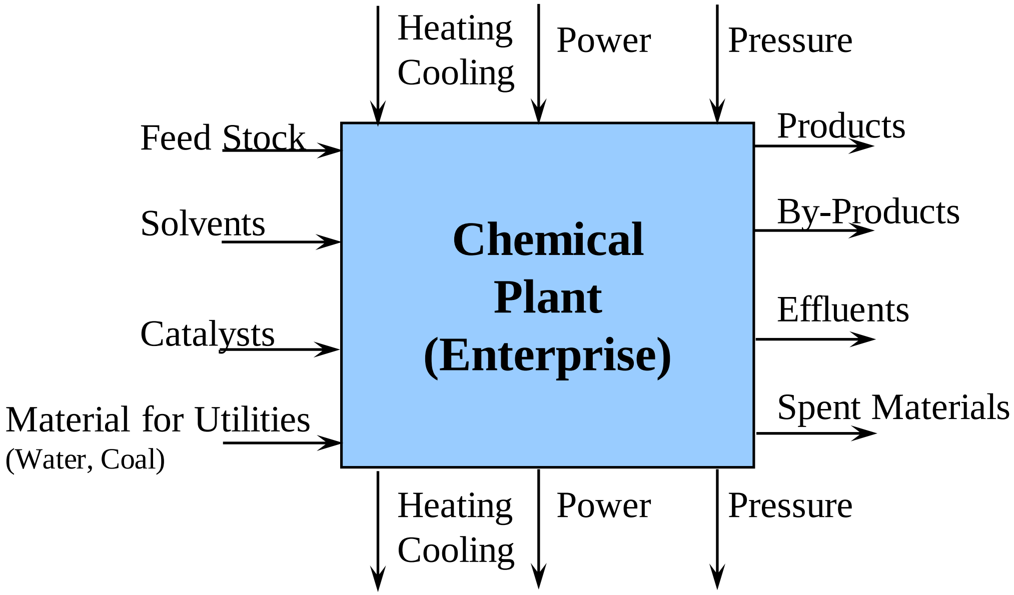
Lecture 9: Introduction of Process Integration

Chapter 10 of text-book plus additional notes on pinch diagram construction and use

Process Integration Tools Allow Analysis of the "Enterprise"

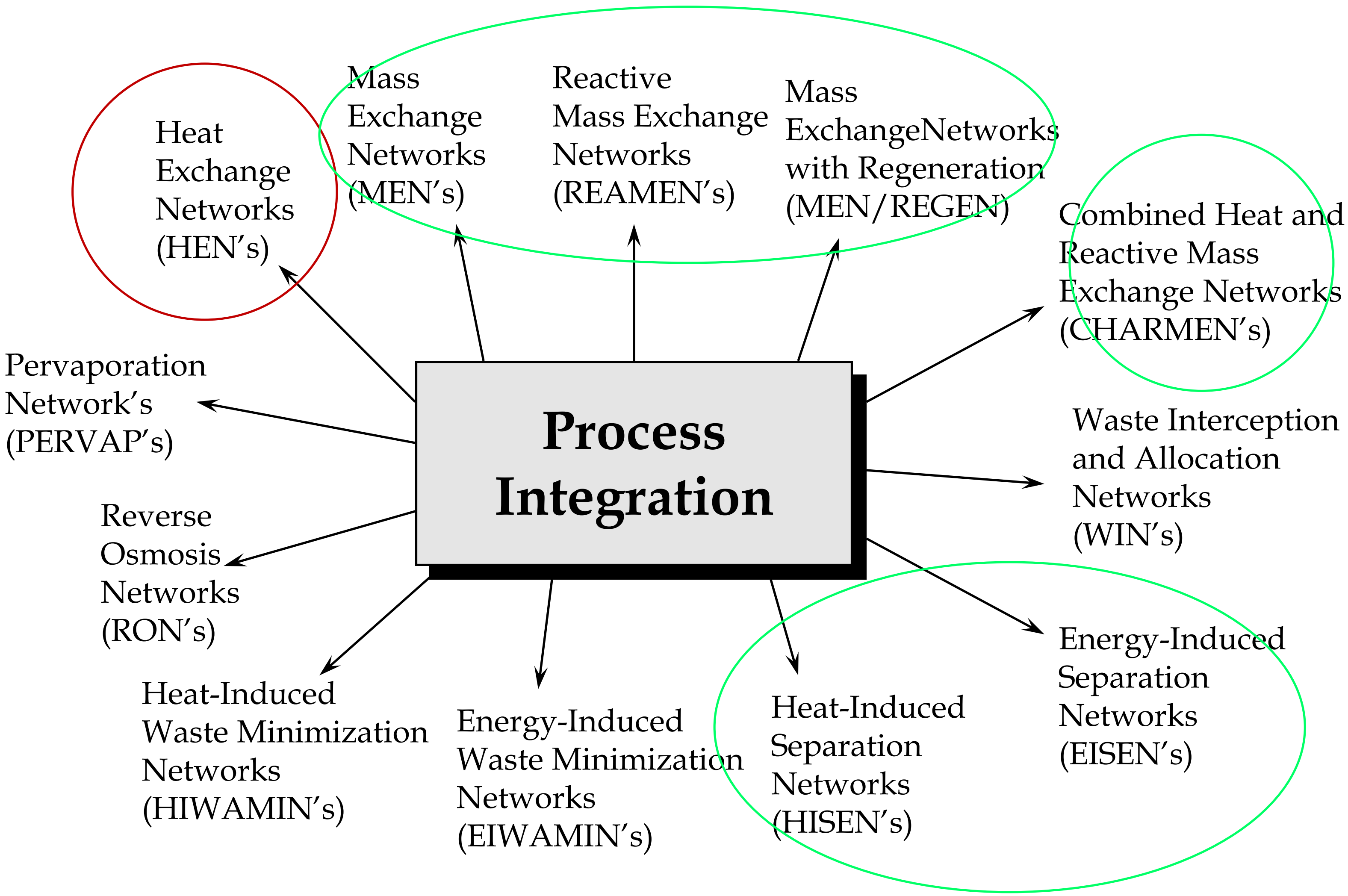
- **The optimal allocation of mass and energy within a unit operation, process and/or site.**
- **Optimal allocation can be based on economic, environmental or other important objectives.**



Mass Integration (Mass Exchange Network – MEN)

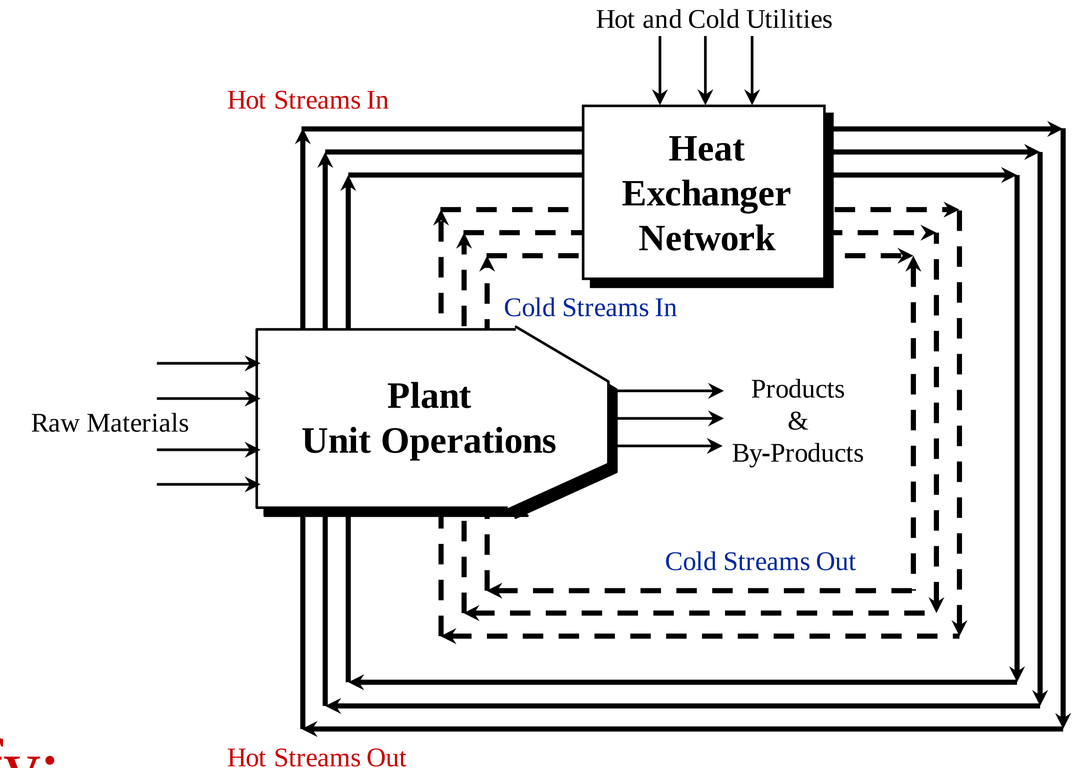
Energy Integration (Heat Exchange Network – HEN)

Process Integration Techniques



Heat Exchange Network (HEN)
(Linnhoff, Grossmann et al, 1978-Present)

A Heat Exchange Network is a System of One or More Heat Exchangers



Want to Identify:

– Optimal matching between hot and cold streams to minimize utility consumption
– Minimum number of heat exchangers needed

Heat Exchanger Network Synthesis (HENS) Problem

Given

- A set of hot process streams to be cooled and a set of cold process streams to be heated
- The flowrates and the inlet and outlet temperatures for all these process streams
- The heat capacities for each of the streams versus their temperatures as they pass through the heat exchange process
- The available utilities, their temperatures, and their costs per unit of heat provided or removed

Determine

the heat exchanger network for energy recovery that will minimize the annualized cost of the equipment plus the annual cost of utilities.

Information needed to solve the problem?

- The streams that need heating or cooling
- The flowrates and inlet-outlet temperatures
- Pressures of the streams as they pass through the heat exchangers

What is our model and which are our design variables?

$$Q = F\ Cp\ (T_1 - T_2) = U\ A\ \Delta T$$

Utility model **HEX sizing model**

What is our model and which are our design variables?

Known variables: F, Cp, U, T_1; Design (decision) variables: T_2, A; Unknown (dependent) calculated variable: Q

That is, look at temperature versus energy relationships

EXAMPLE 10.1 A Small but Interesting Problem

Consider the example problem shown in Figure 10.1. It consists of a reactor into which we are feeding two reactant streams. Each is available at 100°F and has to be heated to 580°F. The reaction is slightly exothermic. Thus, the reactor produces an outlet stream at 600°F, which we want to cool to 200°F.

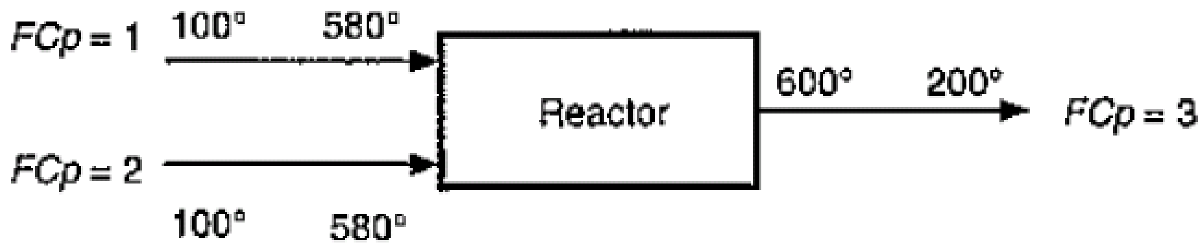
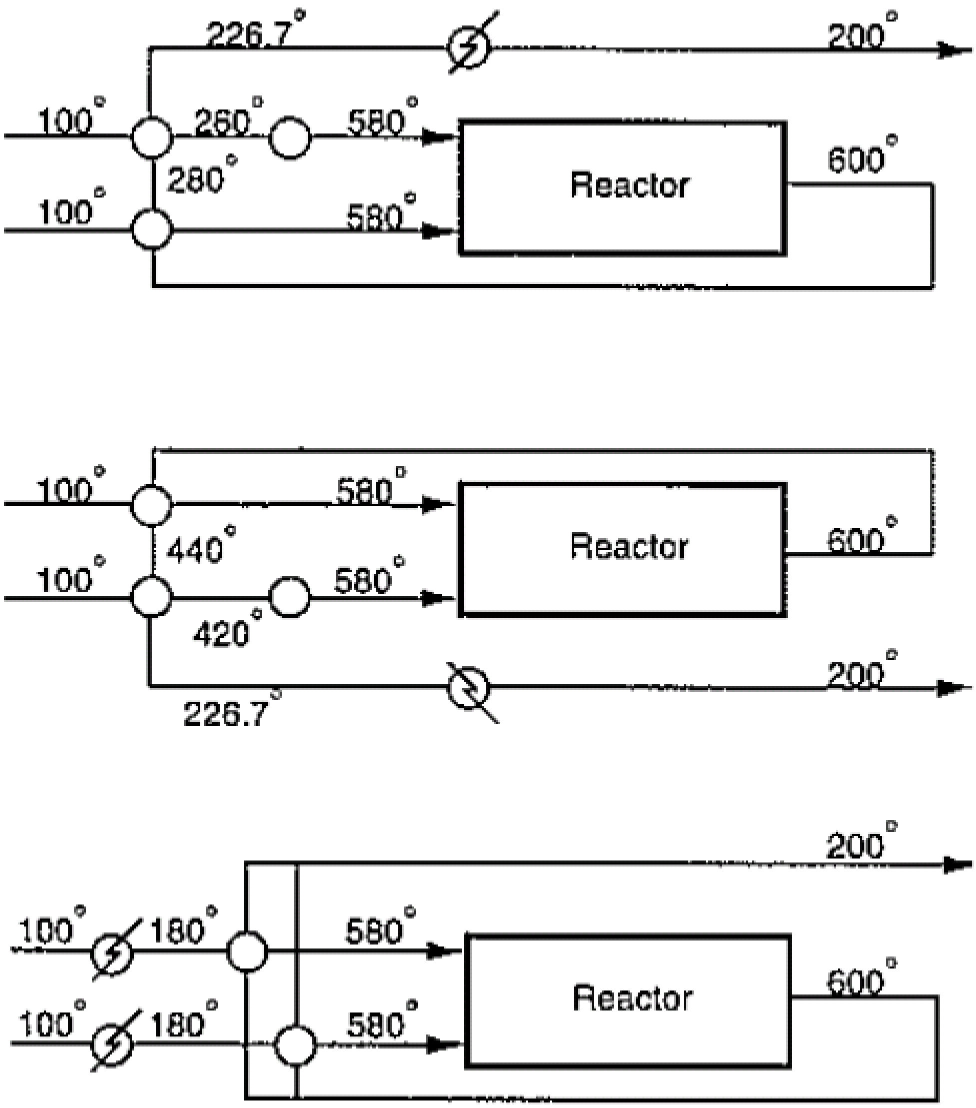


TABLE 10.1 Heat Exchanger Synthesis Problem for Example 10.1 in Tabular Form

Stream	T_{in}, °F	T_{out}, °F	FCp, BTU/°F	Heat out, BTU/s	Cost per lb
C1	100	580	1	−480	$0
C2	100	580	2	−960	$0
H1	600	200	3	+1200	$0
				Net = −240	
Utilities					
Steam, S	650	650			High
Hot water, HW	250	>130			Low
Cooling water, CW	80	<125			Moderate

How many networks are there?



Exchange heat between H1& C1-C2

- How much more heat can H1 give to C2? What is the exit temperature of H1 after exchange with C2?
- How much more heat can H1 give to C1? What is the exit temperature of H1 after exchannge with C1?
- Does H1 and C1 need additional cooling & heating?

Predicting the utilities required?

TABLE 10.2 Partitioning the HENS Problem into Temperature Intervals

		Cold Temp	Hot Temp		Heat Leaving Network
		(590)	600		
					(−3) (600 − 590) = −30
		580	(590)		
					(1 + 2 − 3) (580 − 190) = 0
		(190)	200		
					(1 + 2) (190 − 100) = 270
		100	(110)		
C1	C2			H1	Stream
1	2			3	*FCp* for stream

Concepts: partitioning, intervals; driving force; heat leaving a network

Predicting the utilities required?

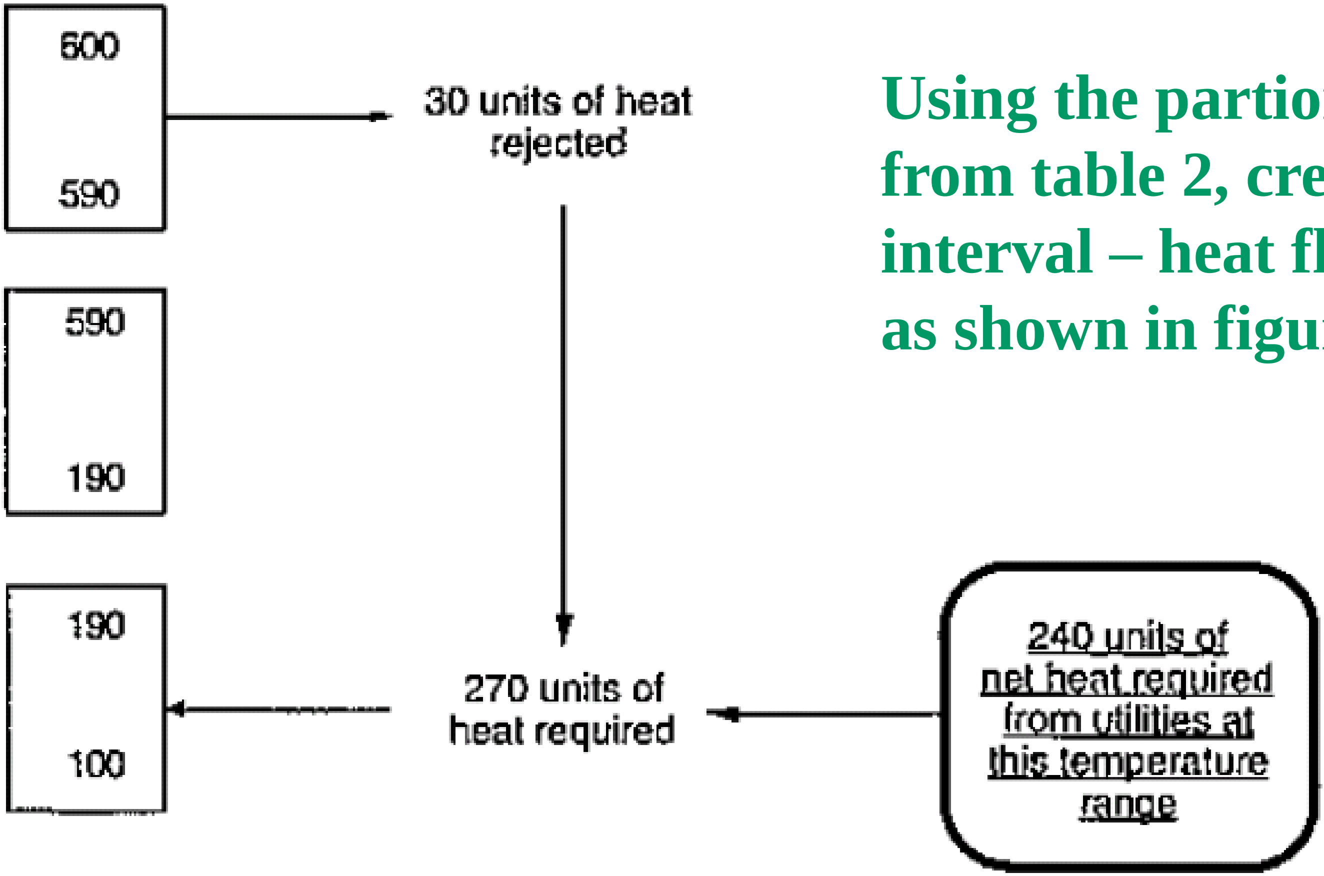
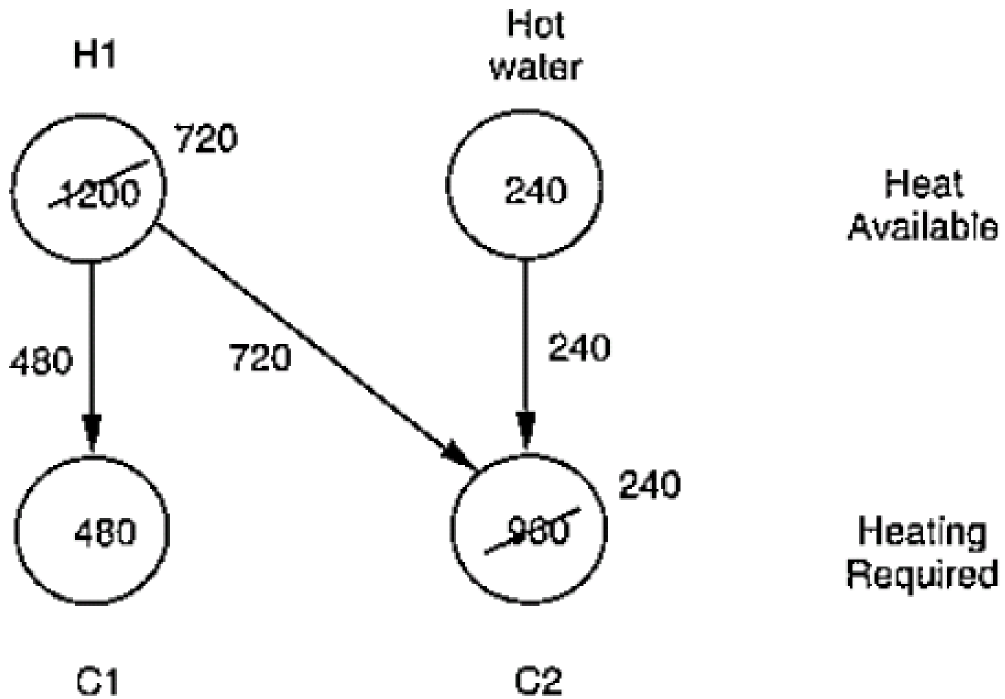


FIGURE 10.3 Flow of heat into and out of intervals for Example 10.1.

Using the partioning data from table 2, create the interval – heat flow diagram as shown in figure 3

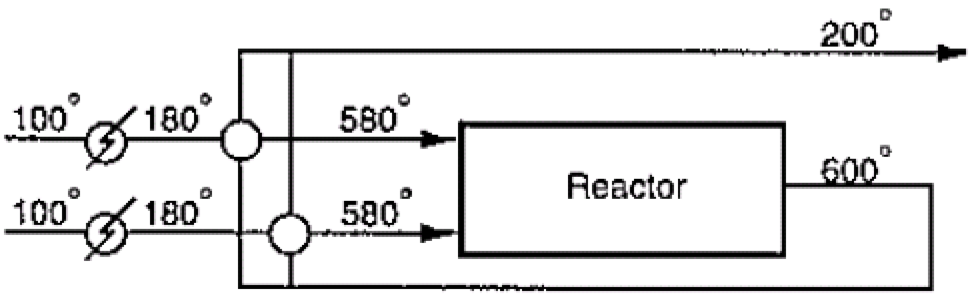
Estimating the fewest matches needed



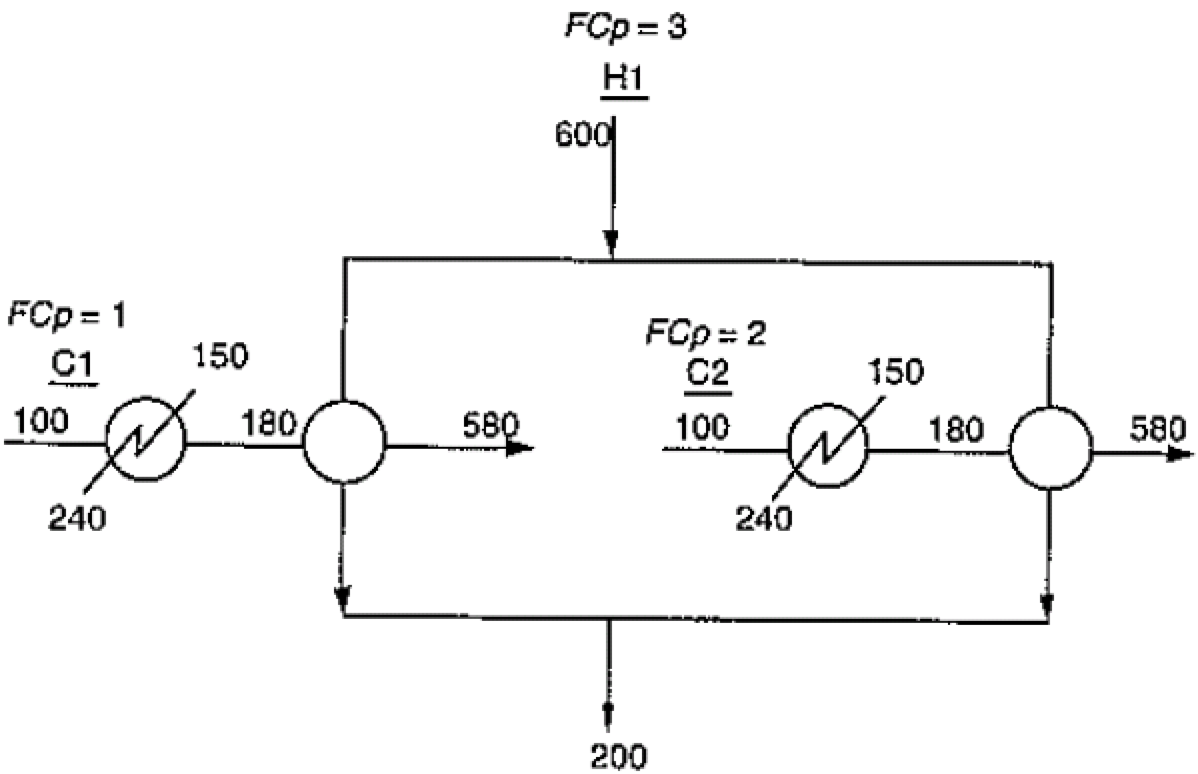
- Place heat source H1 & hot water) nodes at top and heat sink (C1 & C2) nodes at bottom
- **Within the nodes place the heat that needs to be removed or added**
- Assign heat from the largest heat source to the smallest heat sink
- **Repeat the above procedure until all nodes (source-sink) have been matched.**

Note: Minimum number of matches is N-1; N is the number of nodes

Inventing a first solution



This alternative needs only heating at the lower temperature – let us investigate



Can we improve this alternative further?

Discovering and breaking cycles for improvement in HENS

TABLE 10.3 Looking for Cycles in a Network

	HW	H1	Heat into
C1	80–	400+	480
C2	160+	800–	960
Heat from	240	1200	

TABLE 10.4 One Set of Results from Breaking a Cycle

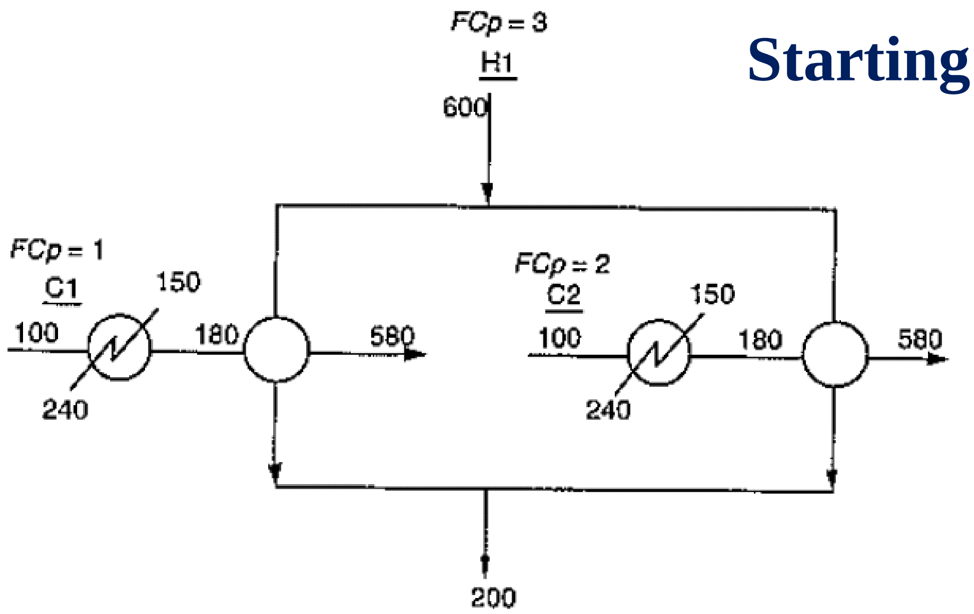
	HW	H1	Heat into
C1	0–	480+	480
C2	240+	720–	960
Heat from	240	1200	

1.Start by creating a matrix with heat source nodes as columns and heat sink nodes as rows
2. Assign in matrix index, the heat added to row from column
3. Sum the heats in each column and in each row
4. Identify cycles from any starting point & mark with symbols (- & + alternately)
5.Add an equivalent heat to the starting index to make it zero

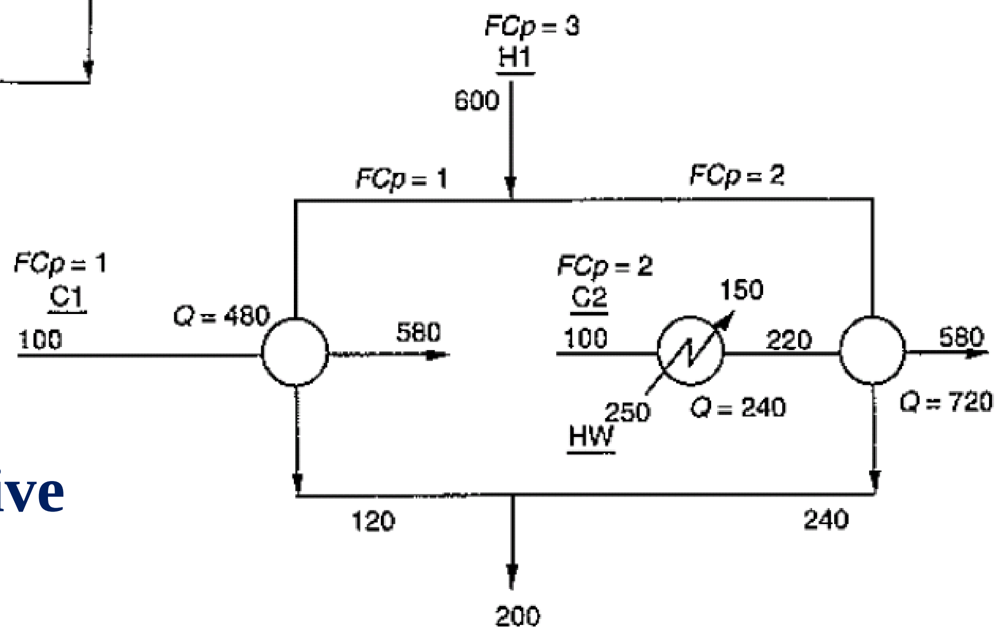
Update heat values in all other rows and columns. Note that totals will remain the same. If a zero is obtained in the cycle, then a loop is broken - that is, one heat exchanger is removed and a new alternative has been obtained.

Check for feasibility of new design alternative

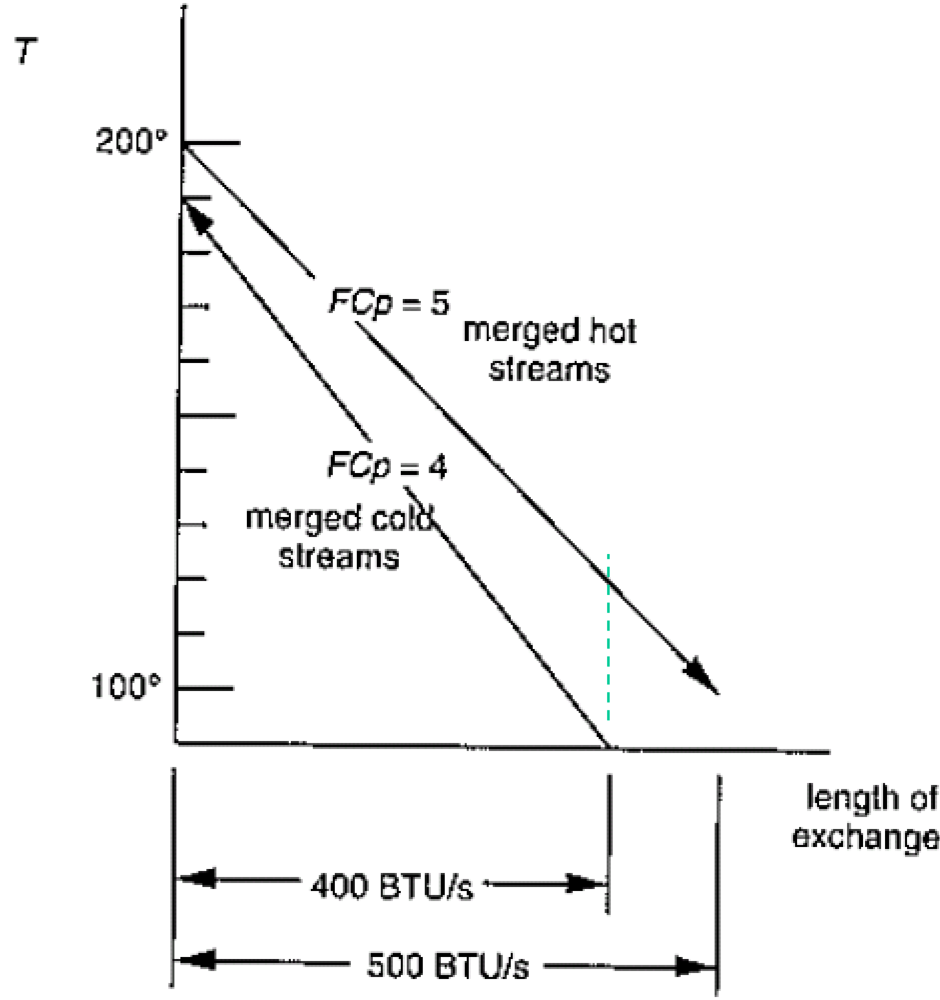
Starting HEN design



New HEN alternative



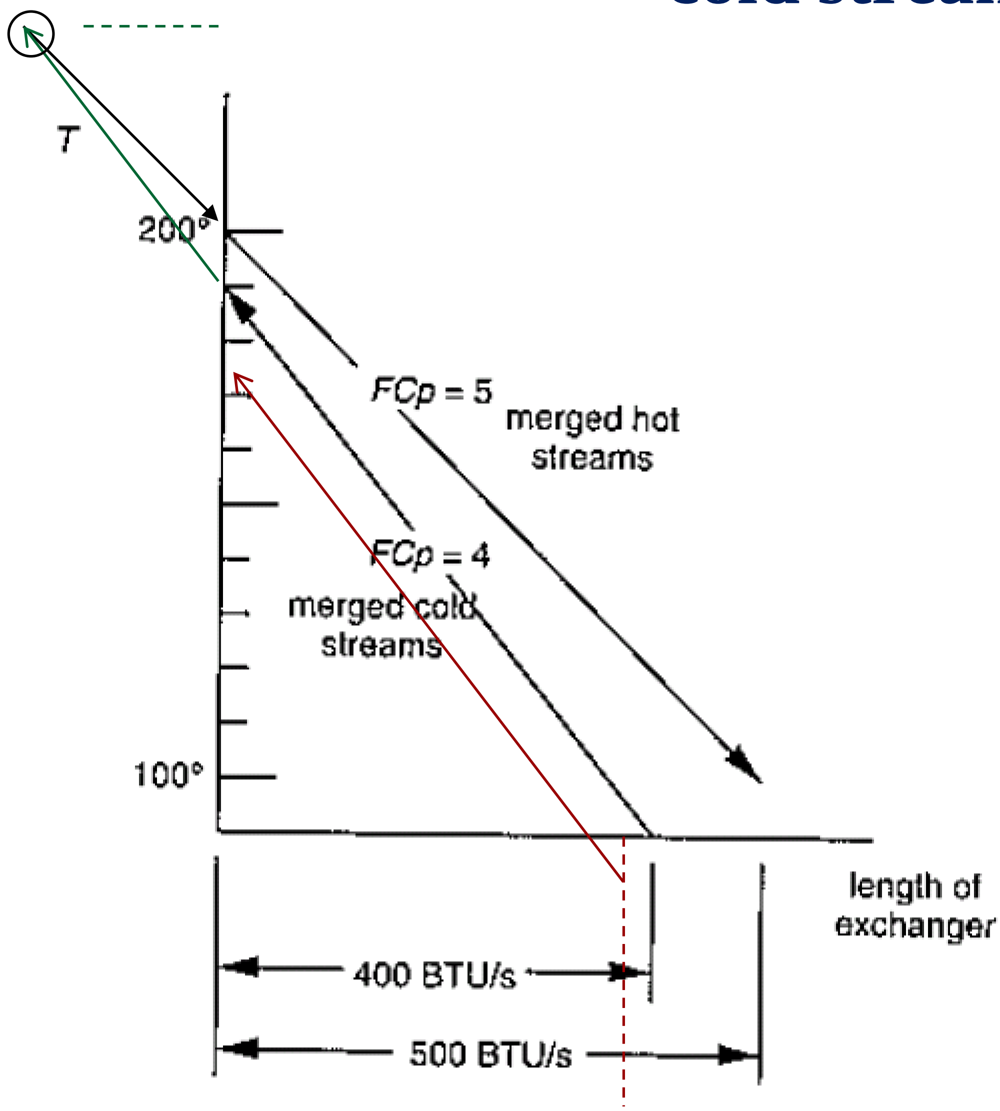
Composite curves (T versus Q plots for hot & cold streams)



- Driving force of 10 F
- One hot stream to be cooled from 200 F to 100 F
- Two cold streams to be heated from 90 F to 190 F
- Hot stream FCp = 500/100= Q/ΔT; cold streams FCp = 4 (therefore, they have same slope if they are merged), FCp of hot stream is larger

Note: at start, ΔT = 10; as more heat is exchanged (moving right), ΔT increases; the hot stream needs extra cooling; heat not transfered is at the cold end

Composite curves (T versus Q plots for hot & cold streams)



Note: at start, ΔT = 10; as more heat is exchanged, ΔT decreases; the hot stream needs less cooling; heat not transfered is at the cold end

What happens if ΔT >10 , or, the starting temperature is > 200 F?

What happens if there are multiple hot and cold streams?

C_1 at FCp = 1 and C_2 at FCP = 3; temperature start & end are the same, or, different?

Composite curves : Merging of streams

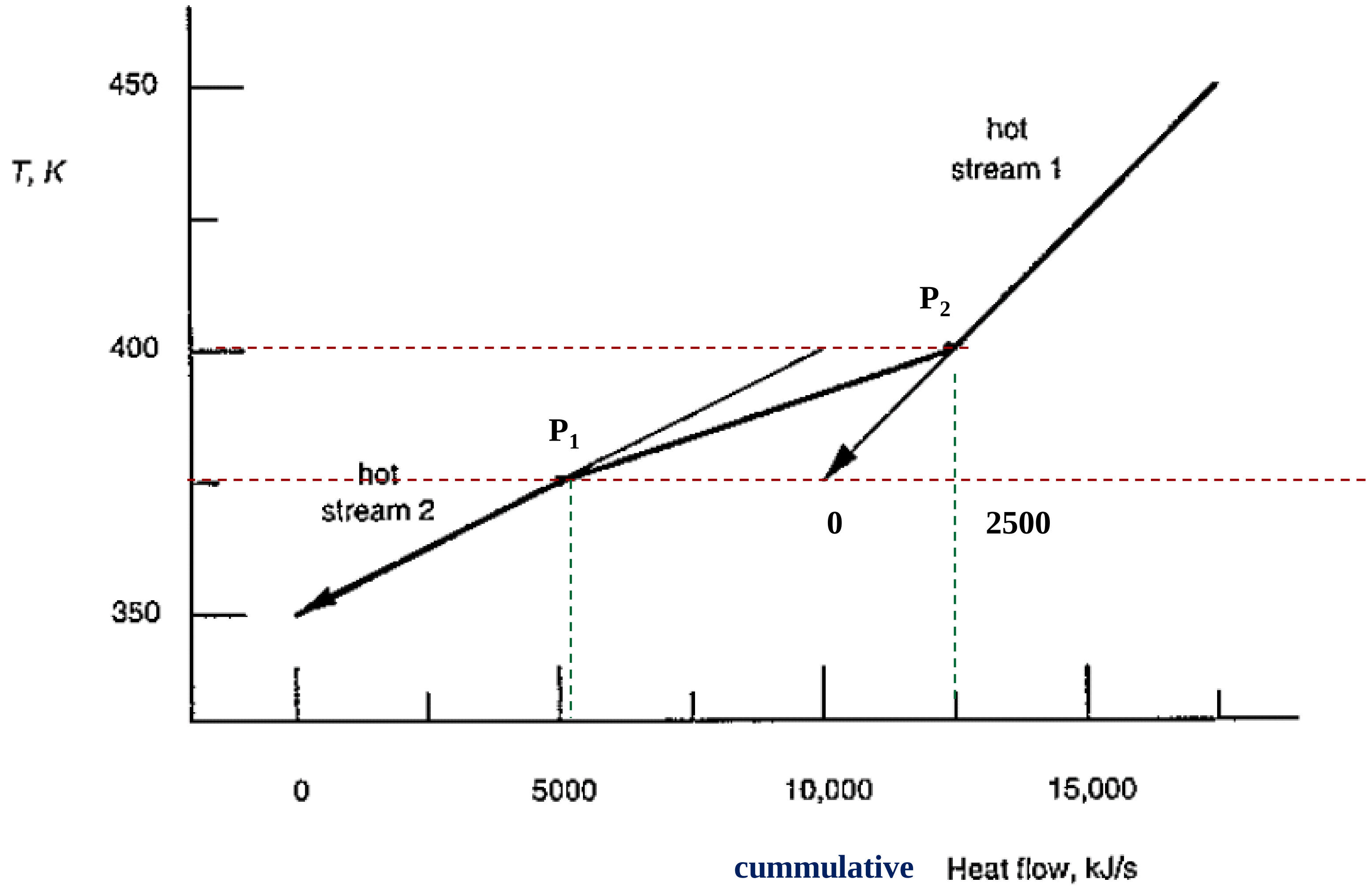
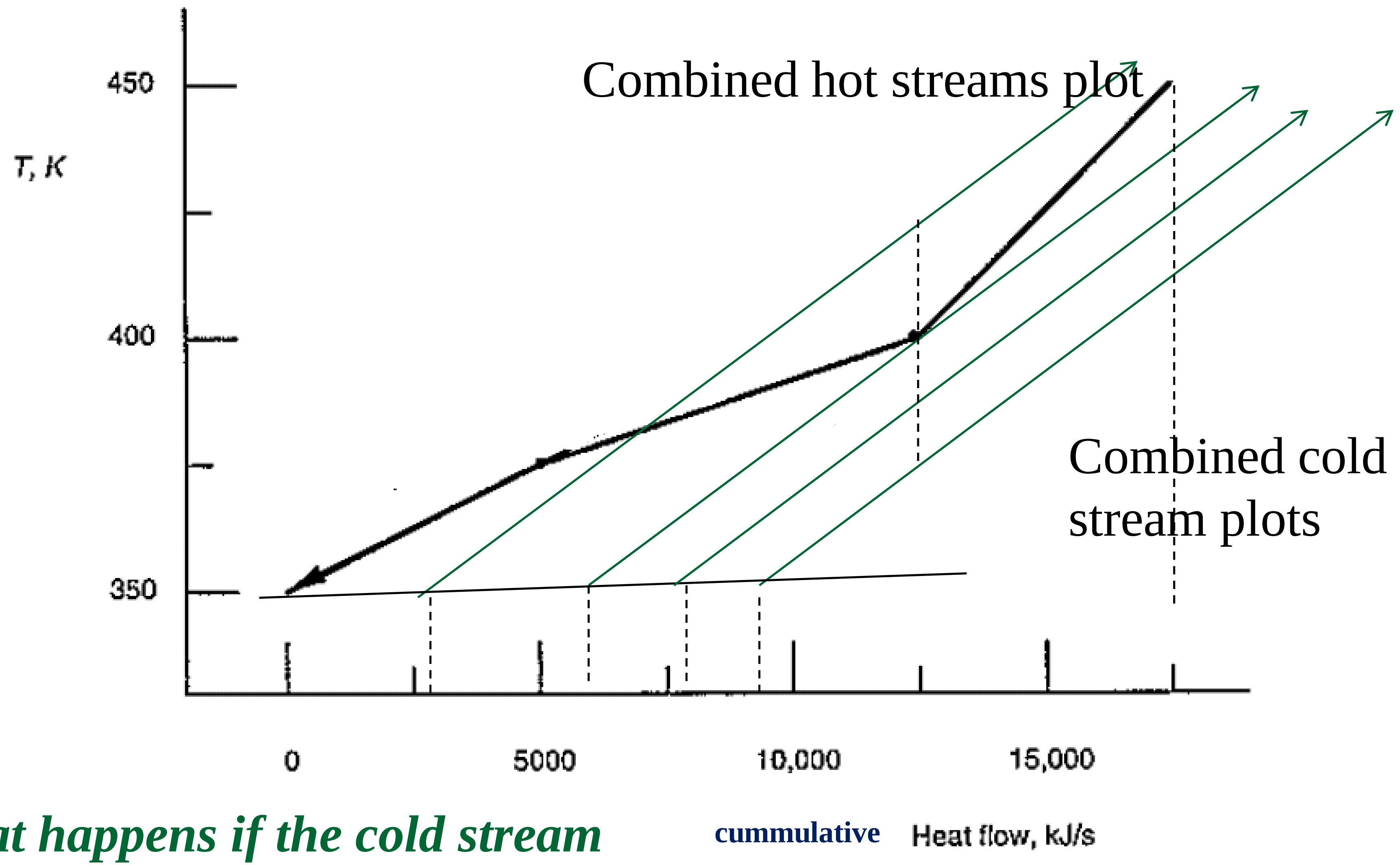


FIGURE 10.9 Merging two hot streams within a common temperature

Composite curves : Merging of streams



What happens if the cold stream plots move to the right or left?

Determination of the pinch-point and the minimum utilities requirements for the HENS

EXAMPLE 10.2 HENS Problem 4SP1

The literature contains several test problems for testing the effectiveness of heat exchanger network synthesis algorithms. Problem 4SP1 (four stream problem number 1) is one of them. We shall use it to illustrate how to use Hohmann/Lockhart composite curves to compute minimum utility use for a heat exchanger network synthesis problem. Table 10.6 gives the data for this problem.

TABLE 10.6 Stream Data for Problem 4SP1

Stream	FCp, kW/°C	T_{in}, °C	T_{out}, °C	Heat flow out, kW
C1	7.62	60	160	−762.0
C2	6.08	116	260	−875.5
H1	8.79	160	93	588.9
H2	10.55	249	138	1171.1

Create a grand composite table – that is, apply the tabular method

Creating Table 10.7: Step 1

TABLE 10.6 Stream Data for Problem 4SP1

Stream	FCp, kW/°C	T_{in}, °C	T_{out}, °C	Heat flow out, kW
C1	7.62	60	160	−762.0
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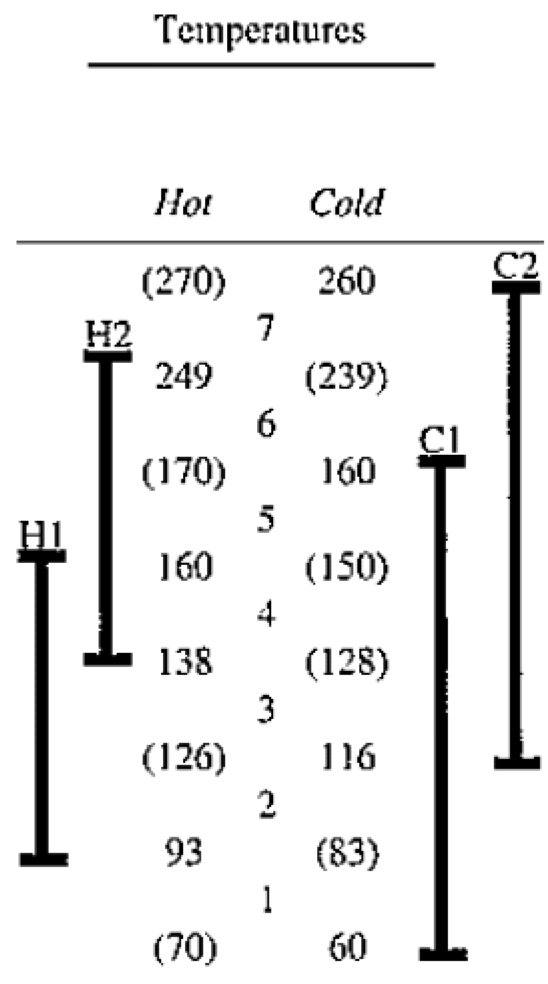
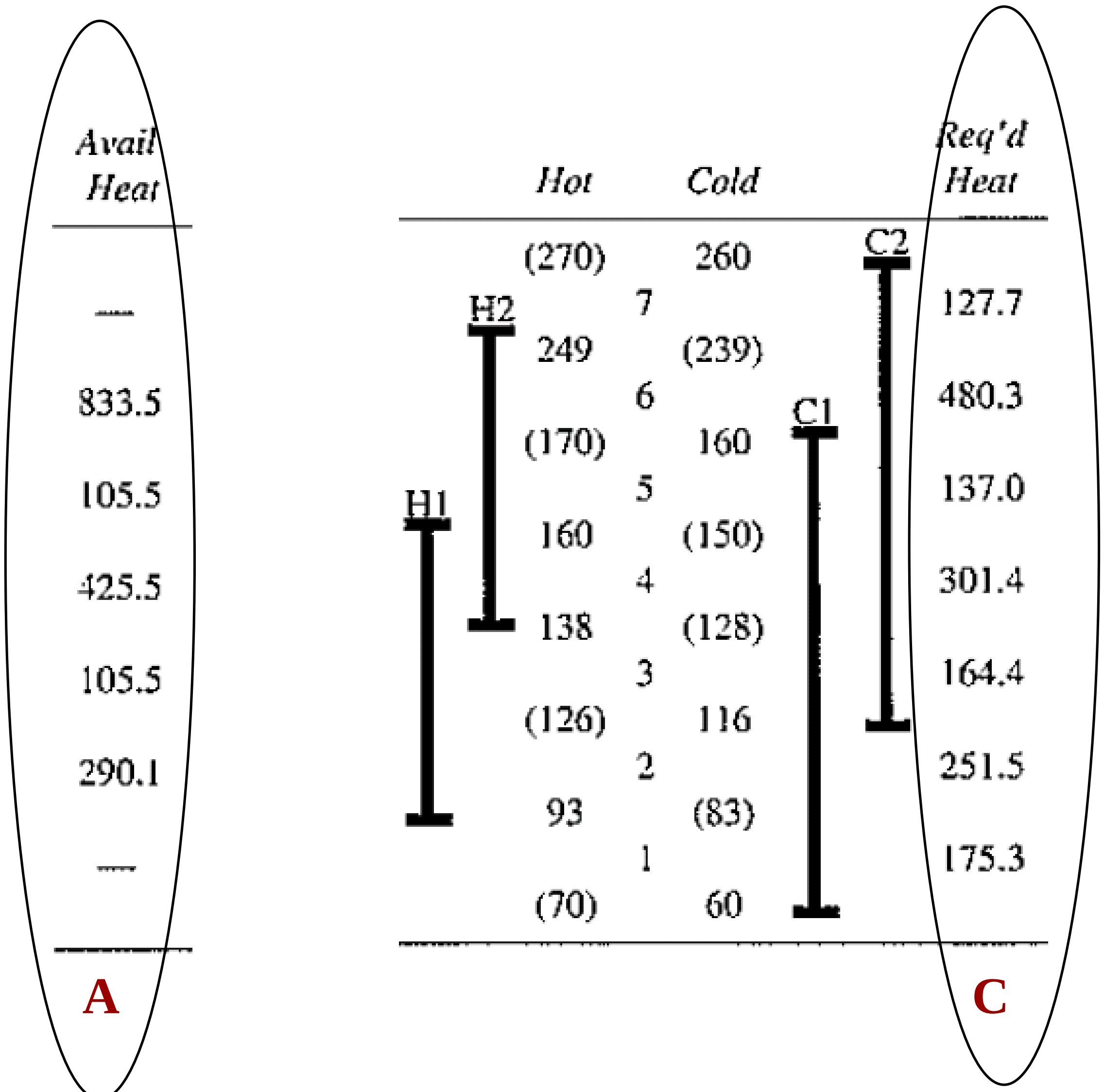


$\Delta T = 10^{o}$ C

- Create the list of intervals as shown on the right
- First use the given temperatures from table 10.6 and then either add or subtract ΔT to find the number (x)
- Draw vertical lines showing the stream temperatures

Creating Table 10.7: Step 2



Add column A (for hot stream) and column C (for cold stream)

Columns A & C are the heat contents (available heat - Q) for hot & cold streams

Calculate $Q_i = F\, Cp\, (T_2 - T_1)$ for each interval

$Q_6(\text{hot}) = 10.55 * 79$

$= 833.5$

Creating Table 10.7: Step 3

Composite Hot Streams		Temperatures			Composite Cold Streams	
Avail Heat (A)	*Cas-caded Heat* (B)	*Hot*		*Cold*	*Req'd Heat* (C)	*Casc'd Heat* (D)
		(270)		260		0.0
—			7		127.7	
	0.0	249		(239)		127.7
833.5			6		480.3	
	833.5	(170)		160		608.0
105.5			5		137.0	
	939.0	160		(150)		745.0
425.5			4		301.4	
	1364.5	138		(128)		1046.4
105.5			3		164.4	
	1470.0	(126)		116		1210.8
290.1			2		251.5	
	1760.1	93		(83)		1462.3
—			1		175.3	
	1760.1	(70)		60		1637.6

Add columns B (hot) and D (cold)

Start from top (N-1 is the top row for interval i on each side); i is the interval corresponding to rows N and N-1

$B_N = B_{N-1} + A_i$

$D_N = D_{N-1} + C_i$

Repeat for all i

Creating Table 10.7: Step 4

Composite Hot Streams		Temperatures			Composite Cold Streams		Gra: Hot ar
Avail Heat	*Cas-caded Heat*	*Hot*		*Cold*	*Req'd Heat*	*Casc'd Heat*	*Net Heat*
		(270)		260		0.0	
—			7		127.7		−127.7
	0.0	249		(239)		127.7	
833.5			6		480.3		353.1
	833.5	(170)		160		608.0	
105.5			5		137.0		−31.5
	939.0	160		(150)		745.0	
425.5			4		301.4		124.1
	1364.5	138		(128)		1046.4	
105.5			3		164.4		−58.9
	1470.0	(126)		116		1210.8	
290.1			2		251.5		38.6
	1760.1	93		(83)		1462.3	
—			1		175.3		−175.3
	1760.1	(70)		60		1637.6	
A	**B**				**C**	**D**	**E**

Add the column E, which is the grand composite net heat, defined as,

Starting from the top interval

$$E_i = A_i - C_i$$

Repeat for all i

Creating Table 10.7: Step 5

Composite Hot Streams		Temperatures			Composite Cold Streams		Grand Compo… Hot and Cold St…	
Avail Heat	*Cas-caded Heat*	*Hot*		*Cold*	*Req'd Heat*	*Casc'd Heat*	*Net Heat*	*Casc'd Heat*
		(270)		260		0.0		0.0
—			7		127.7		−127.7	
	0.0	249		(239)		127.7		−127.7
833.5			6		480.3		353.1	
	833.5	(170)		160		608.0		225.4
105.5			5		137.0		−31.5	
	939.0	160		(150)		745.0		193.9
425.5			4		301.4		124.1	
	1364.5	138		(128)		1046.4		318.0
105.5			3		164.4		−58.9	
	1470.0	(126)		116		1210.8		259.1
290.1			2		251.5		38.6	
	1760.1	93		(83)		1462.3		297.7
—			1		175.3		−175.3	
	1760.1	(70)		60		1637.6		122.4
A	**B**				**C**	**D**	**E**	**F**

Add the column F, which is the grand composite cascade net heat, defined as,

Starting from the top

$$F_N = B_N - D_N$$
$$= F_{N-1} + E_i$$

Repeat for all i

Creating Table 10.7: Step 6

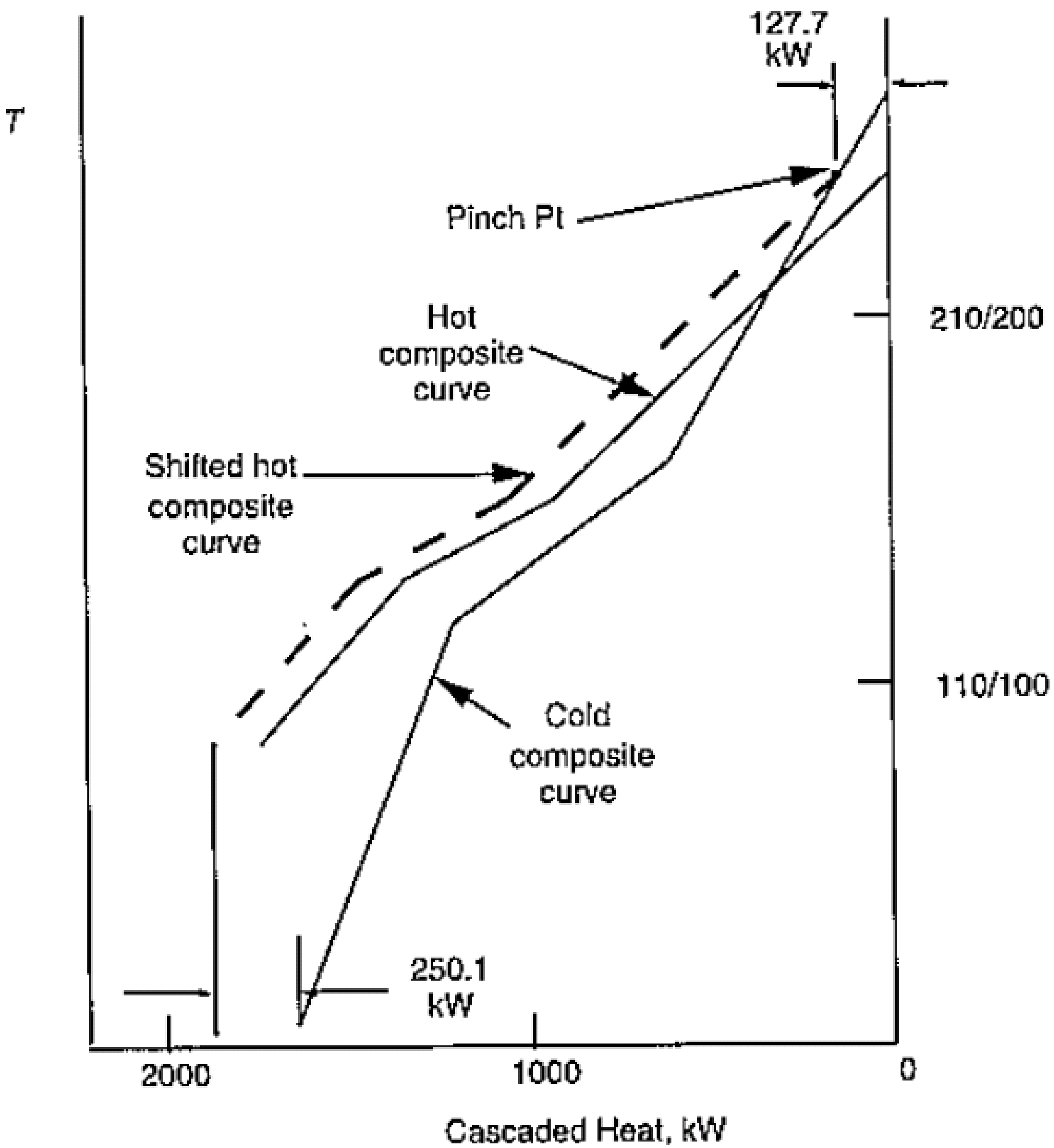
Composite Hot Streams		Temperatures			Composite Cold Streams		Grand Composite Hot and Cold Streams		
Avail Heat	*Cas-caded Heat*	*Hot*	*Cold*		*Req'd Heat*	*Casc'd Heat*	*Net Heat*	*Casc'd Heat*	*Adj Casc'd Heat*
		(270)	260			0.0		0.0	127.7
—				7	127.7		−127.7		
	0.0	249	(239)			127.7		−127.7	0.0
833.5				6	480.3		353.1		
	833.5	(170)	160			608.0		225.4	353.1
105.5				5	137.0		−31.5		
	939.0	160	(150)			745.0		193.9	321.6
425.5				4	301.4		124.1		
	1364.5	138	(128)			1046.4		318.0	445.7
105.5				3	164.4		−58.9		
	1470.0	(126)	116			1210.8		259.1	386.8
290.1				2	251.5		38.6		
	1760.1	93	(83)			1462.3		297.7	425.4
—				1	175.3		−175.3		
	1760.1	(70)	60			1637.6		122.4	250.1

H1 H2 C1 C2

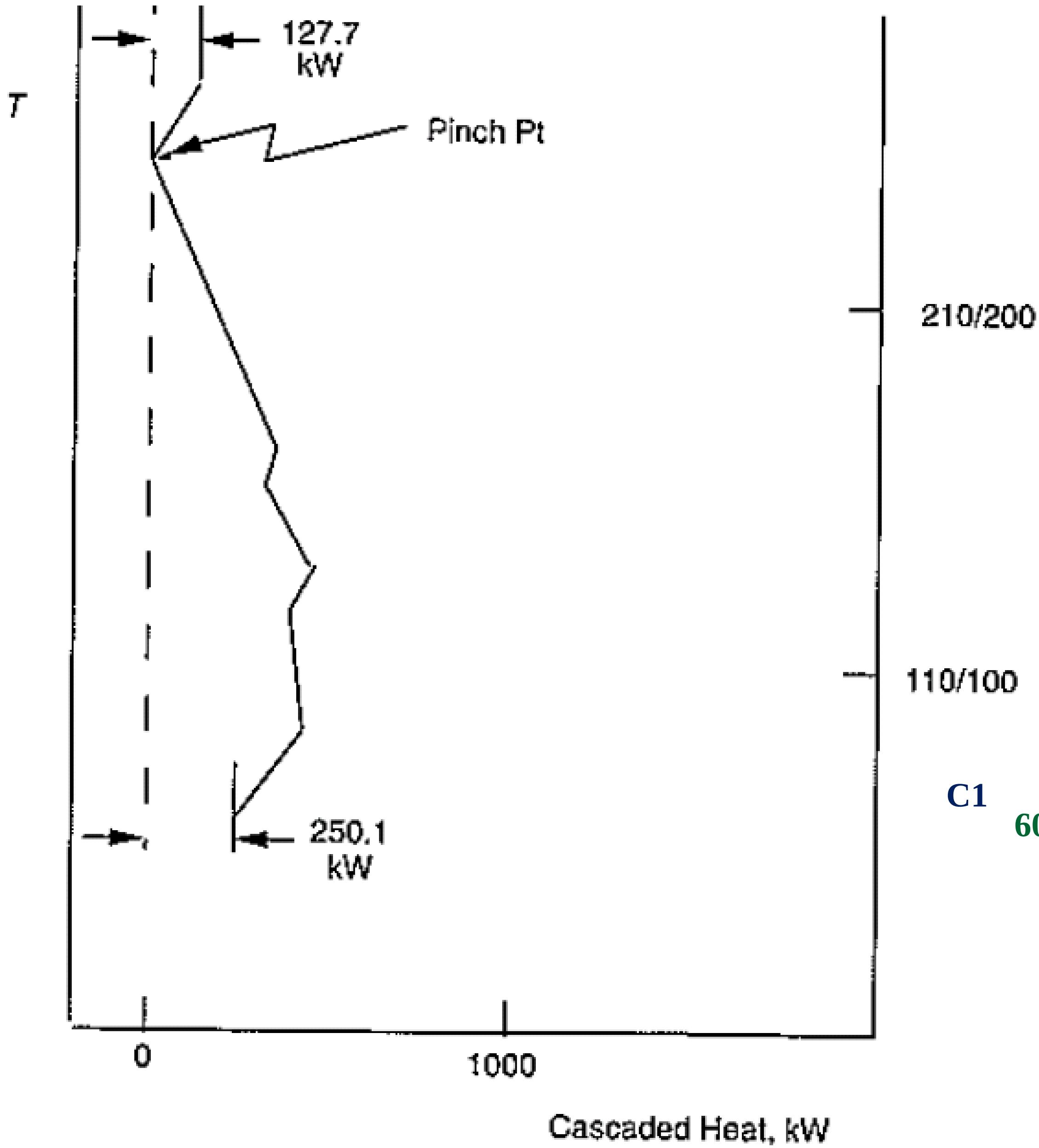
Add

Remove

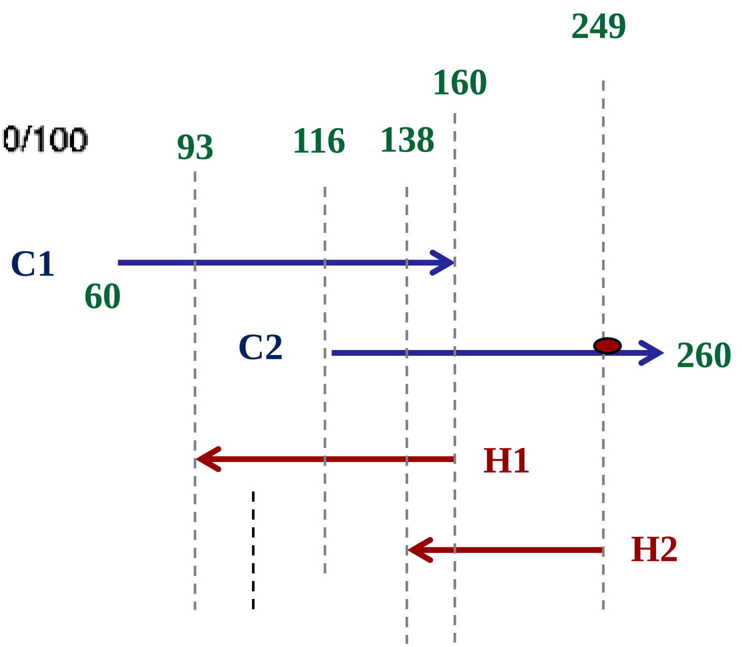
Add the adjascent cascade heat column by removing the –ve sign from column F by adding at the top, the largest –ve value from column F. A zero in any row indicates the pinch point



Plot of the hot & cold composite curves (plots of temperature versus 2nd & 6th columns (cascade heat-cold & cascade heat-hot)



Plot of the grand composite curve (temperature versus the last column from Table 10.7)



Additional notes: Graphical method for pinch point location and minimum utilities prediction

Consider the problem of two hot stream and two cold streams:

Table 1*

Stream No.	Condition	FCp, BTU/(hr°F)	T_{in}	T_{out}	Q available 10^3 BTU/hr
1	Hot	1000	250	120	130
2	Hot	4000	200	100	400
3	Cold	3000	90	150	-180
4	Cold	6000	130	190	-360
					-10

First Law Analysis (Conservation of Energy):

$$Q_1 = F_1 Cp_1 \Delta T_1 = \frac{1000\,BTU}{hr\,^oF}(250-120)^o F = 130x10^3\,BTU/hr$$

$$Q_2 = F_2 Cp_2 \Delta T_2 = \frac{4000\,BTU}{hr\,^oF}(200-100)^o F = 400x10^3\,BTU/hr$$

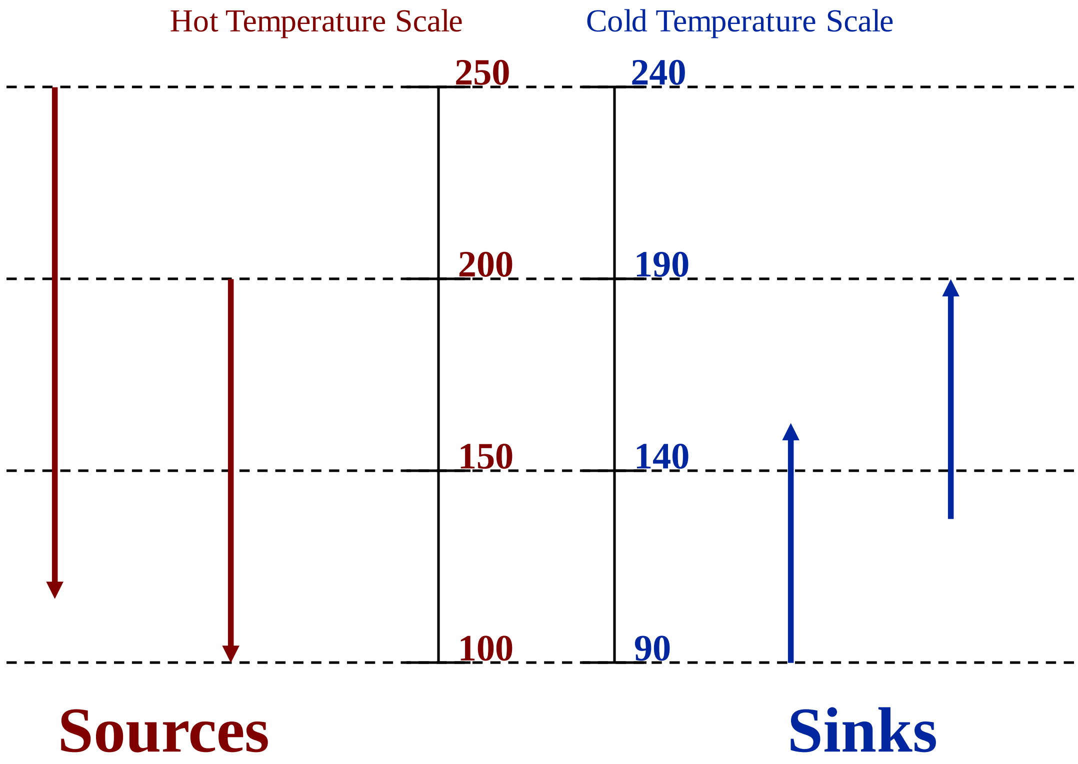
Calculate Q_3 and Q_4

Therefore, 10x10³ BTU/hr must be supplied from utilities (if there are no restrictions on temperature driving force)

How can we check driving force restrictions? Second Law Analysis (You can not transfer heat from a lower temperature to a higher temperature)

***Ref.** Douglas, 1988, Conceptual Design of Chemical Processes, McGraw-Hill Publishers, p. 218.

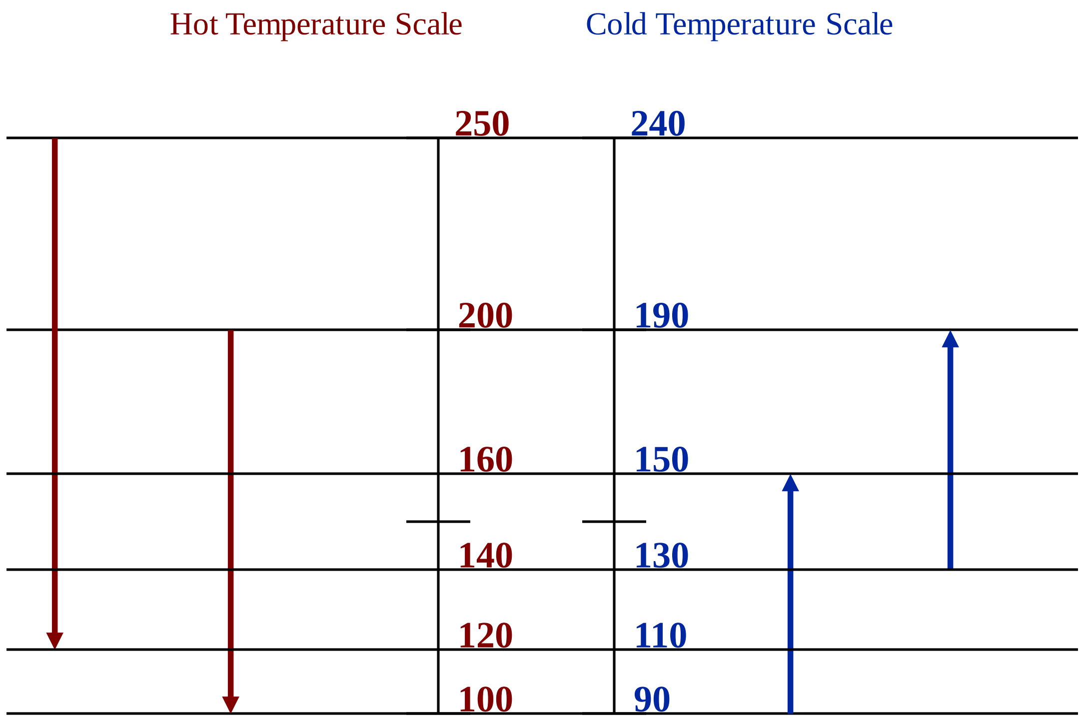
Shifted Temperature Scales *(using Table 1 data):*



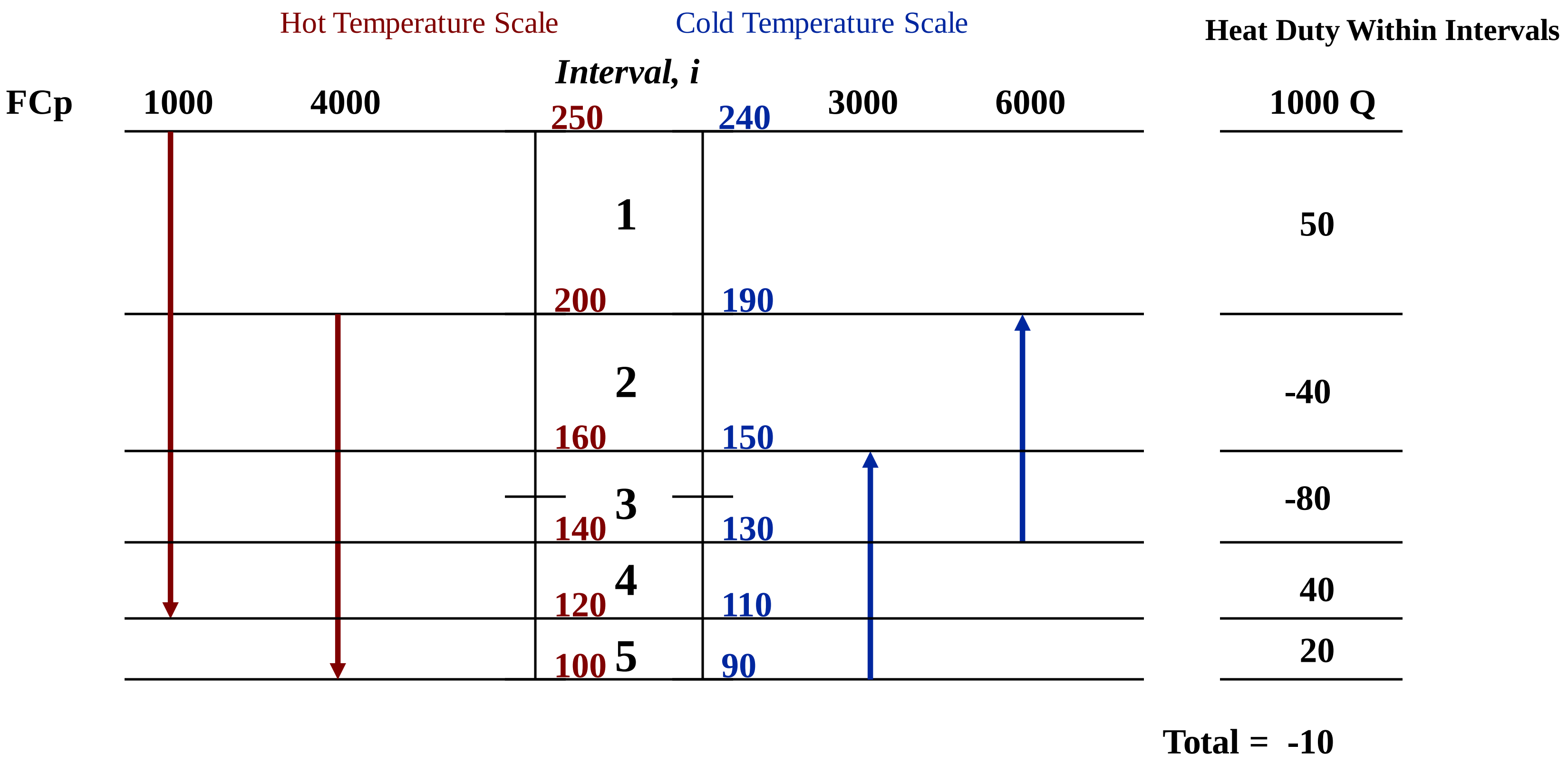
These streams need to be cooled

These streams need to be heated

Temperature Interval Diagram (TID)



Net Energy Required at Each Interval



$$Q_i = \left[\sum (FCp)_{hot,i} - \sum (FCp)_{cold,i}\right]\Delta T_i$$

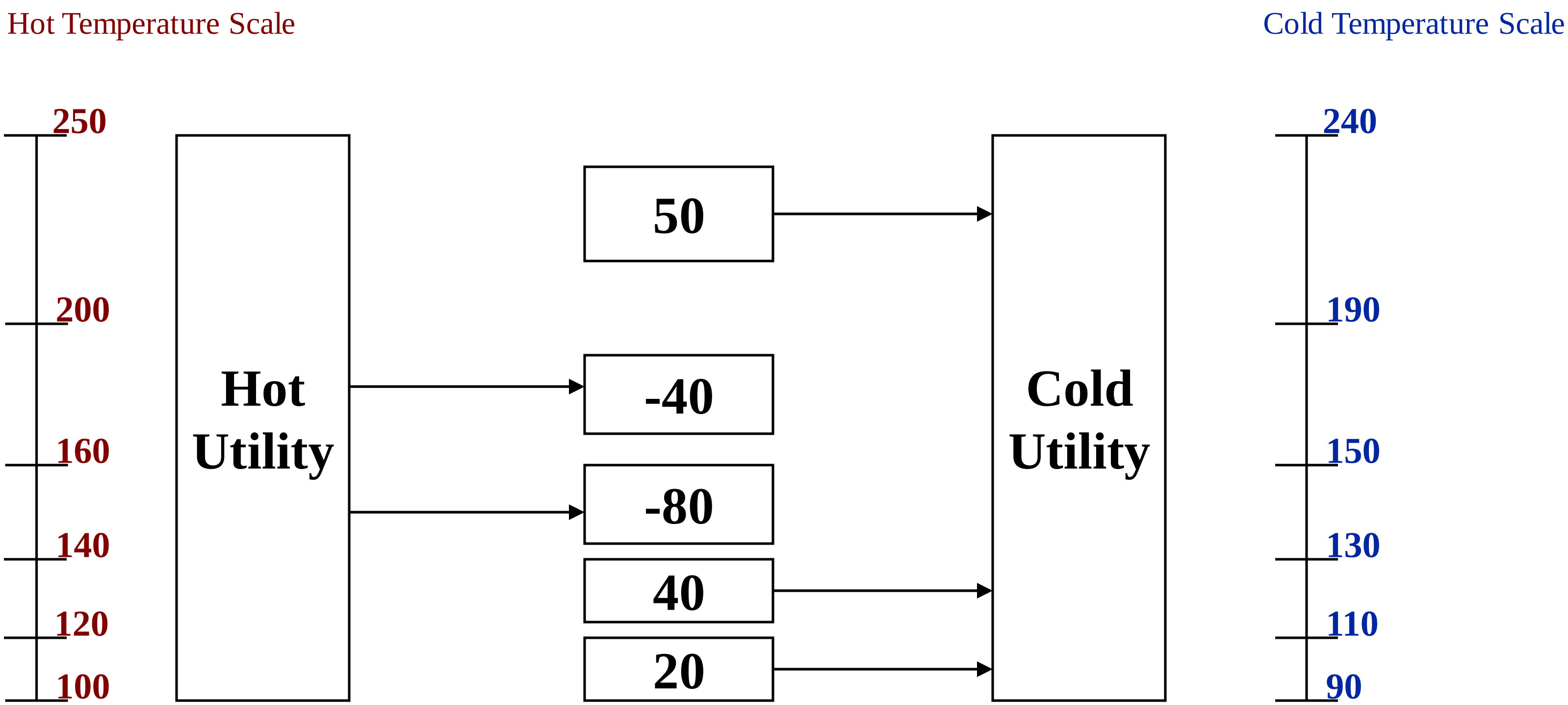
Therefore,

$$Q_1 = (1000)(250-200) = 50x10^3$$

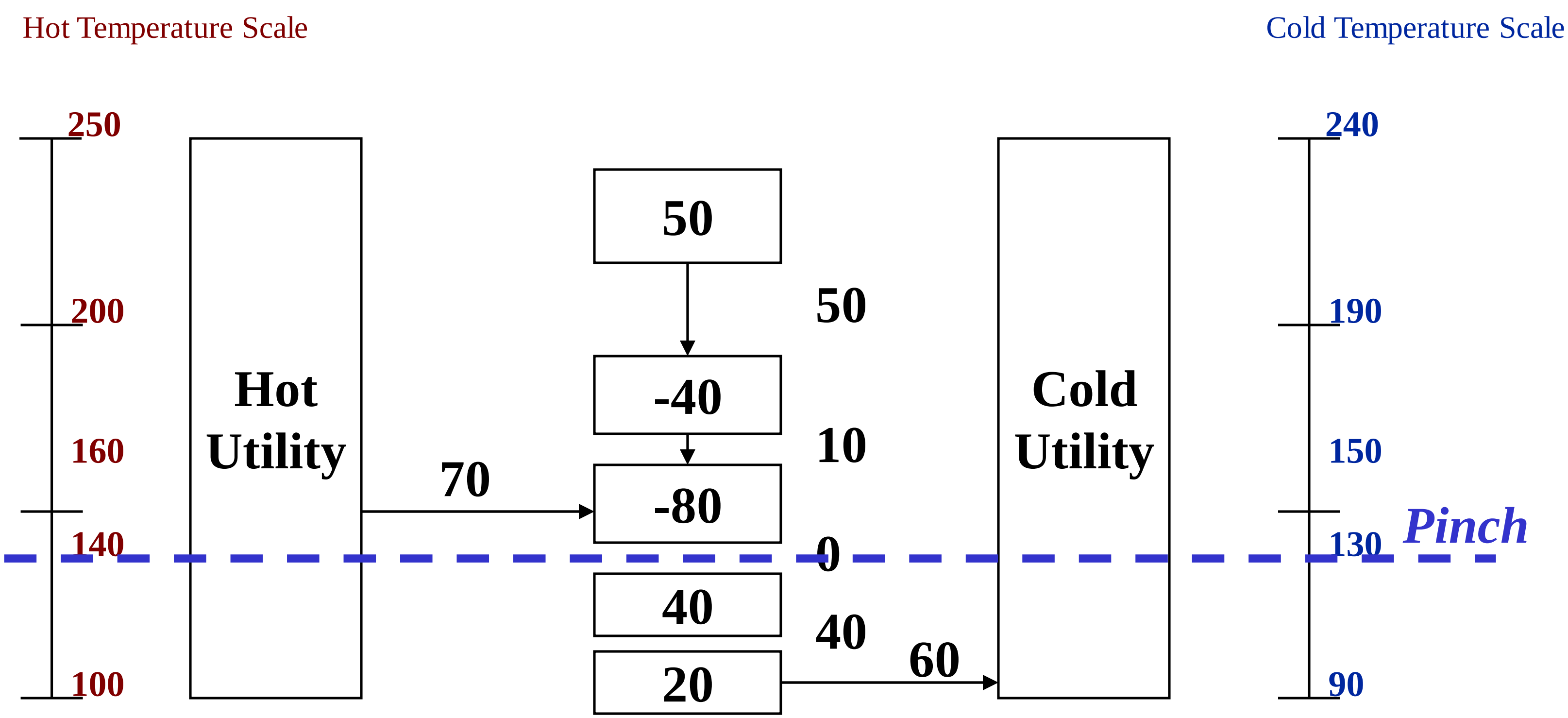
$$Q_2 = (1000+4000-6000)(200-160) = -40x10^3$$

$$Q_3 = (1000+4000-3000-6000)(160-140) = -80x10^3$$

Heat Transfer to and from Utilities for Each Temperature Interval



Cascade Diagram



Hot Composite Curve

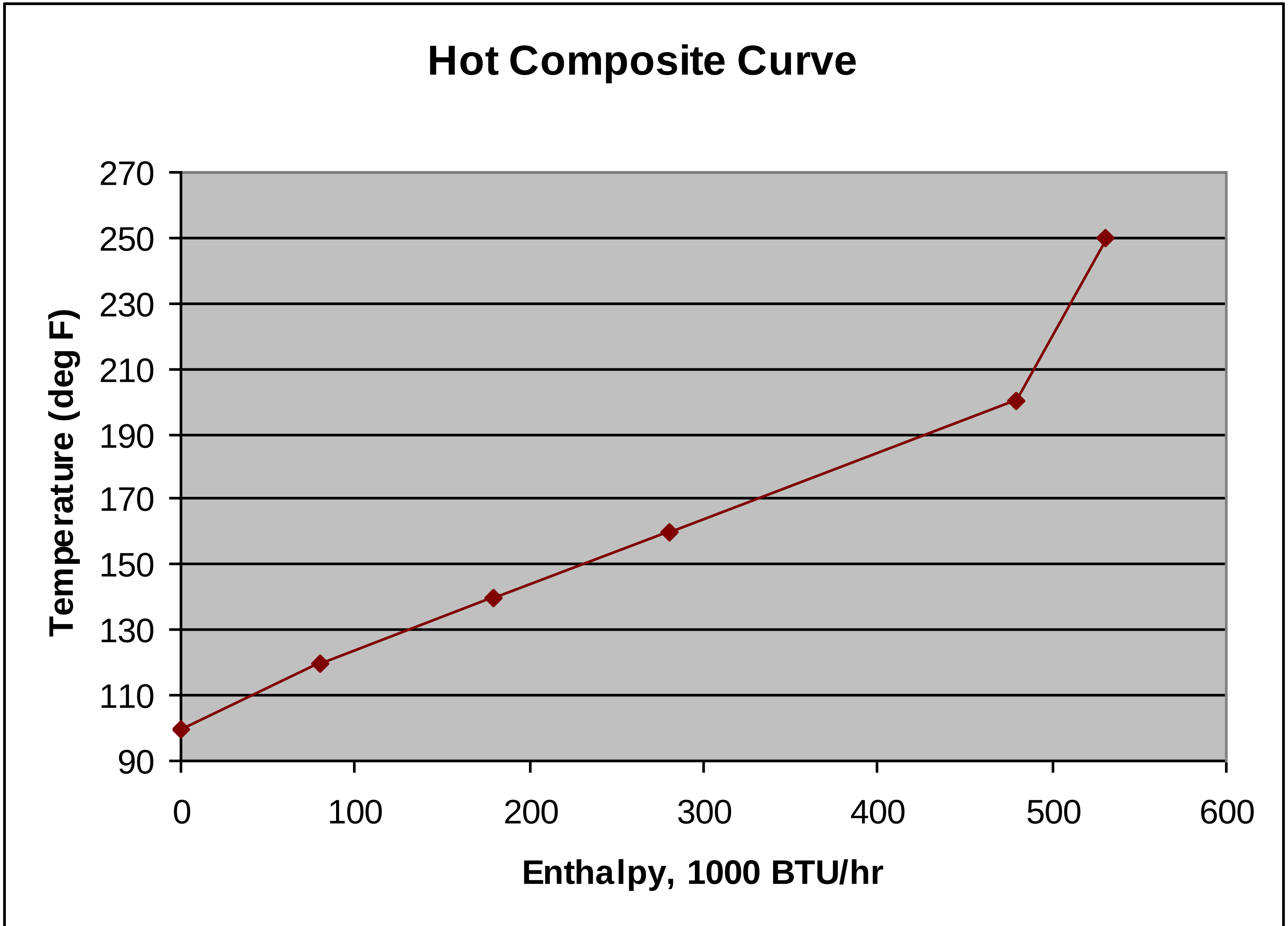
Table 2*

Hot streams, °F		Cumulative H
T=100	H_0=0	0
T=120	H_1=4000(120-100)=80,000	80,000
T=140	H_2=(1000+4000)(140-120)=100,000	180,000
T=160	H_3=(1000+4000)(160-140)=100,000	280,000
T=200	H_4=(1000+4000)(200-160)=200,000	480,000
T=200	H_5=1000(250-200)=50,000	530,000

Since FCp values are constant, we could have replaced the calculation for H_2, H_3, H_4 with a single expression:

$H_{2,3,4}$=(1000+4000)(200-120)=400,000

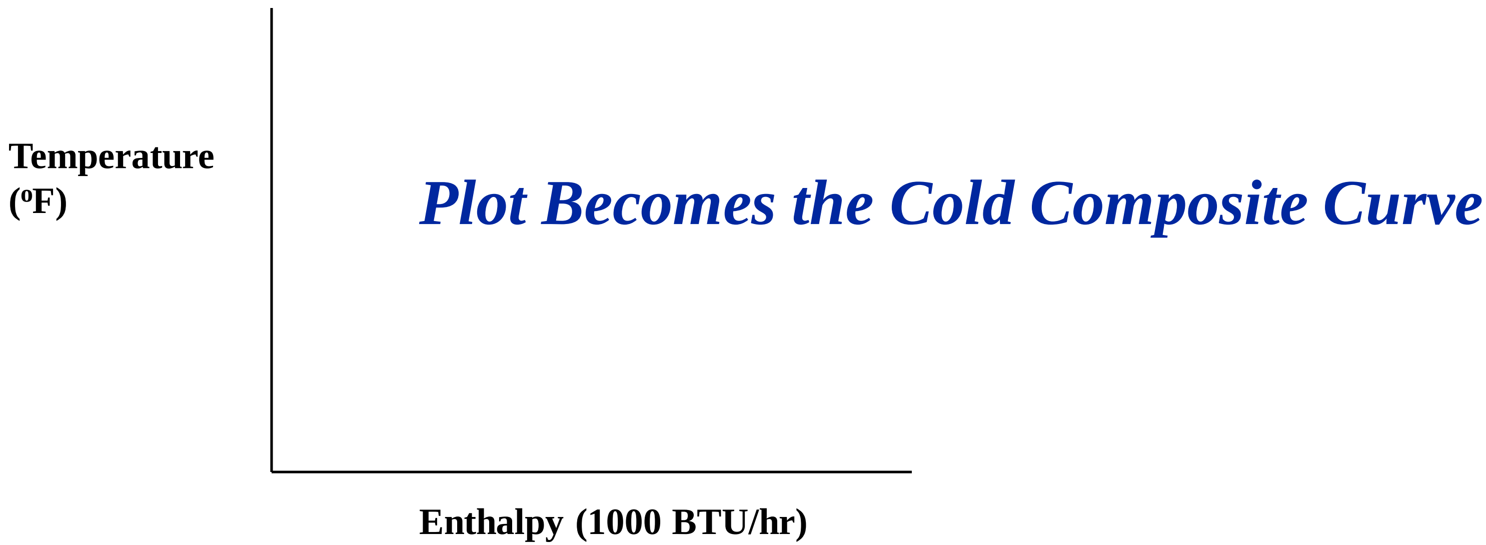
****Ref.*** Douglas, 1988, Conceptual Design of Chemical Processes, McGraw-Hill Publishers, p. 218.


Hot Composite Curve
Temperature (deg F)
270
250
230
210
190
170
150
130
110
90
0
100
200
300
400
500
600
Enthalpy, 1000 BTU/hr

Cold Composite Curve

Table 2.3*

Cold streams, °F		Cumulative H
T=90	H_0=60,000	60,000
T=130	H_1=3000(130-90)=120,000	180,000
T=150	H_2=(3000+6000)(150-130)=180,000	360,000
T=190	H_3=6000(190-150)=240,000	600,000



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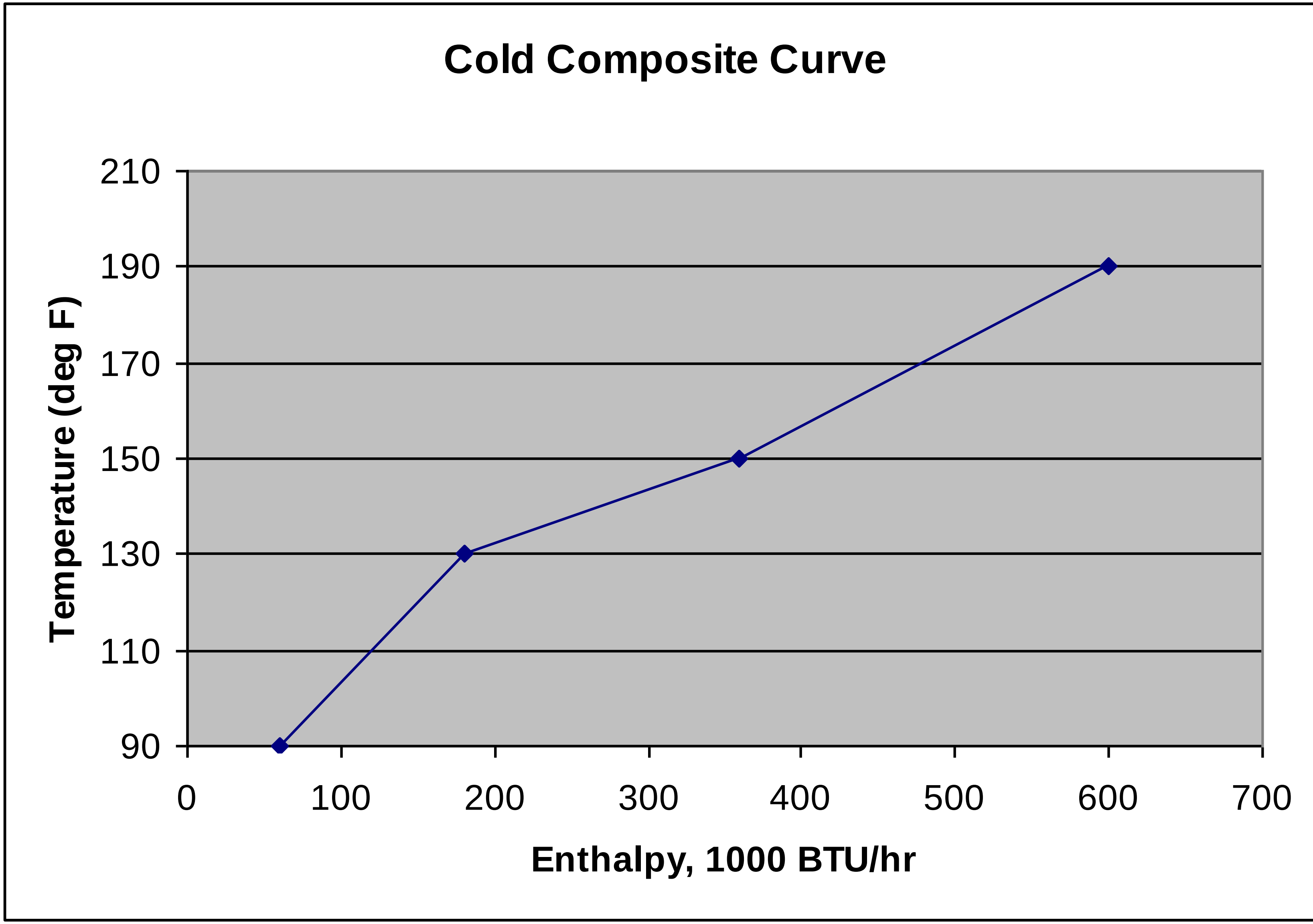
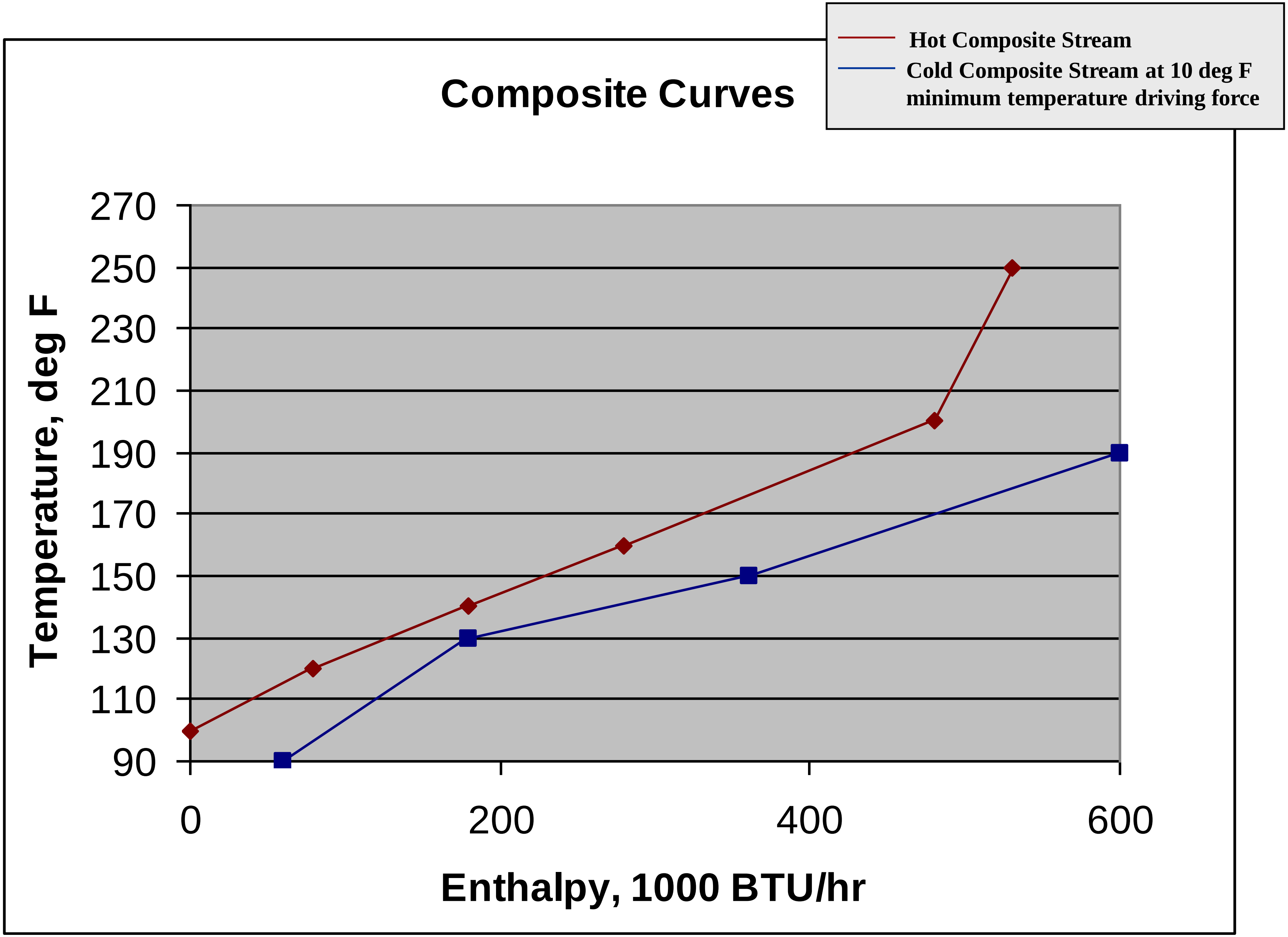
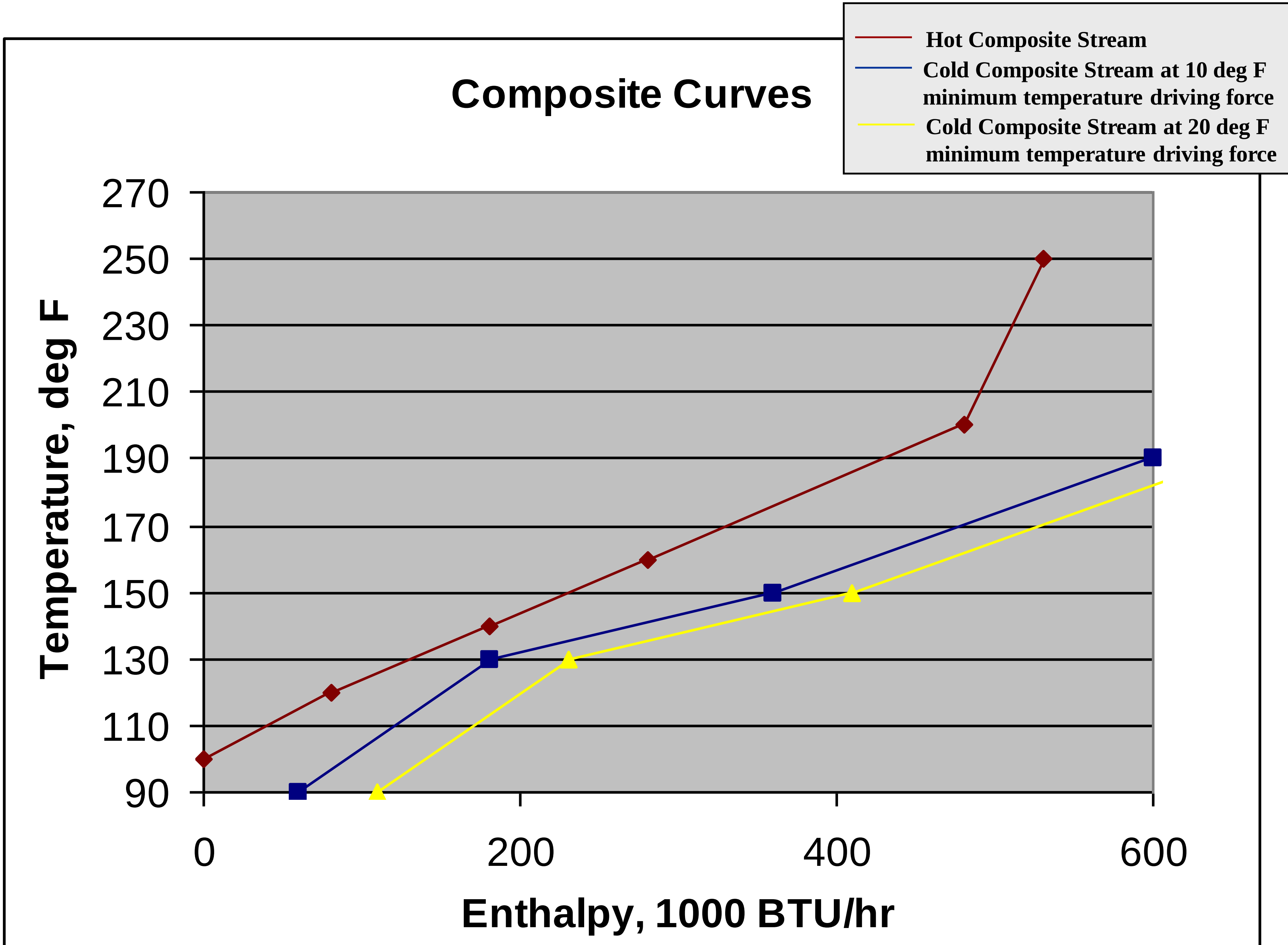

Cold Composite Curve
210
190
170
150
130
110
90
0
100
200
300
400
500
600
700
Temperature (deg F)
Enthalpy, 1000 BTU/hr


Composite Curves
Hot Composite Stream
Cold Composite Stream at 10 deg F minimum temperature driving force
Temperature, deg F
270
250
230
210
190
170
150
130
110
90
0
200
400
600
Enthalpy, 1000 BTU/hr


Composite Curves
Hot Composite Stream
Cold Composite Stream at 10 deg F minimum temperature driving force
Cold Composite Stream at 20 deg F minimum temperature driving force
Temperature, deg F
270
250
230
210
190
170
150
130
110
90
0
200
400
600
Enthalpy, 1000 BTU/hr

Composite "Pinch" Diagram