Improve Energy Efficiency via Heat Integration

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Process heat integration using pinch analysis is a respected tool for achieving energy efficiency. This article explains what pinch analysis is and how to use it in process design and operation to attain real-world energy efficiency gains.

Process integration consists of numerous techniques that allow engineers to evaluate entire processes or sites, rather than focus on individual unit operations. It includes hierarchical design methods, knowledge-based systems, numerical and graphical techniques, and pinch analysis *(1, 2)*. In the area of energy efficiency, pinch methods dominate. Indeed, the terms pinch analysis and process integration (PI) are often used interchangeably.

Fundamentals of pinch analysis

Pinch analysis is a systematic technique for analyzing heat flow through an industrial process based on fundamental thermodynamics. The Second Law of Thermodynamics requires that heat flows naturally from hot to cold objects. This key concept is embodied in the hot and cold composite curves (Figure 1), which represent the overall heat release and heat demand of a process as a function of temperature.

The hot composite curve represents the sum of all the heat sources (hot streams) within the process in terms of heat load and temperature level. Similarly, the cold composite curve represents the sum of all the heat sinks (cold streams) within the process. When these curves are placed together on a single temperature-enthalpy plot (as in Figure 1), it is apparent that heat can be recovered within the process wherever there is a portion of the hot composite curve above a portion of the cold composite curve — that is, heat can flow from a higher-temperature part of the process to a lower-temperature part *(3, pp. 17–31)*. To keep the size of the heat-recovery equipment reasonable, the temperature difference (approach) must be larger than or equal to a defined minimum allowable temperature approach, ΔT_{min}.

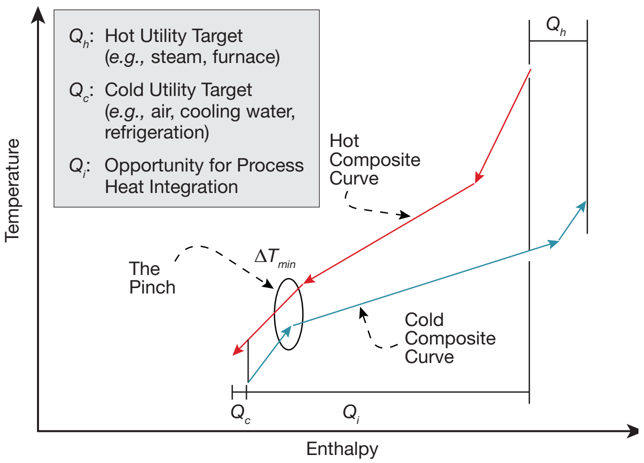
Most processes display a pinch — a region where the curves are separated vertically by ΔT_{min}. The pinch divides the process into two distinct regions:

• above the pinch (*i.e.*, in the higher temperature range) — some heat integration is possible (where the hot composite curve sits above the cold composite curve), but there is a net heat deficit and an external utility heat source (Q_h) is required

• below the pinch (*i.e.*, in the lower temperature range) — some heat integration is possible (where the hot composite curve sits above the cold composite curve), but there is a net heat surplus and an external utility heat sink (Q_c) is required.

The distinction between the net heat source and net heat sink regions is a key characteristic of the pinch approach, and it forms the basis for the pinch principle:

Do not transfer heat across the pinch.



▲ **Figure 1.** Composite curves show the combined heat sources and combined heat sinks in any process as temperature vs. enthalpy plots. The curves can be used to determine how much heat can be recovered by heat integration and how much has to be supplied or removed by external utilities.

This has two corollaries — do not use external (utility) cooling above the pinch, and do not use external (utility) heating below the pinch.

Composite curves and the pinch principle are the most widely recognized pinch tools. Many other pinch-based techniques also assist in process heat integration, such as heat exchanger grid diagrams *(3, pp. 32–35)*, grand composite curves *(3, pp. 52–61)*, and the CP rules *(3, p. 36)*. (CP is the product of flowrate and specific heat capacity. The CP rules dictate when it is feasible to match a given hot stream with a given cold stream, based on their respective CP values.)

Related tools and techniques include algorithms to define the trade-off between energy consumption and capital investment, as well as pressure drop trade-offs in heat recovery, distillation column optimization, and total site analysis *(4)*. Many of the more recent developments in pinch analysis have focused on the management of material resources, such as water and wastewater *(5, 6)* and hydrogen *(7)*. The primary purpose of this article, however, is to show how simple pinch techniques can be applied to real world problems to improve energy efficiency, as illustrated in the following example.

Retrofit pinch procedure

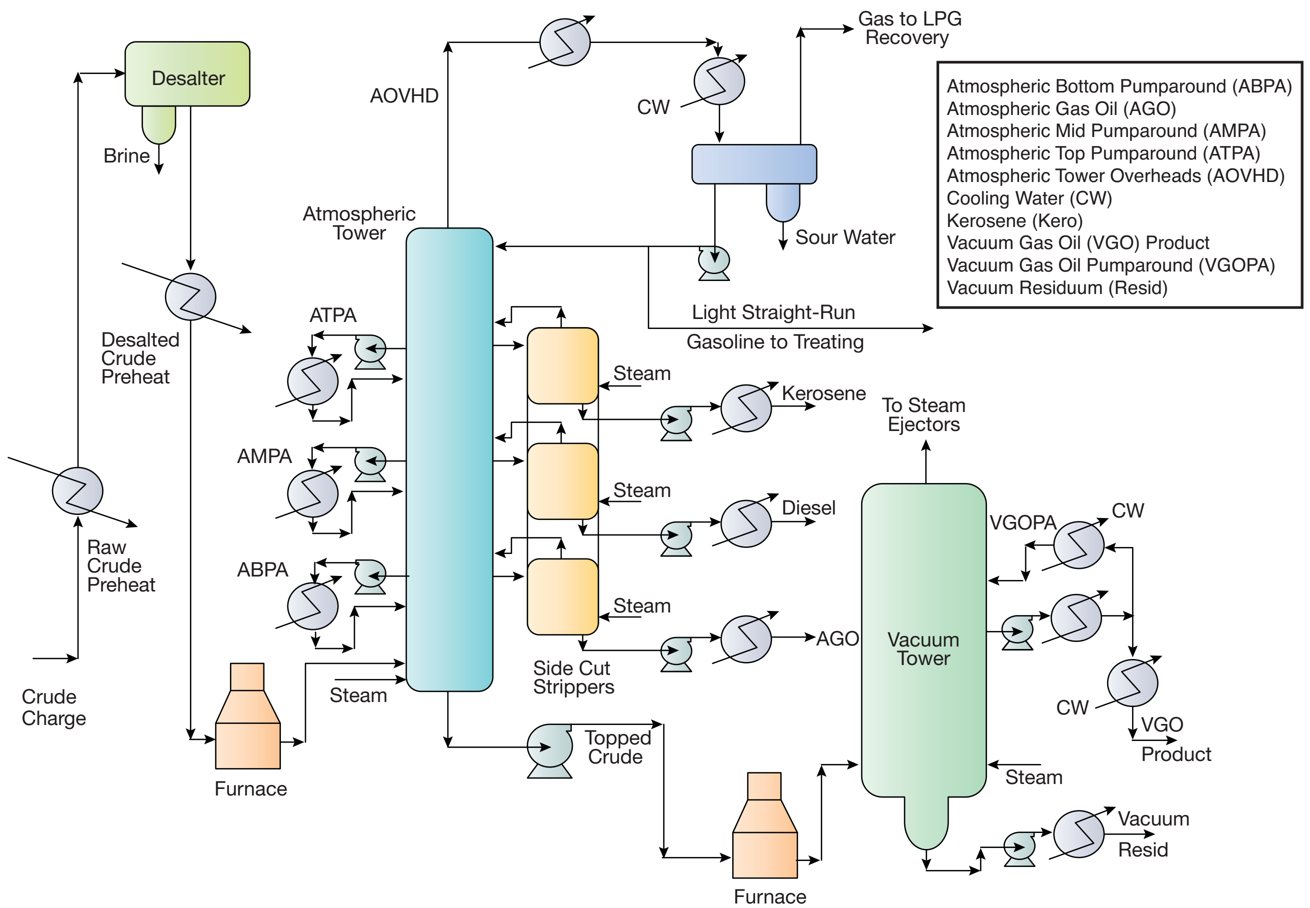
Pinch analysis was initially developed for new plant designs. For retrofit work, the techniques need to be modified. The key difference is that in retrofit situations, the revamp must take into account existing equipment and plot space, whereas the designer of a new plant has the flexibility to add or delete equipment at will.

Many different approaches to retrofit pinch analysis are possible. The example discussed here uses one of the simplest:

1. Obtain data.
2. Generate energy targets and utility targets.
3. Identify major inefficiencies in the existing heat exchanger network.
4. Define options for reducing or eliminating the largest inefficiencies.
5. Evaluate options.
6. Select the best option or combination of options.

Retrofitting an oil refinery's crude distillation unit

This example describes the steps required to carry out a retrofit pinch analysis of a 90,000-bbl/d crude distillation unit



▲ **Figure 2.** The crude distillation unit uses both an atmospheric tower and a vacuum tower to fractionate crude oil. Pumparounds are used to control cut points and remove heat at the highest practical temperature levels.

(CDU) that includes both atmospheric and vacuum towers. The process flow diagram in Figure 2 shows the main process streams, equipment items, and heaters and coolers in relation to the heat recovery network, and Figure 3 gives details of the crude preheat train.

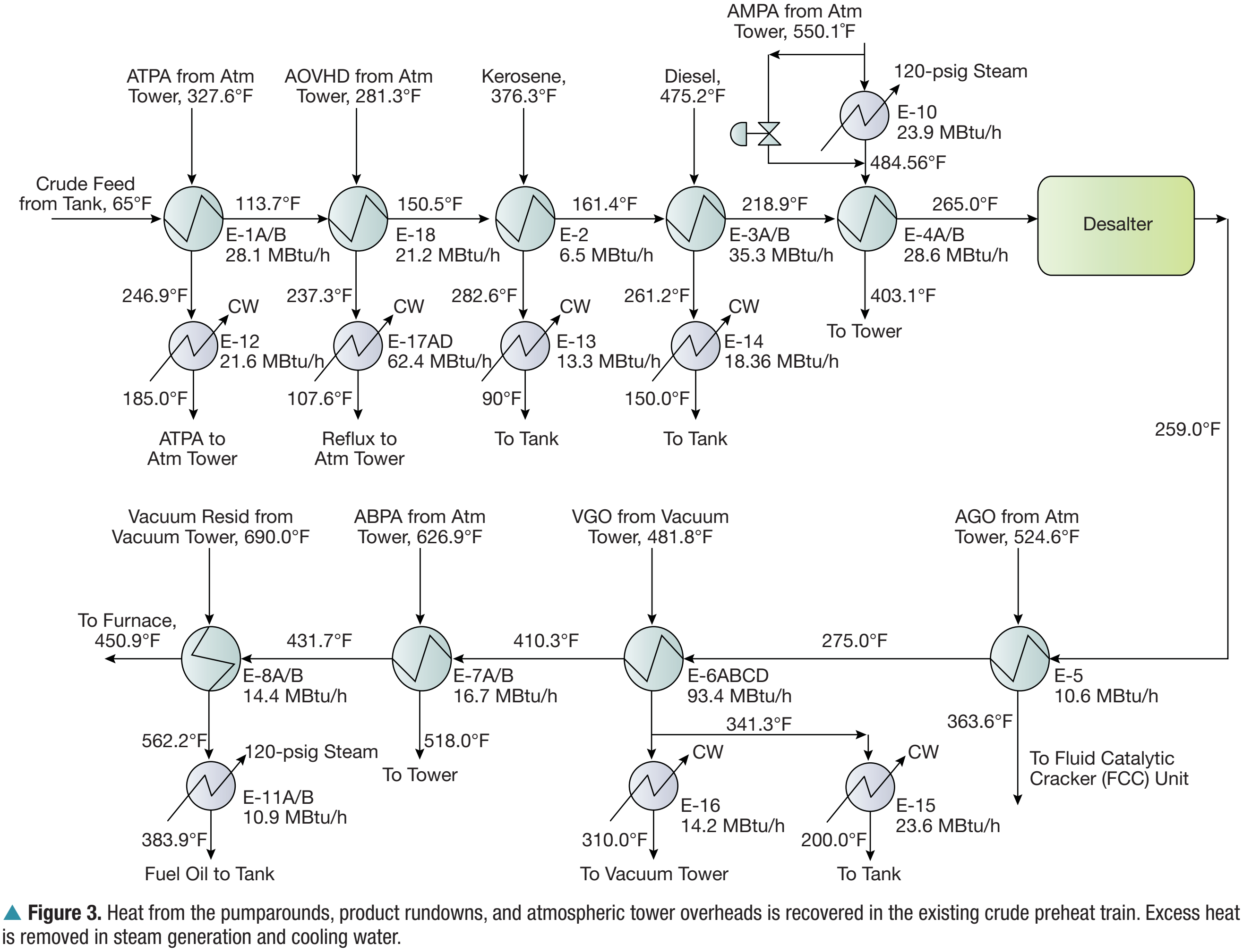
The first major processing units in a refinery *(8)*, CDUs separate crude oil by distillation into fractions based on boiling range. The separation is generally performed in two steps (Figure 2). First, the raw crude oil is fractionated at close to atmospheric pressure in an atmospheric tower. Then, the high-boiling bottom fraction (topped crude or atmospheric reduced crude) from the atmospheric tower goes to a second fractionator (vacuum tower) operating at high vacuum, which is generally provided by steam ejectors. A vacuum is used because the high temperatures required to vaporize topped crude at atmospheric pressure would cause thermal cracking.

The products from the CDU include the overheads, bottoms, and sidestreams from the two towers. Some of the fractions, especially those drawn as side cuts from the atmospheric tower, contain excessive amounts of low-boiling components that have to be removed by steam stripping in order to meet specifications.

The fractionation process requires a large amount of energy. The highest-temperature heat input is provided by feed furnaces. Lower-temperature heat invariably comes from a network of exchangers that recover heat to preheat the crude oil.

The heat sources to the crude preheat train in this example include the atmospheric tower overheads (AOVHD) and product rundown streams: kerosene (Kero), diesel, atmospheric gas oil (AGO), vacuum gas oil (VGO) product, and vacuum residuum (Resid).

In addition, the atmospheric and vacuum towers have pumparound circuits, specifically the atmospheric top pumparound (ATPA), atmospheric middle pumparound (AMPA), vacuum gas oil pumparound (VGOPA), and atmospheric bottom pumparound (ABPA). These pumparounds provide a mechanism for removing heat from the towers at intermediate temperature levels, rather than taking all of the distillation heat out in the overheads. The amount of heat that can be removed in each pumparound is governed by the cut



▲ **Figure 3.** Heat from the pumparounds, product rundowns, and atmospheric tower overheads is recovered in the existing crude preheat train. Excess heat is removed in steam generation and cooling water.

points required for the various fractions. Most of the pumparound heat is used to preheat the crude feed, and excess heat from the pumparounds is either used to generate steam or rejected to cooling water.

The VGO product and the VGO pumparound streams are combined through the preheat train, and are only split into separate streams downstream of exchanger E-6ABCD.

Another important component of most CDUs is the desalter. Raw crude oil contains inorganic salts, metals and various organic compounds that can cause fouling, corrosion and catalyst deactivation in downstream equipment. These undesirable materials are removed to acceptable levels by adding water (typically 3%–10% by volume) and separating the aqueous and oily phases in the desalter vessel. This also removes suspended solids from the oil. The desalter typically operates at about 270°F, so it is placed partway through the preheat train.

Step 1. Obtain data

The most important data for a pinch study are the heat loads and temperatures for all of the process streams and utilities. In most cases, this information is obtained from a combination of test data, measured plant data, and simulations often supported by original design data. Heat exchangers in crude preheat trains, especially the higher-temperature exchangers, are subject to significant fouling, and most companies perform scheduled cleaning to maintain heat-transfer rates and minimize blockages. It is important that the data for the pinch study represent realistic, sustainable heat exchanger conditions.

Once the data required for the analysis have been collected, they must be organized in the proper format for the pinch study. This process is referred to as data extraction. The requirements vary somewhat depending on which software package is being used, but in general, the extracted data provide a simplified representation of the heat duties and inlet and outlet temperatures associated with all of the heaters, coolers, and process-to-process heat exchangers in Figure 3. Any data that are not potentially useful for heat integration purposes are omitted. Table 1 presents the resulting data set for input to pinch software.

Heating and cooling utilities must also be specified. Fired heaters are typically represented simply as heat sources at a single temperature (in practice, most software requires a small temperature range) that is hot enough to satisfy any anticipated heat load in the unit. Ambient cooling

Table 1. The data extracted for the pinch analysis represent the heating and cooling of the process streams and the utility requirements of the existing process.

Heat Exchanger		Duty, MBtu/h	Hot Side			Cold Side		
			Stream Name	*Ts*, °F	*Tt*, °F	Stream Name	*Ts*, °F	*Tt*, °F
E-1A/B	ATPA vs. Raw Crude	28.1	ATPA	327.6	246.9	Raw Crude	65.0	113.7
E-18	AOVHD vs. Raw Crude	21.2	AOVHD	281.3	237.3	Raw Crude	113.7	150.5
E-2	Kero vs. Raw Crude	6.5	Kero	376.3	282.6	Raw Crude	150.5	161.4
E-3A/B	Diesel vs. Raw Crude	35.3	Diesel	475.2	261.2	Raw Crude	161.4	218.9
E-4A/B	AMPA vs. Raw Crude	28.6	AMPA	484.5	403.1	Raw Crude	218.9	265.0
E-5	AGO vs. Desalted Crude	10.6	AGO	524.6	363.6	Desalted Crude	259.0	275.0
E-6A-D	VGO vs. Desalted Crude	93.4	VGO	481.8	341.5	Desalted Crude	275.0	410.3
E-7A/B	ABPA vs. Desalted Crude	16.7	ABPA	626.9	518.0	Desalted Crude	410.3	431.7
E-8A/B	Vac Resid vs. Desalted Crude	14.4	Vacuum Resid	693.0	562.2	Desalted Crude	431.7	450.9
E-10	AMPA Steam Generator	23.9	AMPA	550.1	484.5	120-psig Steam Generation		
E-11A/B	Vacuum Resid Steam Generator	10.9	Vacuum Resid	562.2	383.9	120-psig Steam Generation		
F-1	Feed Furnace	200.0	Furnace			Desalted Crude	450.9	665.0
E-12	ATPA Cooler	21.6	ATPA	246.9	185.0	Cooling Water		
E-13	Kero Cooler	13.3	Kero	282.6	90.0	Cooling Water		
E-14	Diesel Cooler	18.4	Diesel	261.2	150.0	Cooling Water		
E-15	VGO Product Cooler	23.6	VGO Product	341.5	200.0	Cooling Water		
E-16	VGOPA Cooler	14.2	VGOPA	341.5	310.0	Cooling Water		
E-17A-D	AOVHD Condenser	62.4	ATM Overheads	237.3	107.6	Cooling Water		

Process Data   Utility Data   *Ts* = Supply Temperature   *Tt* = Target Temperature

Utility	Temperature		Δh, Btu/lb	Cost, \$/MBtu/h per year
	T_s, °F	T_t, °F		
Furnace	750	749	N/A	49,400
120-psig Steam Generation	230	350	124	–36,500*
	350	351	871	
Cooling Water	60	61	N/A	N/A

Table 2. Heating and cooling utilities are defined in terms of temperature, specific enthalpy, and unit cost.

* Steam generation has a negative cost, as steam generation reduces net energy costs.

Basis: Furnace efficiency = 85%. Onstream factor = 96% or 8,400 h/yr. Fuel cost = \$5.00/MBtu (million Btu). 120-psig steam cost = \$4.50/MBtu.

Table 3. Rule-of-thumb ΔT_{min} values have been developed from experience in many pinch studies and have been used to guide the selection of conservative ΔT_{min} values.

Type of Heat Transfer	Rule-of-Thumb ΔT_{min} Values	Selected ΔT_{min} Value
Process Streams against Process Streams	50–70°F	70°F
Process Streams against Steam	15–35°F	35°F
Process Streams against Cooling Water	10–35°F	30°F

(water or air) can be represented as a heat sink at a single temperature. Steam generation (at 120 psig in this case) is considered a cold utility in the pinch analysis, as it provides a means to remove excess heat. It is generally represented as a segmented utility. The colder segment (230°F to 350°F) represents boiler feedwater (BFW) preheat, and the hotter segment (at a constant 350°F) represents the latent heat. The utility data for the pinch study are summarized in Table 2.

The furnace efficiency and onstream factor are derived from historical plant data. The fuel and steam cost data for evaluating projects are typically specified by the company's economics group. The ambient cooling uses cooling water, which is comparatively inexpensive (relative to furnace firing or steam), and it is ignored in utility cost calculations.

Simple equipment cost correlations are used for initial screening. Ideally, these should agree with cost estimators at the site where the study is performed, since site-specific factors are often significant, although literature values can be used.

For this example, the installed cost of the heat exchangers (including foundations, local piping, valves and instrumentation) is \$200/ft^2. Additional allowances are needed for piping costs if significant pipe runs are required for any of the options.

Companies generally specify investment criteria for their projects (*e.g.,* hurdle rates). In this example, the economic cutoff for investments is a 4-yr simple payback.

Step 2: Generate energy and utility targets

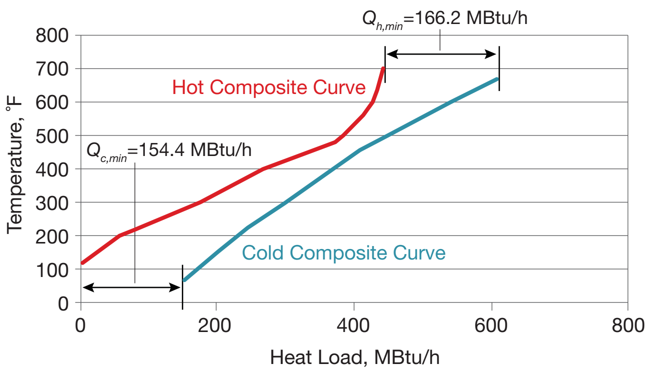
1. Set the value of ΔT_{min}. Targets for minimum energy consumption are calculated based on the value chosen for ΔT_{min}. This parameter reflects the trade-off between capital investment (which usually increases as ΔT_{min} gets smaller) and energy cost (which decreases as ΔT_{min} gets smaller). It is possible to explore this trade-off quantitatively, but in practice that is rarely done. Rather, rule-of-thumb values for ΔT_{min} that optimize the trade-off for different classes of processes, and between process streams and utilities, can be applied, in most instances with a high level of confidence.

Table 3 shows the rule-of-thumb values for CDUs and the actual values that were selected for this example. Similar values are also appropriate for many other refinery processes, such as fluid catalytic cracking (FCC) units, coker units, hydrotreaters and reformers.

2. Determine targets. The next step, energy targeting, involves (conceptually) placing the hot and cold composite curves on a set of x-y axes and moving them horizontally until the smallest vertical distance between the curves is equal to the ΔT_{min} value *(3, pp. 20–24)*. In practice, however, the energy targets are calculated using what is known as the problem table algorithm *(3, pp. 25–30)*. Variants of the problem table algorithm are encoded in the commercially available pinch-analysis software tools. The results are shown in the form of composite curves (Figure 4) and a summary table (Table 4).

The composite curves show overall minimum hot and cold utility targets. Comparing these with the existing utility consumption yields the overall scope for energy saving. Most commercial software tools also quantify targets for each individual utility, as shown in Table 4.

The heat integration opportunities in the CDU are best understood from the summary information in Table 4. The first two columns show the existing heat loads for each utility and the corresponding target loads. In the case of



▲ **Figure 4.** The composite curves for the crude unit example show the combined heat sources and combined heat sinks as temperature vs. enthalpy plots.

120-psig steam, more than 12% of each of these duties is attributable to the sensible heat of raising the BFW from its supply temperature to the saturation temperature. The third column shows the scope for reducing each utility (existing load minus target load). The 120-psig steam is exported, so a negative scope implies added value.

The following broad conclusions can be drawn from Table 4:

• The furnace duty (absorbed heat) can be reduced by 33.8 million Btu/h (MBtu/h) through additional preheating of the crude oil. The savings are seen in reduced firing in the atmospheric feed furnace, F-1. The credit is $1,670,000/yr.

• The 120-psig steam generation can be increased by up to 24.9 MBtu/h. This is worth $909,000/yr.

• If these savings in furnace duty and steam generation are achieved, the cooling water duty is reduced by 58.7 MBtu/h.

Table 4. Pinch analysis yields overall targets for energy and individual heating and cooling utilities. These are used to calculate the scope for reducing utility consumption and the potential for energy cost reductions.

	Existing, MBtu/h	Target, MBtu/h	Scope, MBtu/h	Saving, k$/yr
Total Hot Demand	200.0	166.2	33.8	
Total Cold Demand	188.2	154.4	33.8	
Hot Utilities				
Fired Heater	200.0	166.2	33.8	1,670
Cold Utilities				
120-psig Steam Gen.	34.8	59.7	–24.9*	909
Cooling Water	153.4	94.7	58.7	0
Total				2,579

* Steam generation has a negative cost, as steam generation reduces net energy costs.

Step 3: Identify major inefficiencies in the heat exchanger network

This step incorporates design considerations. Most commercial pinch software has tools to identify major inefficiencies and determine where heat crosses each pinch in a heat exchanger network (HEN). The results may be presented either as a cross-pinch summary table such as Table 5, or as a grid diagram such as Figure 5 *(3, pp. 32–35)*. Both provide essentially the same information, but in different formats.

Two different pinches must be considered. The process pinch (the type of pinch described earlier in the article) divides the process into a net heat sink region (above the process pinch temperature) and a net heat source region (below the process pinch temperature).

In this example, the process pinch temperature for hot streams is 481.8°F. The process pinch temperature for cold streams, by definition, must be less than this by ΔT_{min} (*i.e.*, 411.8°F).

However, it is more convenient to quote a single pinch interval temperature, which is determined as part of the problem table analysis. This is usually the average of the hot and cold stream pinch temperatures, and in this case it is 446.8°F. If heat crosses this pinch, the furnace duty increases and additional heat goes to one of the two cold utilities (120-psig steam or cooling water).

The utility pinch, which in this case is at 350.0°F (interval temperature), arises because there are two cold utilities. Between the process pinch and the utility pinch, any excess heat should be removed from the process by generating 120-psig steam. Below the utility pinch temperature, excess heat has to be removed in cooling water. If heat crosses the utility pinch, less of the valuable 120-psig steam is produced, and more heat is rejected in cooling water.

In the grid diagram (Figure 5), the pinches appear as broken vertical lines. The hot and cold stream pinch temperatures are shown at the top and the bottom of the diagram, respectively. The process streams are shown as horizontal lines, with the hot streams running from left to right and the cold streams from right to left; that is, high temperatures are generally on the left of the diagram and low temperatures are on the right. The temperature scale does not need to be precise. The key is that the initial and final temperatures of each stream are appropriately related to the pinches. It is then apparent which streams have segments above the process pinch temperature, between the two pinches, and below the utility pinch.

Heat exchangers can now be added to the diagram.

Table 5. Tabulating the amount of cross-pinch heat transfer in each heat exchanger focuses attention on the largest inefficiencies in the preheat train.

Heat Exchanger	Hot Stream	Cold Stream	Cross-Pinch Duties, MBtu/h	
			Process, 446.8°F	120-psig Steam, 350.0°F
E-3A/B	Diesel	Raw Crude		14.9
E-4A/B	AMPA	Raw Crude	0.9	28.6
E-5	AGO	Desalted Crude	2.8	9.2
E-6A-D	VGO	Desalted Crude		–1.3*
E-7A/B	ABPA	Desalted Crude	1.2	
E-10	AMPA	120-psig Steam Gen.	23.9	3.0
E-11A/B	Vacuum Resid	120-psig Steam Gen.	4.9	1.3
Total			33.8	55.6

* A negative cross-pinch duty in a heat exchanger indicates that the minimum temperature difference between the cold and the hot streams is less than the specified ΔT_{min}.

Process-to-process heat exchangers are shown as dumbbells linking a hot stream to a cold stream. Utility heat exchangers are shown as circles with a label identifying the type of utility used. If either the hot or cold portion of a heat exchanger extends across one or more pinch boundaries, the appropriate circle is elongated to show the temperature range relative to the pinches. Wherever possible, the bar of a dumbbell is drawn vertically. However, this is not possible when the entire duty of a heat exchanger crosses a pinch (as is the case for exchanger E-4A/B).

Table 5 reveals that the largest inefficiencies are in the two AMPA heat exchanger services, E-4A/B (AMPA vs. raw crude, with 28.6 MBtu/h crossing the 120-psig steam pinch) and E-10 (AMPA steam generator, with 23.9 MBtu/h crossing the process pinch). In Figure 5, this inefficiency in E-4A/B is indicated by the diagonal cross-pinch line. However, the problem with E-10 is less obvious. The user must recognize that 120-psig steam generation should only occur at temperatures below the utility pinch.

These inefficiencies occur for two reasons. The highest-temperature heat in the AMPA is used to generate 120-psig steam; it would be wiser to use it to preheat desalted crude at the hot end of the preheat train. The rest of the AMPA heat is used to preheat much colder raw crude, although it is hot enough to generate 120-psig steam. Therefore, the preheat train redesign must focus on redistributing the AMPA heat.

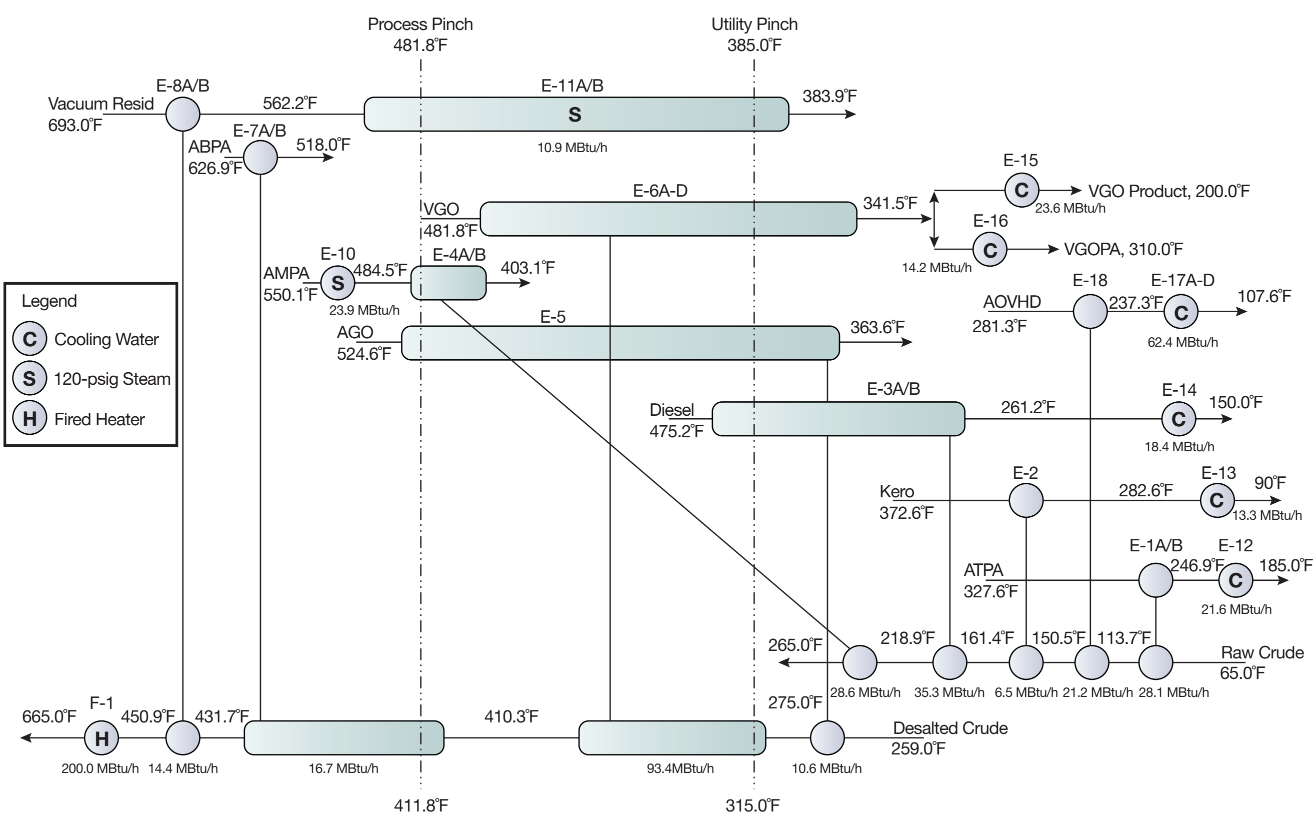
The next largest inefficiency (14.9 MBtu/h crossing the steam generation pinch) is in E-3A/B, the diesel vs. raw crude exchanger. This indicates an opportunity to generate 120-psig steam using part of the diesel rundown heat, and using lower-temperature heat sources to replace heat from the diesel stream to preheat the raw crude.

All of the remaining cross-pinch duties are significantly smaller (<10 MBtu/h). Although there are sometimes viable projects for savings of this magnitude, it is best to focus, at least initially, on the larger opportunities, which in this case account for more than 70% of the heat crossing the process pinch and nearly 80% of the heat crossing the utility pinch.

Step 4: Define options for reducing or eliminating the largest inefficiencies

In retrofit projects, three types of opportunities should generally be considered: rearrange existing heat exchangers to increase feed preheat and/or steam generation; add heat-transfer area to existing matches, for example by adding new heat exchanger shells; or add new heat exchangers to match streams that are not currently matched.

The inefficiencies in Table 5 and the stream data in Table



▲ **Figure 5.** Representing the existing preheat train as a grid diagram highlights inefficient cross-pinch heat exchangers.

1 provide the information required to generate specific ideas. The most promising opportunities are:

• rearrange the existing heat exchangers in the AMPA circuit (E-4A/B and E-10)

• add process-to-process heat exchangers to increase the feed preheat; the VGO (product plus pumparound) is the best heat source since it rejects a large amount of heat at high temperatures to cooling water in E-15 and E-16

• add 120-psig steam generators; Step 3 showed that the largest opportunity of this type is on the diesel stream, ahead of E-3A/B

• add a BFW preheater to increase production of 120-psig steam (the existing design has no BFW preheating); if the BFW can be preheated with waste heat, steam production can be increased by up to 12% in the existing steam generators.

Step 5: Evaluate the options

A technical and economic comparison of the various options that have been identified is now needed to see which ones meet the investment criteria and which of those are the most attractive.

In any heat exchanger network, each change in any particular heat exchanger is likely to have knock-on effects on other heat exchangers. This is particularly true in CDU preheat trains, which are generally the most complex HENs in a refinery.

Some commercially available pinch-analysis software packages incorporate tools for estimating these effects, although many practitioners prefer to use spreadsheets or other simulation tools to assess these interactions. Regardless of which approach is used, some type of model is needed to assess the performance of the HEN and to quantify the utility savings attributable to each option and combination of options evaluated.

It is also important to consider any constraints that could affect the viability of a new heat integration scheme. For example: Hydraulic constraints may limit the number of heat exchangers that can be added. Minimum flowrates must be maintained in all heat exchangers to keep fouling rates to acceptable levels. Better heat integration often results in closer temperature approaches that may reduce the heat load in existing pumparound heat exchangers, but the pumparounds must still be able to remove sufficient heat to control fractionation cut points. The desalter temperature must be kept within an acceptable range. There must not be excessive vaporization of the crude before it reaches the furnace. It is often necessary to make significant compromises to accommodate all of these factors, so the final design is often very different from an ideal pinch design.

Using the model and allowing for all known constraints, screening-quality economic evaluations are carried out for the opportunities identified in Step 4. These calculations:

• quantify the utility savings attributable to each option and combination of options. The utility savings are converted to monetary savings using the utility costs data in Table 2.

• estimate the cost of implementing each option. Generally, this requires estimating the sizes of new heat exchangers and any other new equipment needed, and the lengths of new pipe runs, then using cost correlations to develop cost estimates.

• assess economic viability. The estimated costs and savings for an option are used to calculate the simple payback (cost/annual savings), as well as other measures of value, such as return on investment (ROI) or net present value (NPV), to quantify the attractiveness of each option.

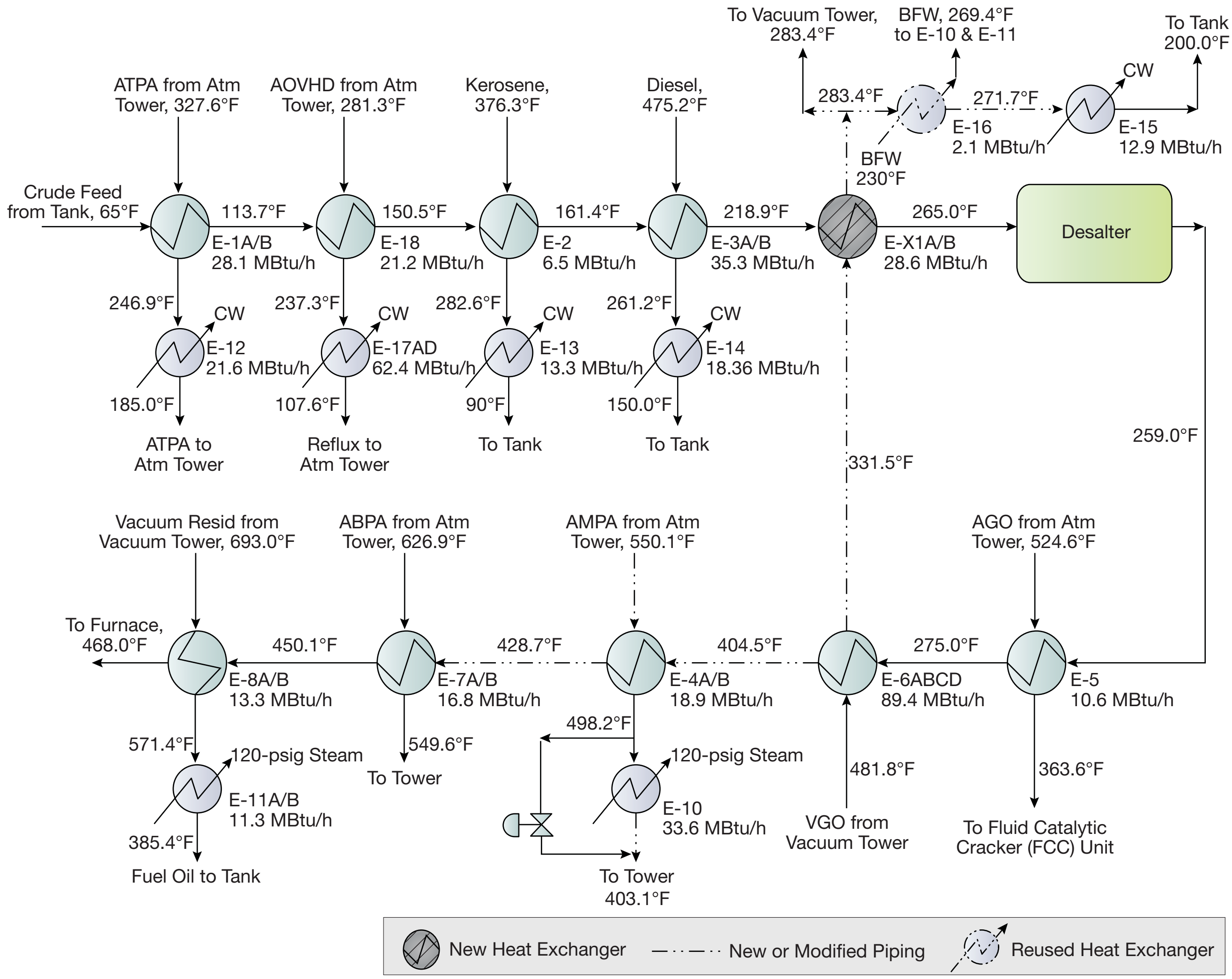
Step 6: Select the best option or combination of options

As noted in Steps 3 and 4**,** the largest opportunity involves realigning the AMPA stream so that its hottest portion is matched against the desalted crude above the process pinch and its lower-temperature portion is used to generate 120-psig steam. This can be achieved fairly easily. The existing AMPA vs. raw crude heat exchanger, E-4A/B, has a high enough temperature rating to be reused in this hotter service, and the sequence of E-4A/B and the existing AMPA steam generator, E-10, can be reversed with a minor piping change, as shown in Figure 6.

However, moving E-4A/B from its existing location between E-3A/B and the desalter reduces heat input to the raw crude, and this needs to be replaced. The easiest way to do this is by adding a new service, E-X1A/B, to recover heat from VGO and apply it to the raw crude immediately ahead of the desalter, where E-4A/B is currently located. E-X1A/B consists of two large shells (approximately 7,000 ft^2 each). These changes (rearrange AMPA and add E-X1A/B) constitute the core modifications for this revamp project.

The core modifications increase crude preheat by 14.0 MBtu/h, which increases the coil inlet temperature by 17.1°F and translates into equivalent feed furnace savings. In addition, these changes also increase heat to 120-psig steam generation (in E-10 and E-11A/B) by a total of 10.1 MBtu/h. These combined savings are worth $1,060,000/yr. The cost for the modifications is $3,335,000, most of which is associated with the addition of E-X1A/B. The simple payback time is 3.1 yr.

When E-1XA/B is added to recover additional heat from the VGO (pumparound and product), the VGO pumparound cooler, E-16, is no longer needed. The E-16 shell is therefore available for an alternative use, such as to preheat BFW using the VGO product rundown ahead of cooler E-15. This arrangement is also shown in Figure 6. This change recovers 2.1 MBtu/h of rundown heat to BFW, which results in an increase in steam generation worth $76,000/yr. The cost is $250,000, giving a simple payback time of 3.3 yr. This covers the cost of changing the tube bundle in E-16 (which is necessary because the existing bundle is not rated for the pressure



▲ **Figure 6.** The final design requires just one new pair of heat exchanger shells and repiping of some existing equipment.

of boiler feedwater) and making some piping modifications.

Ordinarily, it would not be economical to add a heat recovery exchanger in a CDU for a duty as low as 2.1 MBtu/h. However, in this case, the option of reusing an existing piece of equipment greatly improves the economics.

The other options described in Step 4 were also evaluated. However, they were either uneconomical or had technical problems and were impractical to implement. Table 6 summarizes the two economical project options.

Table 6. Evaluating the options shows that two projects satisfy the economic requirement for a payback time of less than 4 years.

Project Description	Duty, MBtu/h	Credit, $/yr	Investment, $	Payback Time, yr
Core Modifications	24.1	1,060,000	3,335,000	3.1
BFW Preheat	2.1	76,000	250,000	3.3
Total	26.2	1,136,000	3,585,000	3.2

Overall, these changes save 14.0 MBtu/h in crude preheat and recover 12.2 MBtu/h for additional 120-psig steam generation (26.2 MBtu/h total), worth $1,136,000/yr. These results compare with a target crude preheat saving of 33.8 MBtu/h and a target increase of 24.9 MBtu/h in heat recovery for 120-psig steam generation (58.7 MBtu/h total), with a net monetary target saving of $2,579,000/yr (Table 4). Therefore, the selected design achieves about 45% of the target savings for both energy and monetary value.

The economically achievable saving is a relatively low percentage of the "ideal" target because of the interactions in the preheat train. Adding heat recovery in a preheat train reduces temperature differences in all downstream heat exchangers, which reduces the load in these heat exchangers. Additional heat-transfer area is needed to recover this lost heat and increases the project cost, making it less attractive.

It is usually simpler and much less expensive to incorporate energy efficiency in the initial design of a CDU than it is to improve its energy efficiency in a revamp. However, as this example shows, some significant revamp opportunities do exist, and pinch analysis is a good tool for identifying them.

Final thoughts

Pinch analysis is a very powerful technique for identifying minimum energy consumption targets for heating and cooling and identifying projects to achieve significant energy savings. This example highlights an important fact about pinch analysis — properly calculated pinch targets are always thermodynamically achievable, and ΔT_{min} values are selected with the intention of generating economically realistic targets. However, achieving savings requires not just targets, but actual projects. In many cases, practical process constraints and interactions limit what can be achieved economically to something significantly less than the pinch targets. CEP

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