

Demand Supply Diagrams

Heat demand-supply diagrams are an extension of the concept of temperature-enthalpy diagrams (Hohmann, 1971; Huang and Elshout, 1976; Naka et. al., 1980; Andreovich and Westerberg, 1985; Terranova and Westerberg, 1989; Dhole and Linnhoff, 1993). In the demand-supply diagram, a stream is represented by a curve. This curve represents the product of mass flowrate and specific heat capacity (true or apparent in the case of phase changing streams) as a function of temperature. A schematic heat demand-supply diagram for typical crude fractionation units, like the one of Figure 1-1, is shown in Figure 3-1.

In setting up the diagram, a heat demand line is first drawn and used as a background. The crude is the only cold stream. In some cases, as proposed by Liebmann *et al.* (1998), water at room temperature to produce steam is also considered a cold stream. However, in many refineries, low-pressure steam is in surplus, and it can be considered as a cheap or even free heat source. To locate the hot streams (heat supply), the usual minimum temperature difference is used. Thus the temperatures of hot streams are shifted to the left by this minimum difference, which has been traditionally named heat recovery minimum approximation temperature (HRAT or $\Delta T_{\min}$). The area below the heat demand line represents the total heat demand of the unit without heat recovery.

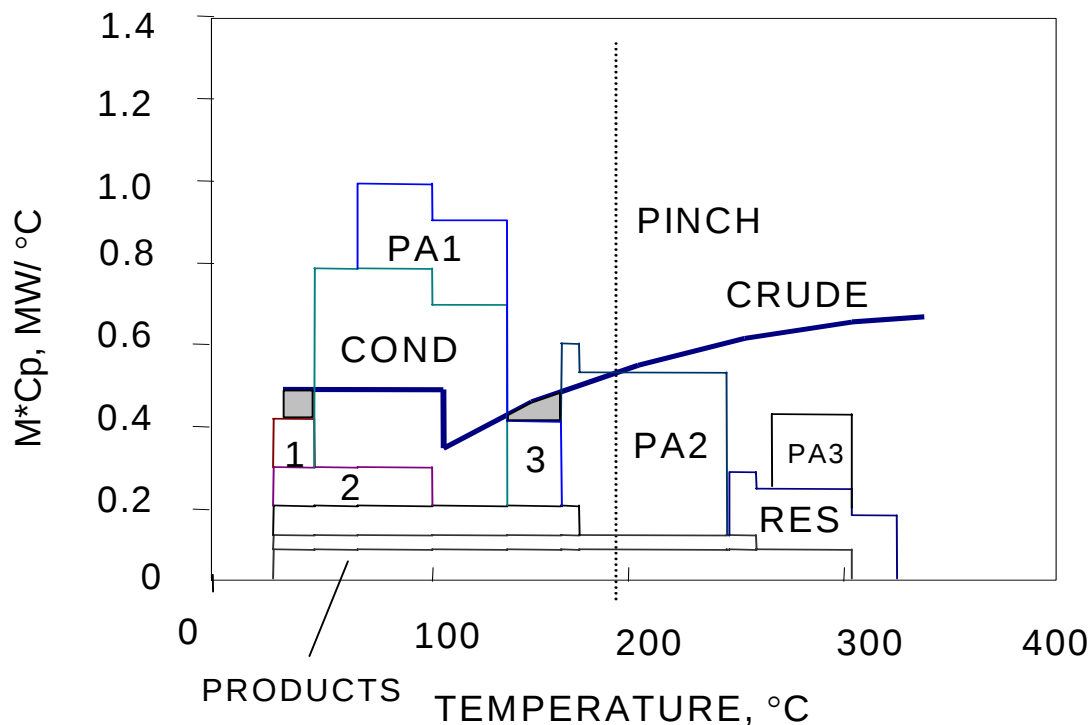


Figure 3-1: Heat Demand-Supply Diagram of an Atmospheric Crude Distillation Unit.

1. Naphtha and condensed water. 2. Sour water from the desalter. 3. Pump-around 1. COND: condenser. PA: pump-around. RES: residue. Products (from top to bottom): kerosene, diesel and gas oil.

In Figure 3-1, we see two different regions:

- Regions where heat supplies are larger than demands
- Regions where heat supplies are smaller than demands

When the supply exceeds the demand, one can move the surplus part of the supply to a lower temperature region where the supply is deficient. Figure 3-1 shows two areas where the supply is in deficit (gray areas). The left gray area can be covered by the heat surplus from the condenser or from PA1. The right one can be covered using the excess of PA2. This illustration is omitted, assuming that this area matching is implicit.

The location of the pinch point can be easily obtained from this diagram. It is the lowest temperature at which the demand is larger than the supply after the shifting and area matching has been performed. Finally, the heating utility is given by the unmatched demand on the right, and the cooling utility is given by the extra supply on the left.

Three options to reduce energy consumption exist: decreasing demand, increasing supply and improving the match between the supply and the demand.

- *Decrease of demand*
 - a) A decrease in heat demand can be realized by moving the demand line down, that is, decreasing the flowrate. One way of doing this is to flash the crude at lower temperatures and send the vapor to a tray above the flash zone. In practice, vaporization before the furnace inlet is pressure suppressed to avoid two-phase flow. This reduces energy saving opportunities. Such opportunity is analyzed in a separate work (Bagajewicz and Ji, 2002).
 - b) Another way to decrease heat demand is to reduce the target temperature of the crude. This can be achieved by lowering the pressure drop from the outlet of the furnace to the overhead reflux drum of the column. In this sense, a vacuum operation is even better, but it is excluded for other reasons (mainly cost). Another way of decreasing the final temperature is using larger amount of steam, but the introduction of steam has complicating effects on energy consumption.

- *Increase of the supply and/or the thermal quality*

Withdrawing certain products in the vapor phase instead of in a liquid phase has the advantage that condensation heat is released at a higher temperature.

- *Improvement of match between demand and supply*

Assume there is a large heat surplus in a moderate temperature range and a heat deficit in a higher temperature range. One way to improve this mismatch is to move a part of the heat surplus to a higher temperature by increasing the duties of the pump-around circuits.

The design procedure that we will see in the next unit relies on the idea of distributing heat among the condenser and pump-around circuits.

PUMP-AROUND CIRCUITS AND HEAT RECOVERY

The original purpose of adding pump-around circuits was to reduce vapor and liquid traffic at the top section of the column (Watkins, 1979). Without pump-around circuits, all condensation heat has to be removed from the condenser, which results in a large vapor flowrate at the top trays. We explore now the limit of heat that could be removed from a pump-around circuit.

Maximum Heat Duty of Pump-Around Circuits

In Figure 3-2, envelope *III* contains k pump-around circuits. In order to calculate the maximum pump-around duty, we carry out a heat balance for this envelope.

$$\begin{aligned} V_{FZ}^W \cdot h_{FZ}^W + V_{FZ}^O \cdot h_{FZ}^O + L_{j-1} \cdot h_{L_{j-1}} + \sum_{i \in III} F_{si} \cdot h_{si} + \sum_{k \in III} Q_k \\ = L_O \cdot h_{L_O} + \sum_{i \in III} F_{pi} \cdot h_{pi} + V_j^W \cdot h_{V_j}^W + V_j^O \cdot h_{V_j}^O \end{aligned} \quad (3-1)$$

In equation (3-1), V_{FZ}^W , V_{FZ}^O are the steam flowrate at the flash zone and the hydrocarbon vapor flowrate at the flash zone respectively, V_j^W , V_j^O are the steam flowrate at tray j and the hydrocarbon vapor flowrate at tray j respectively. In Figure 3-2, we use $V_{FZ} = V_{FZ}^W + V_{FZ}^O$ and $V_j = V_j^W + V_j^O$. It is assumed that water is insoluble in liquid streams.

By applying material balance of hydrocarbons to envelope *I*, one obtains:

$$V_{FZ}^O = L_O + \sum_{i \in I} F_{pi} \quad (3-2)$$

Similarly, material balances for envelope *II* and *III* are:

$$\begin{aligned} V_j^W &= V_{FZ}^W + \sum_{i \in III} F_{si} \\ V_j^O &= L_{j-1} + \sum_{i \in II} F_{pi} \end{aligned} \quad (3-3)$$

Replacing V_{FZ}^O , V_j^W and V_j^O in equation (3-1), one obtains:

$$\sum_{k \in III} Q_k = L_O \cdot (h_{L_O} - h_{FZ}^O) + \sum_{i \in III} F_{pi} \cdot (h_{pi} - h_{FZ}^O) + \sum_{i \in II} F_{pi} \cdot (h_{vi}^O - h_{FZ}^O) + V_{FZ}^W \cdot (h_{V_j}^W - h_{FZ}^W) + \sum_{i \in III} F_{si} \cdot (h_{vi}^W - h_{si}) + L_{j-1} \cdot (h_{V_j}^O - h_{L_{j-1}}) \quad (3-4)$$

There are six terms on the right hand side of equation (3-4). From left to right, these terms represent condensation heat of the overflash stream L_O , condensation heat of the products leaving envelope *III*, apparent heat released by the hydrocarbon vapor V_j^O , and apparent heat released by the steam streams. The sixth term stands for the vaporization heat of internal reflux L_{j-1} . Apparently, when L_{j-1} goes to zero, the heat removal from envelope *III* reaches its maximum. By including more pump-around circuits in envelope *III* and applying equation (3-4) accordingly, one can find the maximum heat duty for each pump-around circuit.

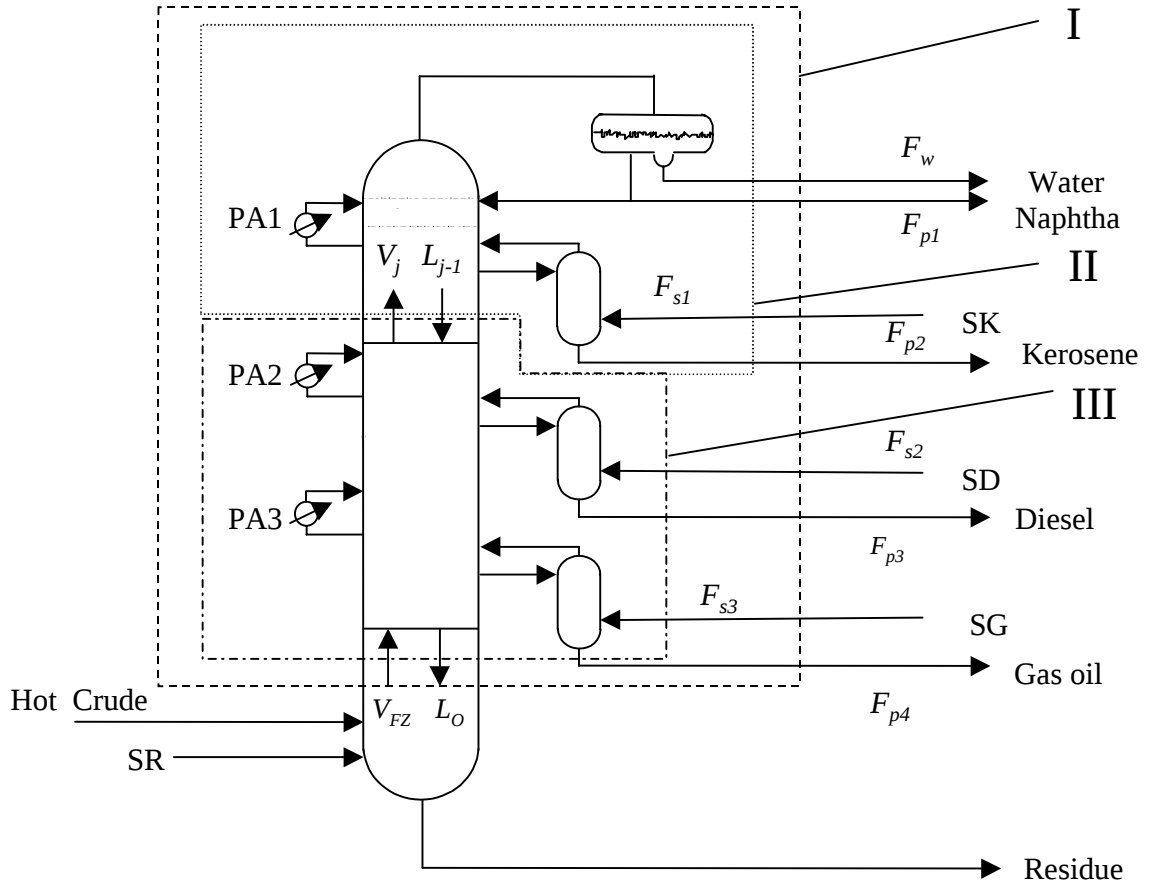


Figure 3-2: Heat Balance of an atmospheric distillation column

It can be shown through an overall heat balance that the total amount of heat to be removed from the column depends on the yields of the products. In addition, shifting heat from envelope *II* to envelope *III* results in a decrease of L_{j-1} . Thus, the shifting can take place as long as L_{j-1} remains positive.

Effect of Heat Shifting on Separation

It is well known that heat shifting reduces separation efficiency. The presence of the pump-around circuit decreases the number of effective ideal trays (Bagajewicz, 1998). The effect can be even more detrimental to separation if the flowrate of a pump-around circuit is increased. As we shall see later, these effects can be compensated to a certain extent by increasing the steam rate in the side strippers. Another solution is to increase the number of trays. However, with the total number of trays kept constant, the aforementioned relationship between heat recovery and steam consumption can be incorporated into the design procedure.

The conventional atmospheric-vacuum distillation design: Basically, there are two rules to determine if a new pump-around is needed (*Step 6*). One is the existence of heat surplus in the pump-around last added and the other is that the addition of a new pump-around should reduce the total energy consumption. For the vacuum tower, the two pump-around circuits already exist at the beginning of the procedure. The problem is then to minimize the objective function without violating the product gap.

Table 3-1 shows the resulting energy consumption after the corresponding steps in the targeting procedure are implemented. The resulting heat demand-supply diagram is shown in Figure 3-3.

Table 3-1: Variation of energy consumption with the addition of each pump-around circuit in the case of the conventional-vacuum design

	Energy consumption (MW)
No pump around (Step 3)	97.29
With PA1 (Step 4)	95.33
With PA1 and PA2 (Step 6)	86.46
With PA1, PA2 and PA3 (Step 6)	76.94
With VPA2 optimized (Step 7)	75.13

$\Delta T_{\min} = 22.2^{\circ} \text{C}$. (Vacuum jet steam consumption not included)

The installation of PA1 or VPA2 only results in a small reduction of energy consumption because the temperature of the heat provided by PA1 is still low and most of this heat is in the region where heat supply is already in surplus. In the case of VPA2, its duty is comparatively small. Although smaller, the heat loads of the vacuum pump-around circuits and products, they affect the heat distribution in the atmospheric pump-around circuits. With additional heat sources available in the intermediate temperature region (PA2 region), it is beneficial for the complete design to shift more heat from PA2 to PA3. Table 4 compares the loads for both cases.

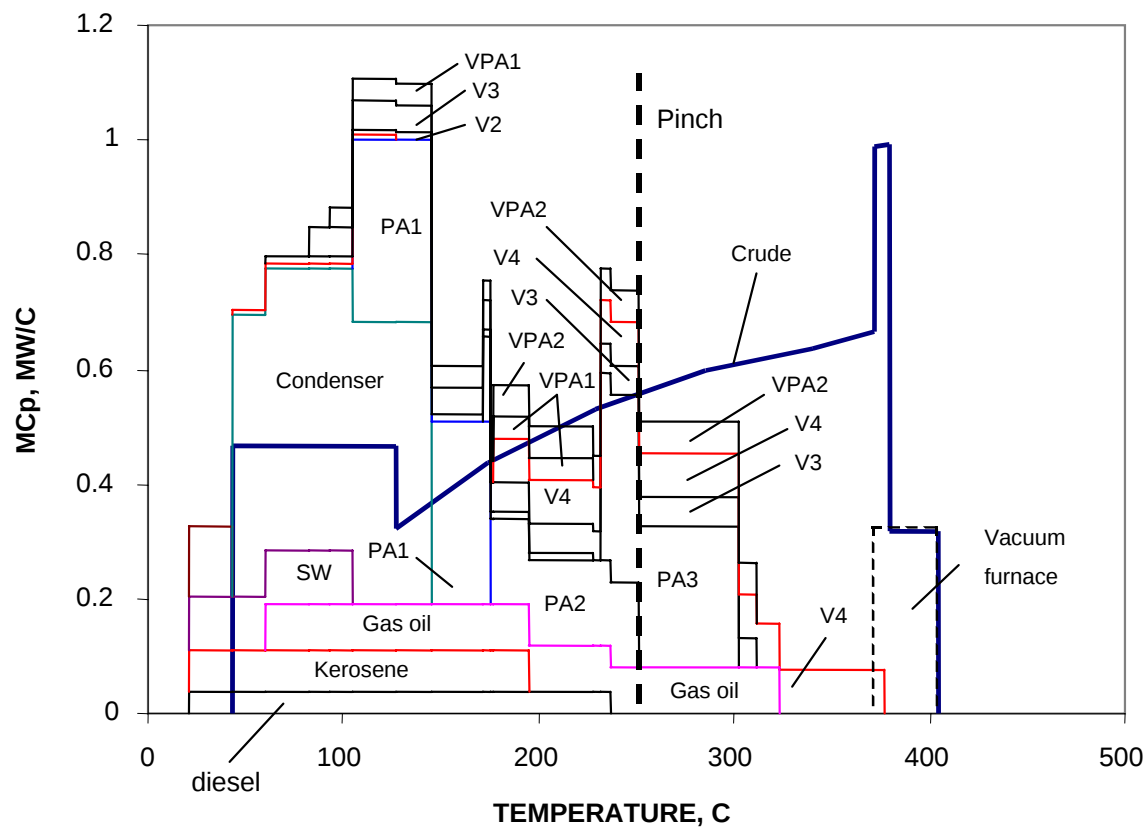


Figure 3-3. Heat demand-supply diagram for light crude (Conventional Atmospheric + Vacuum Column)
V2: LVGO. V3: HVGO. V4: vacuum residue.

Pump-around circuit	Conventional design*	Atmospheric-vacuum
PA1	22.28 MW	23.07 MW
PA2	33.71 MW	12.87 MW
PA3	8.79 MW	22.69 MW

We consider now an existing unit. Figure 3-4 depicts a simplified diagram, where the heat exchanger network is omitted. There are also a few flashes in this unit, which for reasons of simplicity of presentation, we also omit. Figure 3-5 and Figure 3- 6 depict parts of the heat exchanger network. Finally Table 3-3 describes the current status of heat exchange indicating which part of the supply is given to the crude and which other is delivered to cooling water (the plant makes use of several coolers). To get an idea how well the heat is recovered we look at the demand-supply diagram of Figure 3-7. The shaded regions depict supply that is satisfied using utilities. The rest is used to exchange with crude. The duty of the three pump-around circuits is -76, -115 and -24.7 MMBtu/hr, for PA1, PA2 and PA3 respectively. The total furnace load of this plant is 284 MMBtu/hr.

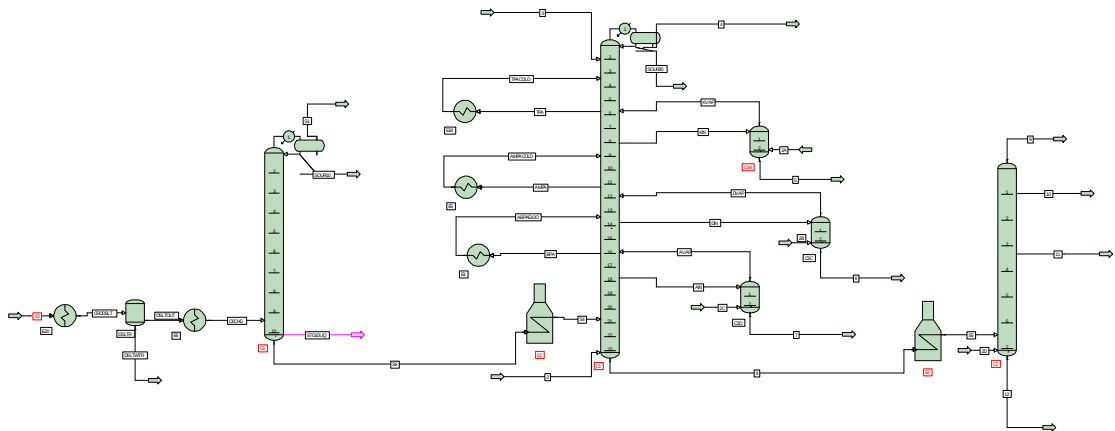


Table 3-3. Matching of each supply.

	Duty (MM BTU/HR)		
	TOTAL	Heat exchanged with the crude	Heat exchanged with the cooling water
Condenser	146.0	64.9	81.1
PA1	76.2	46.0	30.2
PA2	113.8	69.9	43.9
PA3	23.8	23.8	-
Kerosene	35.4	10.2	25.2
Diesel	28.7	13.6	15.1
Gasoil	67.5	19.7	47.8
Residue	59.8	59.8	-
TOTAL	551.2	307.9	243.3

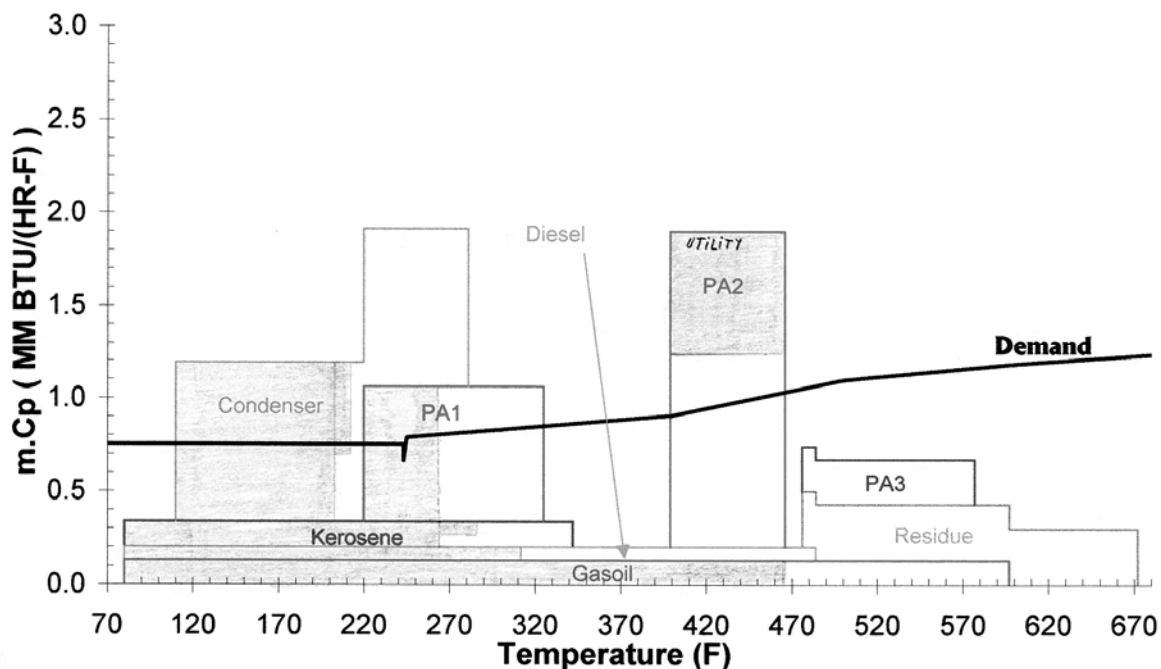


Figure 3-7: Demand-Supply diagram. Plant as is.

Although Figure 3-7 suggests that a transfer heat from PA1 to PA2, may improve heat transfer, this is in fact not possible in this plant, because such a transfer reduces the liquid rate above the pump around. However, the liquid rate from the tray above the pump around is already at a minimum value. Thus, the duty of PA1 cannot be further reduced.

The liquid rate above the tray of pump around PA2 is high, which suggests that a transfer from PA2 to PA3 is possible. By observing the diagram we also notice that such a transfer can be beneficial even with the same area. This is because at the temperature

level of pump around PA3, there is unsatisfied demand currently covered by the furnace. In fact only 4 MMBtu/hr can be transferred, the heat exchanger handling the contact between PA3 and the crude being the limitation (it does not have enough area). At a rate of 5\$/MMBtu, this implies a savings of around 250,000 \$/year. The resulting demand-supply diagram is shown in Figure 3- 8. If the exchanger handling PA3 had more area, then it would be possible to recover additional energy (2 MMBtu/hr). This will be discussed again in Unit 5.

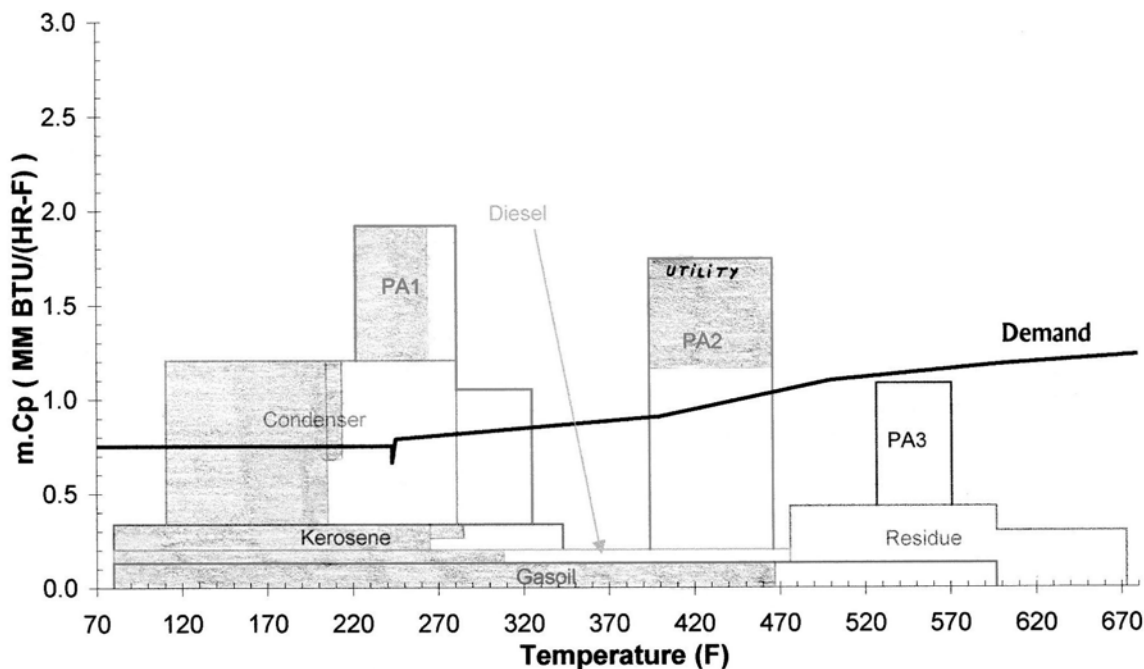


Figure 3- 8: Demand-Supply diagram. New Pump-around loads.

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