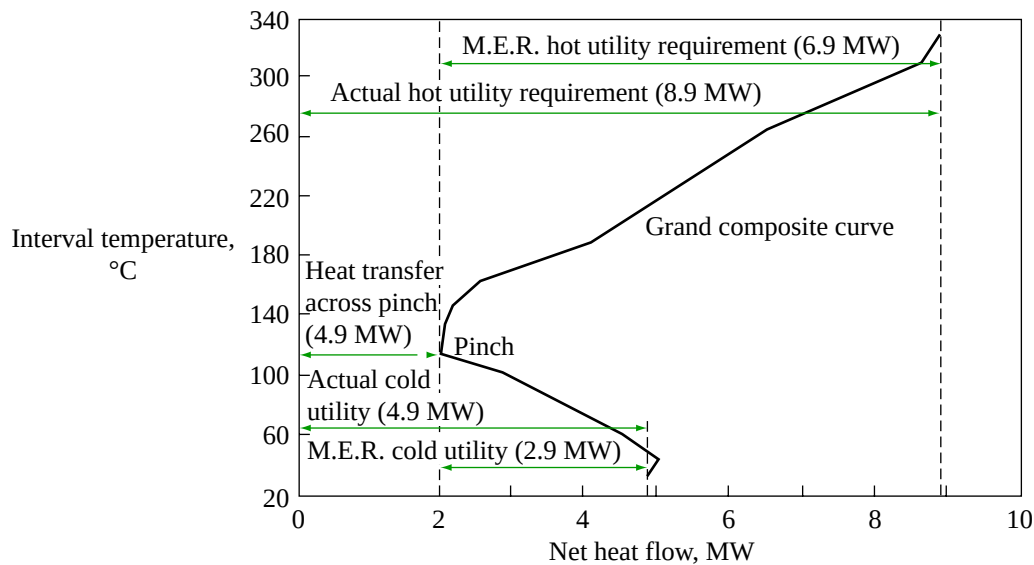
Sketch 5.2 Grand composite curve

The grand composite curve is a plot of net heat flow through the process against interval temperature. It is the most important design tool of all, at least for the early stages of utility system analysis (and also for identifying process changes), because of the following features.

- (i) The hot and cold utility targets can be read off instantly; they are the enthalpy values at the top and bottom ends of the graph respectively.
- (ii) The pinch temperature can also be read off instantly; it is the point where net heat flow through the process is zero.
- (iii) The G.C.C. is a plot of the amount of heat required by or released by the process at any given temperature. Therefore it shows how much hot or cold utility can be used at any given temperature level.
- (iv) It is apparent from a study of the plot that above the pinch only hot utility is required and below the pinch, only cold utility.
- (v) It is a plot of the heat cascade or problem table, so intermediate values are easily and precisely obtained. Table 5.2 shows the heat cascade corresponding to the grand composite curve in Sketch 5.2.

The G.C.C. thus shows not only how much utility should be used, but also the temperature at which it should be used, as a result of feature (iii).

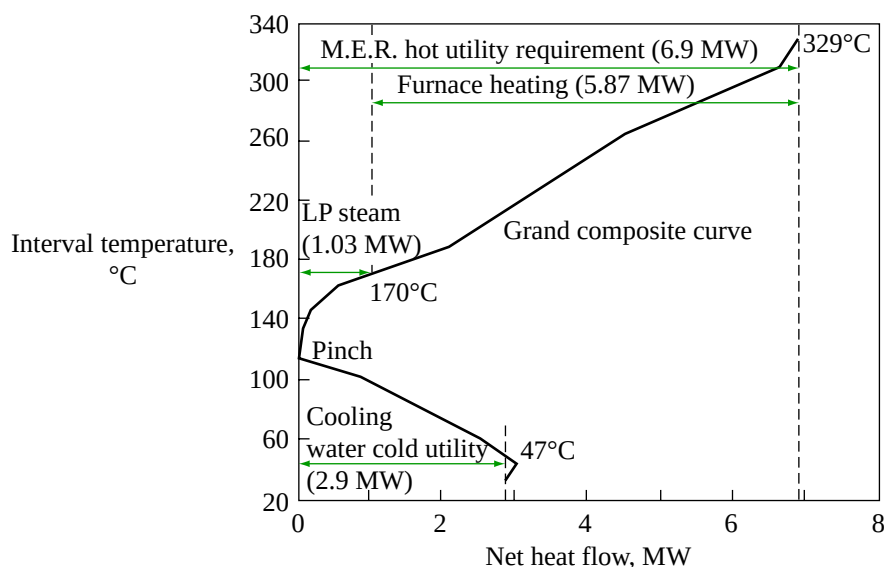
After the heat exchanger network design stage, network relaxation will usually have been carried out, accepting a small increase in energy requirement in order to eliminate small or uneconomic exchangers. There will then be a small heat flow, Q_x , across the pinch and the actual use of both hot and cold utility is then higher than the targets by an amount, Q_x . This is the equivalent of shifting the G.C.C. to the right by Q_x , as shown in Sketch 5.3. The maximum utility use at any temperature level can still be read off and will in fact be Q_x greater than that found from the original G.C.C. at that level.



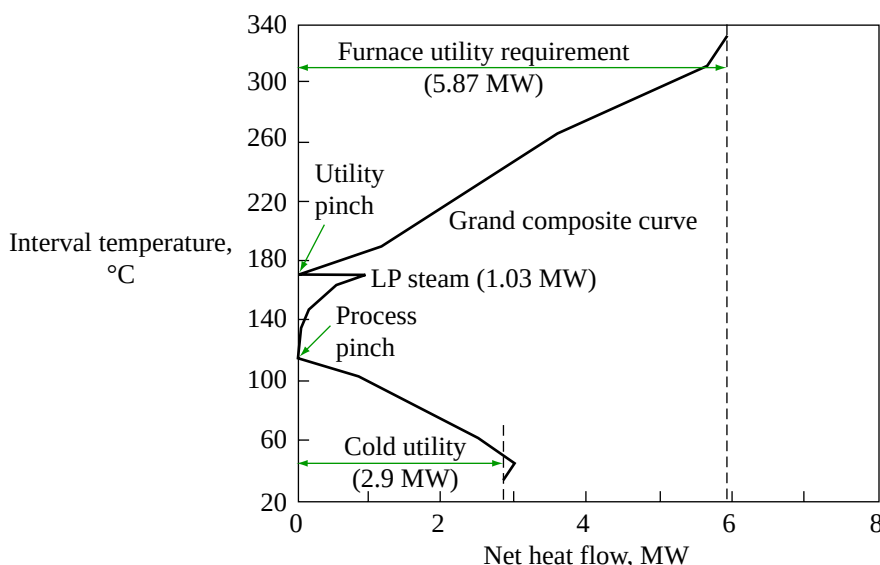
Sketch 5.3 Effect of heat transfer across the pinch

5.2 Multiple Utility Levels

In many cases, a low-grade utility close to ambient temperature (for example: LP steam, cooling water, near-ambient refrigeration levels) will be significantly cheaper than a high-grade utility (for example: HP steam, low temperature refrigeration levels), as was shown in Section 4.3. The use of the low-grade utility may be maximised by finding the interval temperature at which it can be supplied and reading the corresponding net heat flow from the problem table or G.C.C. Sketch 5.4 illustrates this for the LP steam level on the G.C.C. of the core example. The low-grade utility can then be treated as a fixed hot stream, because its heat load and temperature are known. Adding this to the set of stream data gives a corresponding reduction in the high-temperature utility requirement and also a second point of zero net heat flow at the utility temperature. This point acts as a second pinch or 'utility pinch' and is illustrated in Sketch 5.5.



Sketch 5.4 Multiple utility levels on the grand composite curve



Sketch 5.5 Grand composite curve with LP steam utility included in stream data set to show utility pinch

This part of the heat exchanger network is designed by starting at the utility pinch and working outwards, just as for the true process pinch. If the network has to be relaxed then, instead of incurring an actual energy penalty, a high-grade utility must be used in place of a low-grade one. The difference in cost between the two utilities must be balanced against the increase in complexity of the network around the utility pinch.

Multiple utility levels are particularly important in refrigeration and cryogenic applications, where lower cooling levels are particularly expensive. The grand composite curve clearly indicates the opportunities for putting in additional levels and making the most effective use of existing ones.

Trade-offs include those between utility cost at higher levels and heat exchanger size, and between capital cost of pressurised equipment and capital cost of exchangers.

5.3 Calculation of Utility Load at a Given Level

The simplest situation to analyse is for an existing site where there is already a low-grade utility available at a given temperature. The heat load which it can supply can then be found very rapidly from the G.C.C.

It may not be appropriate to use a DT_{min} contribution for the utility stream that is the same as that for the process streams. Several factors are involved. Heat transfer coefficients from gaseous streams will be appreciably lower than those for liquid, boiling or condensing streams so that a higher DT_{min} contribution will be required. The energy cost savings from replacing high-grade by low-grade utility are less per unit of heat than those from heat recovery.

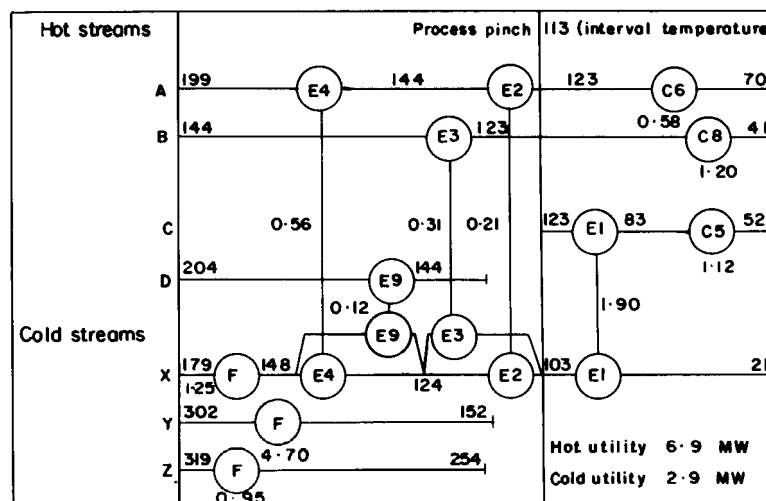
Assume, using the core example, that low-pressure steam is available on site at 10 bar (132 lbf/in² g), condensing temperature 180°C. The heat transfer coefficient from this will be high, above that for sensible cooling of a liquid in an exchanger. On the other hand the cost savings from replacing HP by LP steam will be less than those from heat recovery. It is assumed here that the DT_{min} contribution for the condensing steam may be taken as 10°C, giving an overall DT_{min} , on any match of 20°C, just as for heat exchange between process streams.

The steam is therefore available at an interval temperature of 170°C. The net heat flow at this temperature can be calculated from the problem table by interpolation; alternatively, it can be read graphically from the G.C.C. if the plot is clear enough. Here the problem table, Table 5.2, is used; the net flow is 0.58 MW at 162°C and 2.11 MW at 189°C, and since the G.C.C. is made up of a series of straight lines (all CPs are constant in each temperature interval), linear interpolation gives the heat load at 170°C as 1.03 MW. The remaining 5.87 MW must be supplied at a higher level. This is illustrated on the grand composite curve in Sketch 5.4.

5.4 Network Design to Achieve Maximum Low-level Utility Load

When utility heat is being supplied at a low level, it is necessary to ensure that it is used to heat the right streams, just as hot streams near the pinch must be matched carefully with cold streams. In fact, the best method is to turn the utility stream into an additional hot stream, thereby creating a second pinch. This is a 'utility pinch' as distinct from the true or process pinch, see Sketch 5.5. There can be several utility pinches.

The network must be designed working away from the utility pinch, in precisely the same way as for the process pinch (Data Item 87030, Section 8). First, an ideal network is designed that uses the maximum possible low-grade heating: the equivalent of the M.E.R. network with no heat flow across the utility pinch. This network is then relaxed, eliminating small and uneconomic heaters, coolers and heat exchangers by allowing some heat flow across the pinch until one or two 'best' solutions are found.



Sketch 5.6 Minimum energy requirement (M.E.R.) design with single hot utility

The method will now be illustrated using the core example. Sketch 5.6 shows the M.E.R. network; the development of this network was traced in Data Item 87030, Sections 8.2 and 8.3. Cheap low-pressure steam is available at 10 bar, 180°C. Note that it is not advisable to try to work from the relaxed network as the trade-offs are changed by the existence of the utility pinch. The design procedure is now as follows.

- (i) Find the net heat flow at the given interval temperature from the problem table, as in Section 5.3.
- (ii) Add a new stream, S, to the network, consisting of steam at interval temperature 170°C and heat load 1.03 MW. This gives the new set of streams shown in Sketch 5.7.

Hot streams		Utility pinch 170	Process pinch 113	(Interval temperature)	Heat load
Steam	S		180 180		MW 1.03
	A	199 180		123 70	1.35
	B		144	123 41	1.51
	C			123 52	3.02
	D	204 180	144		0.12
Cold streams					
	X	179 160		103 21	4.35
	Y	302 160	152		4.70
	Z	319 254			0.95

Sketch 5.7 Stream grid including utility stream, S

- (iii) List the streams between the utility pinch and the process pinch, as in Table 5.3.

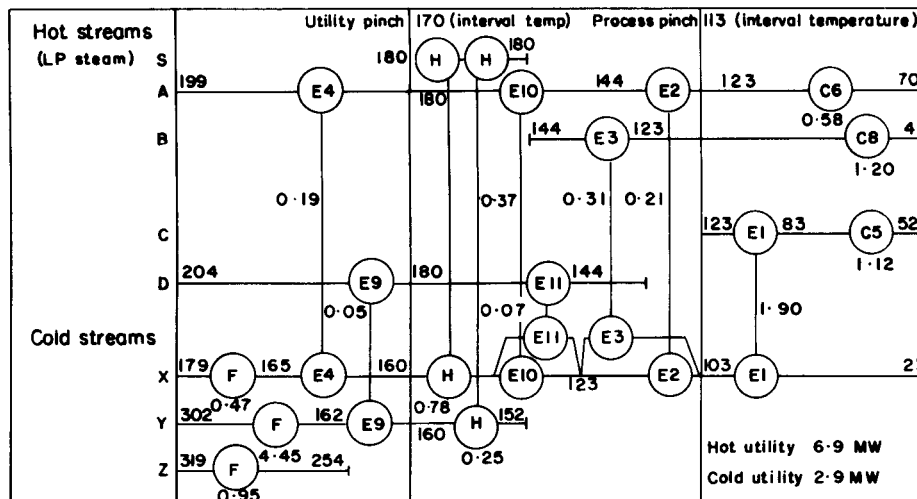
TABLE 5.3 Streams Existing Between Utility and Process Pinches

Stream	Temp. Range, °C	CP Range, MW/K	Heat Load, MW
Hot Streams:			
A	180 – 123	0.0101	0.58
B	144 – 123	0.015	0.31
D	180 – 144	0.002	0.07
S	180		1.03
Cold Streams:			
X	103 – 160	0.0253 – 0.0376	1.74
Y	152 – 160	0.0313	0.25

A crosscheck should be made to ensure that the hot and cold streams between the two pinches (including the utility streams – here, S) add up to equal heat loads (here 1.99 MW).

- (iv) Choose the matches between the two pinches. Start below the utility pinch. There are three hot streams (S, A and D) and two cold streams (X and Y). S has an infinite heat capacity flowrate, CP , as it is a condensing stream. Neither A nor D has a sufficiently high CP to fulfil the below-pinch inequality $CP_H \geq CP_C$, so S must be matched with both X and Y at the utility pinch.
- (v) Design the network immediately above the process pinch in the same way as for the original M.E.R. network and work up the temperature range until the utility pinch matches are reached. This completes the network design between the two pinches. The calculations are given in Appendix B. Two stream splits are required on X.

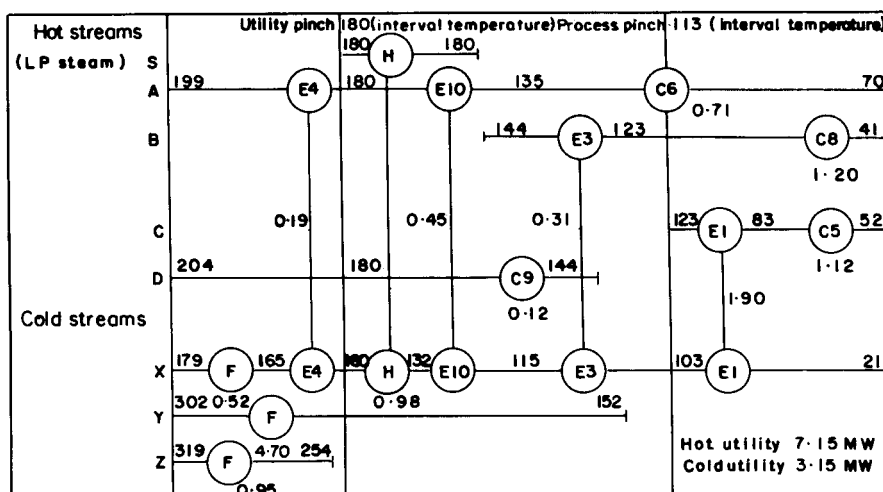
- (vi) Complete the network by designing above the utility pinch and below the process pinch; calculation details are in Appendix B. The modified M.E.R. network, maximising use of low-pressure steam, is shown in Sketch 5.8. Note the increase in complexity relative to the original M.E.R. network. 1.03 MW of LP steam is used, the figure calculated from the problem table.



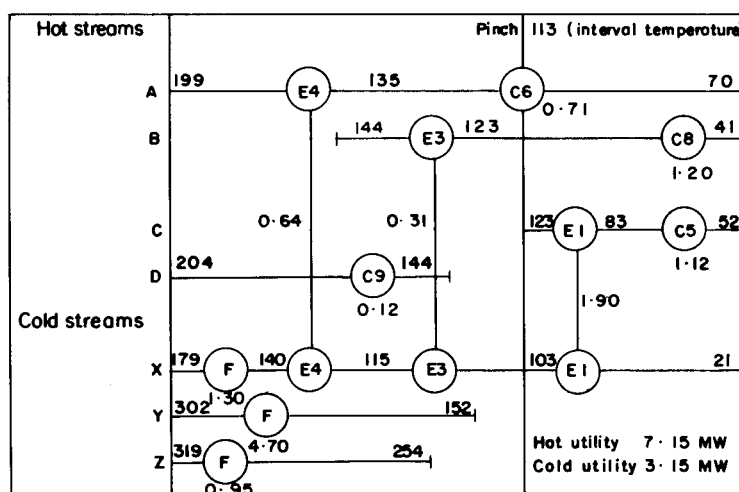
Sketch 5.8 Minimum energy requirement (M.E.R.) design with multiple utilities

- (vii) Relax the network using standard methods as described in Data Item 87030, Section 8.4.
- Eliminate exchanger E11 using a path from heater H to a new cooler, C9, on stream D. Additional hot utility: 0.07 MW LP steam.
 - Eliminate exchanger E9 using a path from furnace F to cooler C9. Additional hot utility: 0.05 MW furnace.
 - Eliminate exchanger E2 using a path from heater H to cooler C6. Additional hot utility: 0.13 MW LP steam.
 - The additional heater on stream Y, using only 0.25 MW LP steam in place of furnace heating, is unlikely to be economic (this will again depend on the marginal costs of the two utilities). Replace it with 0.25 MW furnace heating.

Overall, these operations have increased furnace heating by 0.30 MW, (b) + (d), and decreased LP steam use by 0.05 MW, (a) + (c) – (d), giving a net increase in hot utility of 0.25 MW. Cold utility will of course increase by the same amount. Three matches, one heater and both stream splits on X have been eliminated, giving the network of Sketch 5.9, with only one exchanger on each hot stream between the two pinches.



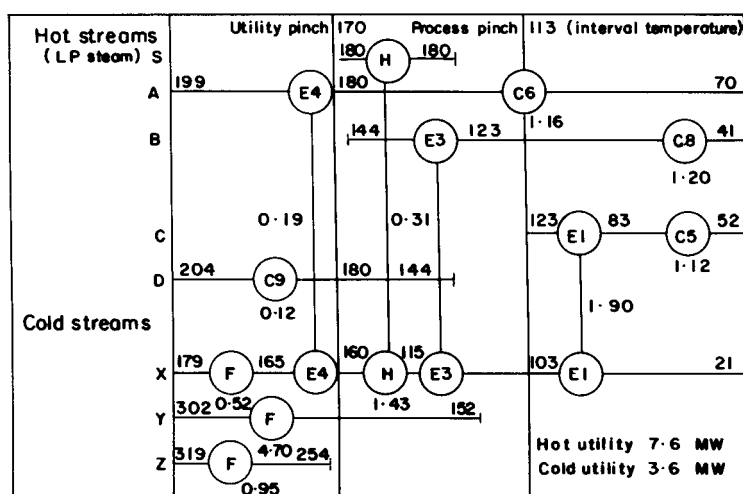
Sketch 5.9 Relaxed network with exchangers E2, E9 and E11 and stream splits eliminated



Sketch 5.10 Relaxed network with single utility only

Compare Sketch 5.9 with Sketch 5.10, which shows the relaxed network obtained when only one utility is used (Sketch 8.8 from Data Item 87030). The network of Sketch 5.9 with multiple hot utilities has one more exchanger and one additional heater. The overall hot utility requirement is the same at 7.15 MW, but 0.98 MW of furnace heating has been replaced by LP steam. The operating cost/capital cost tradeoff will depend on the marginal cost of furnace heating relative to LP steam and the cost of additional heat exchange area.

The additional exchanger, E10, also can be eliminated, using a path from H to C6. (The alternative relaxation method, by a loop through E4 and E10, would simply give Sketch 5.10 again.) 0.45 MW heat is switched from heat exchange to LP steam. The resulting network (Sketch 5.11) has just one additional heater compared with Sketch 5.10, 7.6 MW hot utility is used as against 7.15 MW; this includes 1.43 MW of low-pressure steam, so the furnace heating has fallen by 0.98 MW. Therefore, installation of an LP steam main for this process will only be worthwhile if its cost is much lower than that for furnace heating. This might apply where a steam turbine based CHP system is in use, but is unlikely to be the case otherwise.

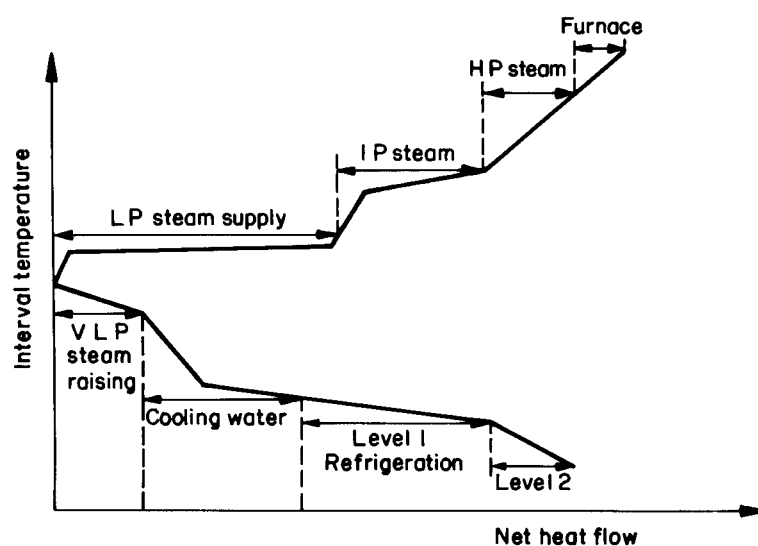


Sketch 5.11 Relaxed network with exchanger E10 eliminated from Sketch 5.8

In refrigeration systems the use of multiple levels is far more economic. Heat loads at each level are calculated from the problem table in the same way as above. Low-temperature refrigeration levels have a very high power consumption and electricity savings from installing intermediate levels will often outweigh the increased complexity of the network. See the case study in Section 8.2 for an example.

5.5 New Plants – Selection of Constant Temperature Utility Levels

Utility levels should preferably be placed near points where the G.C.C. gradient changes in such a way that it is concave to the ordinate axis, as shown in Sketch 5.12. This maximises the heat load on the cheaper low-grade utility. Again, a realistic choice should be made for DT_{min} , not necessarily the same as for process-to-process heat exchange. Rewards from selecting a low DT_{min} (less than 10°C) for utility heating are usually less than for heat recovery, as marginal costs (the excess cost of high-grade over low-grade utility) may not be very high. For refrigeration, however, marginal costs for low temperature levels are high and it is common practice to adopt DT_{min} values of $2\text{--}3^{\circ}\text{C}$.



Sketch 5.12 Ideal fitting of utilities to grand composite curve (maximising use of low grade heat)