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ANALYSIS OF THE HEAT EXCHANGER NETWORK OF THE TOPPING UNIT OF THE TEMA OIL REFINERY[i]

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ABSTRACT

Using the stream enthalpies and temperature data for Bonny Medium, one of the crude oils processed by the Tema Oil Refinery, this paper sought to determine the efficiency of heat exchange in the Topping unit of the plant and to suggest improvements. The techniques of Heat Exchanger Network synthesis, otherwise known as Pinch Technology, were used. An approximate method was used for determining the stream heat transfer coefficients required in these calculations. It involved the calculation of a single heat transfer coefficient value for a given ΔT_{min}, averaging these values for all the ΔT_{min}'s considered, and getting a representative value for the entire plant for further analysis. With this approach a heat transfer coefficient value of 888.5 W/m^2 °C was obtained for the entire network. Pinch Technology methods are used to theoretically determine the minimum utility requirements of a given process requiring heat exchange. The heat exchangers for the process are then linked up or networked in order to, as much as possible, approach the minimum energy requirements suggested by theory. With the TOR topping unit, for a ΔT_{min} of 20°C used for the analysis, a savings of 8.53MW of energy was realized in this theoretical analysis. This savings called for investment in the acquisition and installation of five new heat exchangers. Simulation data used for the initial design of the topping plant was used for this analysis.

Keywords: Efficient energy utilization, Heat Exchanger Network Synthesis, hot utility, cold utility, composite curves

1. INTRODUCTION

The Tema Oil Refinery first came into operation in 1963 with an installed capacity of 28,000 barrels of crude oil per day. The plant handles three types of crude oil, namely Bonny Light, Bonny Medium and Brass River. In 1997, the capacity of the plant was upgraded to handle 45,000 barrels of crude per day to create a viable stock for a catalytic cracking plant. In the intervening thirty-four years, a lot of innovations occurred in the refinery business, including a systematic method for integrating heat and power on a processing plant. This study was meant to assess the suitability of the existing heat exchanger network of the Topping Unit in the light of modern methods of heat exchanger network synthesis and power integration.

While the question of efficient energy utilization has always been at the heart of thermodynamics, it was not until the Arab oil embargo of the early 1970's and the concomitant sudden hike in oil prices, that serious efforts were put into reducing the sometimes drab concepts of this subject into practical terms for the design of heat exchanger networks. The research activities initiated in those days have resulted in various principles for the design of heat exchanger networks. Since then documented results have shown that using these techniques in the design of new plants and the revamp of existing ones can, in some cases, result in significant operational and even capital savings.

If a process stream needs to be cooled and another needs to be heated, both tasks can be accomplished by using an external cooler and external heater respectively. On the other hand, if the heat contents of both streams are comparable in magnitude and if their temperatures overlap, it is possible to exchange heat between the two streams by means of a heat exchanger. Where there is only one suitable hot stream and one suitable cold stream, the engineer has no choice but to link the two. As the number of streams increases, however, more and more options become available to the designer and a systematic approach is therefore needed to determine the best energy-saving option. Extensive literature exist on the basic principles of heat exchanger network synthesis (Huang and Elshout, 1976; Linnhoff et al, 1979; Townsend and Linnhoff, 1982; Linnhoff and Hindmarsh, 1983; Douglas, 1988; Linnhoff, et al, 1994)

The most important step in performing a heat exchanger network design is determining the targets that the design is expected to meet. Targets determination for a new design is done differently from that for an already existing plant. This is because it would not be wise to discard already acquired equipment simply because the design says so. Secondly it is counter-intuitive to reduce the existing area and expected to exchange more heat. The best approach to retrofit design is to improve on the existing network using the already acquired exchanger area as basis (Tjoe and Linnhoff, 1986; Linnhoff et al, 1994). The procedure for setting retrofit design targets, which is the essence of this work, is given in the next section.

2. METHODOLOGY

2.1 Retrofit Targeting

It must be pointed out that the data used for this preliminary analysis is simulation data obtained from process flow diagrams employed by TOR contractors in the design of the topping plant. This is a good starting point, since results obtained from this analysis will help to determine whether to invest time and money in the acquisition of actual process data. To set retrofit targets, a plot of area versus energy requirements of the existing network work is needed. The procedure for doing this is as follows:

1. Using the process flow diagram, isolate the various streams in the process, extract their supply and target temperatures and enthalpies and calculate the CP's for each stream.
2. Choose a ΔT_{min} and calculate, using the Problem Table Method (Linnhoff et al, 1994), the corresponding energy requirements at each ΔT_{min}.
3. Calculate the composite curves for the hot and cold streams and draw them both on the same graph.
4. Using the Q_H's and Q_C's obtained from Step 2 as a guide, the composite curves are separated from each other appropriately. In principle the two methods, graphical and analytical, should independently give the same answer.
5. The areas required for heat exchange can be determined using the usual heat equation, by dividing the crooked composite curves into linear segments (as shown in Appendix) and applying the following formula (Tjoe and Linnhoff, 1986)

$$A_{target} = \sum_{i}^{n} \frac{1}{\Delta T_{LMi}} \left[\sum_{j}^{m} \left(\frac{q_i}{h_j} \right) \right]_i \qquad (1)$$

where q_j and h_j are the heat content of each strea (both hot and cold) within a given segment, and the heat transfer coefficient, respectively..
ΔT_{LMi} is the log-mean temperature difference for the segment, and
n and m are the number of intervals identified for a given ΔT_{min} and the number of streams within a given interval, respectively.

6. The calculated areas and energy requirements for each ΔT_{min} should then be used to plot an area-energy diagram as sketched in Figure 1. The area and energy needs of the existing network can also be represented on the same plot as point E, with the existing area and current energy requirements being A_o and E_o respectively. In moving from the existing network, E, to any other design, if area is not to be discarded, then the final network must end up at a point above the line A_oE. Any improvement path starting from E and lying above and to the left of this line would meet our requirement, although the best curve would be the one with the least slope within this region (Tjoe and Linnhoff, 1986).
7. Using the method of Tjoe and Linnhoff (1986), the appropriate curve is determined as the constant-α curve, where α is the ratio of the target to the current area on the existing plant.
8. For a given ΔT_{min}, the existing area will be subtracted from the calculated area to determine the additional area requirement. The cost of this area, which would be determined from a correlation linking heat exchanger area to costs, would be the investment needed at that heat recovery.
9. The savings that can be made at that ΔT_{min}, can also be determined by subtracting the calculated energy requirement from the existing energy consumption, and using a correlation for cost of utilities to calculate the monetary value.
10. A plot of savings versus investment can then be made. By using either the amount of monetary investment, the savings to be made or the payback period as the investment criterion, the appropriate ΔT_{min} corresponding to this target can be found.

It is this ΔT_{min} that would be used for the subsequent design of the network. The design procedure for retrofitting an existing plant is also somewhat different from a grass-root design.

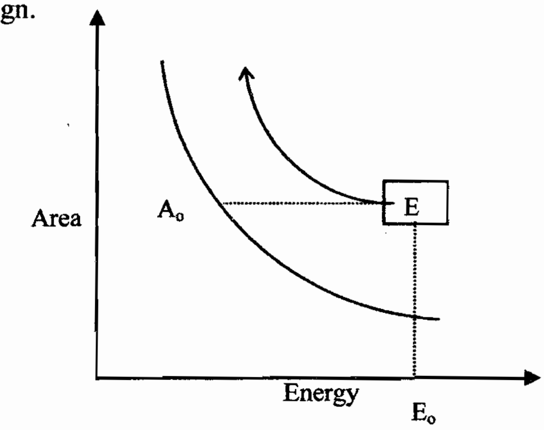

Figure 1: Area-Energy

2.2 Retrofit Design

The procedure for retrofit design is as follows:

i. The existing network is set up in the grid form pioneered by Linnhoff et. al. (1994).

ii. Exchangers that are connected cross the pinch are easily identified and broken. These exchangers are then reconnected on one side of the pinch bearing in mind the design rules.

iii. Appropriate coolers and heaters are inserted as needed.

iv. The actual investment and savings are then subquently determined.

3. RESULTS

3.1 Data Collection

3.1.1 Stream Data

The analyses were based on data for Bonny Medium crude. The stream data for this type of crude oil are presented in Table 1. Data on all the exchangers, heaters, coolers and furnaces in the topping unit have also been summarised in Table 2. These data were all extracted from the process flow diagrams of the topping unit provided by the refinery. In Figure 2, all the components of the network are presented in the form of a grid. Data on the three furnaces, F01, F02, F61 and exchanger E-17 (which heats up the incoming splitter unit stream with medium pressure steam) indicates that the total installed hot utility capacity is 44.61 MW.

3.1.2 Costs correlations

The cost of fuel oil was obtained from the Marketing Department of TOR as roughly \$100/tonne. Using a calorific value for fuel oil of 10,515 kcal/kg, 1MW of energy obtained from fuel oil was calculated to cost \$71,200 per annum. Different types of heat exchangers are in use on the plant. Data gathered indicated that the most common exchanger type had A179 tubing and A516gr60 shell materials respectively. The area, *A*, and costs of the most typical A179 heat exchangers were correlated to give the linear relationship of Equation. (2).

$$Cost(\$)=22834+0.24592A \qquad (2)$$

3.2 Targeting Analysis

In Table 3, the heat demands of the individual streams in processing Bonny Medium crude are tabulated against the capacity of the installed exchangers. It is observed that all but one of them, stream 3, have a higher capacity than the streams need. This gives the plant flexibility in processing different kinds of crude. Streams 17 and 18 involve partial vaporization and splitting of the two phases formed. Their CP's were calculated taking this split into consideration.

In line with the procedure outlined in Section 2-1 regarding targeting, the first step in the procedure, data extraction, has been accomplished for Bonny Medium crude and summarized as Tables 1 and 2. In Step 2 the various Q_H's and Q_C's for different ΔT_{min} were calculated. The temperature layout of the data of Table 1 is given in Figure 3. This is an important diagram because all calculations originate from this plot.

The composite curves were drawn by adding up the enthalpies for the various intervals cumulatively, and plotting them against the temperatures at which these sums occur. These curves were used to calculate the areas required at a given ΔT_{min}. In the accompanying Appendix, sample composite curves and the calculations needed has been provided for ΔT_{min}=50°C.

In the formula provided by Tjoe and Linnhoff (1994) for the calculation of areas, Equation. (1), the heat transfer coefficients of the various streams are required. Apart from the fundamental problem with defining the heat transfer coefficient of a fluid stream without reference to a specific surface, there is also the difficulty of how to calculate these values. A different approach was therefore taken in this work. This approach involved adopting a constant coefficient for a given ΔT_{min} for the entire network. Assuming this was the ΔT_{min} used in the original design, the total surface area of the existing plant was equated to the given formula in which the heat transfer coefficient h_j is the only unknown. The heat transfer coefficients obtained for all the different ΔT_{min}'s, are averaged to get a representative value for the entire network. This value is used back in the area expressions for each ΔT_{min}, to obtain the final area for that temperature. In these calculations, the 'overall' heat transfer coefficient was obtained as 888.5 W/ m^2 °C. The details of these calculations are given in the Appendix. The areas and other parameters calculated have been summarised in Table 4.

The area-energy values in Table 4 have been plotted in Figure 4, along with the constant-α curve. Using an actual exchanger area of 3693 m^2 and a target of 756.4 m^2 at the energy level of 31.19 MW, the α-value may be calculated as 0.205. The energy level of 31.19 MW is obtained by adding up the heating demands of the streams on which the three furnaces (F01, F02, and F61) and the splitter (E17) are located. The target area of 756.4 m^2 is the ideal area equivalent to this energy demand.

The lower boundary curve in this plot represents the area-energy relationship for ideal heat exchange between all the hot and cold streams in the network. The rationale for the so-called constant-α curve is based on the assumption that the ratio of the ideal area requirement and the actual area on the existing plant is valid for other levels of energy utilization. In this case an α-value of 0.205 was calculated. The areas given in column 4 of Table 4 were therefore obtained by dividing the column 2 areas by the α-value. The resultant values were used to plot the upper boundary curve in Figure 4.

In Figure 5 the targets for retrofit designs for 2- and 3-year payback periods is indicated. A 2-year payback requires a financial investment of about \$1.7 million and a savings of \$0.9 million per year. The ΔT_{min} required for designing with these targets is approximately 26°C. For a 3-year payback period, an investment of about \$2.45 million yields a return of \$1.02 million annually, using a ΔT_{min} of 14°C. Since the same plant is used in processing three different kinds of crude oil, it is imperative that the ΔT_{min} used in all three designs is the same. Hence since for a similar analysis involving Bonny Light, a ΔT_{min} of 20°C was used, the same value (which falls between the two extremes determined above) was used here for the purpose of uniformity and comparison. With this value of $\Delta T_{min,}$ the Problem Table method was used to determine the Pinch Point. The range was calculated to be 215° – 235°C. This was used to draw the network grid of the topping unit for Bonny Medium processing shown in Figure 6.

4. DISCUSSION OF RETROFIT DESIGN

Using the principles of Pinch Analysis, above pinch design is done separately from below pinch design. Since the pinch interval was determined as between 215° – 235°C, a given stream could have one part in the above pinch region if its highest temperature is above 235°C, while the other part would be in the below pinch region if its lowest temperature is less than 215°C. Such connections have to be broken and re-linked on the same side of the pinch, where possible. In the final analysis, both the above pinch

and below pinch designs are merged. The following analyses can best be understood by considering Figures 6 and 7 alongside. All the streams mentioned in these discussions can be found in these diagrams.

4.1 Above Pinch Design

1. The capacities of exchangers E06 and E66 are given as 2.64 and 2.53 MW respectively (Table 2). Given that the heat content of stream 4 is 5.1MW [i.e. (325.6-270.9)0.0934], half of this value would give 2.60 as the expected load for each of the two exchangers on it. This load would exceed the recommended duty of exchanger E66. A better connection is made between the split branches of stream 5 and exchangers E6 and E66. The heating duty of 2.48 MW each is below the duty specification for the exchangers. The CP's of the split stream of 5 are of course less than those of 20a, and hence the match is acceptable.
2. To reduce the external heating requirement of stream 20b, the exchangers from stream 4 are connected to the split branches of 20b. This leads to savings in energy of 5.2MW.
3. Stream 1a of heat content 1.49MW can be connected to stream 15 requiring 1.27MW of heat. This connection satisfies the criterion for connection in terms of CP's and would require a new heat exchanger.
4. At this point the hot streams that still need to be brought down to the pinch temperatures are streams 2a (Figure 6) and 3a. Although stream 2a cuts across the pinch, the assumption would be made that it was a below-pinch stream and link it below the pinch. Stream 3a could be linked to 20b. The total heat load of 3.35MW can however not be transferred to 20a in order to avoid violating the ΔT_{min} of 20°C. Thus only a heat load of 1.30MW can be transferred, leading to an outlet temperature of 257°C on stream 3a.
5. By this arrangements, the energy saving made on the above-pinch side are as follows: (2.60+2.60+1.30=6.5MW) from the furnaces, F01, F61 and stream 3a. The elimination of furnace F02 brings in a saving of 1.27MW, yielding a total savings of 7.77MW.
6. It should be noted that the CP criterion is satisfied in each of the connections made above i.e. $CP_{Hot} \leq CP_{Cold}$

4.2 Below Pinch Design

1. A look at the heat loads on the coolers of the network gives a good indication of where savings can be made. While most of the heat loads on the coolers are rather low, a few coolers have significant loads that could be exploited. For instance stream 1b has a heat content of 1.7MW, 2b has 4.8MW, 3b has 5.6MW, 11a has 2.57MW and 13 has as much as 15MW. All these heat quantities are absorbed by external cooling fluids. Instead of cascading all these energies into a cold utility, they could be used in exchange with the crude stream and others to reduce the hot utility demand. This is where saving is expected to be made.
2. Stream 1 (1a plus 1b together in Fig. 6), going to storage at a temperature of 60°C is rather high. More heat can be obtained from this stream by sending it to storage at 40°C. After supplying 1.27MW to stream 15 through exchanger N1 (Figure 7), stream 1a comes out with a temperature of 243°C. A duty of 3.89MW is required to service exchangers E62 and E02 which are connected to stream 19. Out of this 3.81MW is to supplied to maintain the ΔT_{min} of 20°C. This leaves the stream coming out with an outlet temperature of 90°C. It goes through cooler EA63 and comes out at 40°C to storage. This leads to a reduction in the heat load of cooler EA63 from 1.67MW to 1.03MW.
3. Exchanger 61 is expected to send a heat load of 3.81MW from stream 2a to one of the branches of stream 19. The existing exit temperature on 2a does not give the required load. A reduction from 181.1°C to 176.5°C does give 3.81MW. This leads to a reduction of the exit temperature of EA62 if the same duty is maintained.
4. A key criterion of below the pinch design is that $CP_{Hot} \geq CP_{Cold}$. This would seem not to support the connection involving exchangers E62 and E02 between streams 1a and stream 19. The same limitation may be seen with connection E61 between stream 2a and 19, connection E63 and E03 between streams 3a and 19. However these connections are acceptable because the terminal temperatures of the exchangers involved do not violate the ΔT_{min} of 20°C. All the other exchanger connection on the below pinch side do not violate this criterion.
5. The old connections of exchanger E05 and E65 between the split streams of 20a and stream 5 was broken because it crossed the pinch. The connection was remade between stream 3a below the pinch, using the old exchanger E65 and E5. The other connection on 3a is an existing one.
6. The connection between stream 6 and branches of stream 2a is an old one. In this case the exit temperature from E4 and E64 of 176°C is such that 0.76MW can be extracted from this stream to heat stream 18. This brings the total energy saving to 8.53MW (i.e. 7.77+0.76).

5. CONCLUSION

This purpose of this work was essentially to investigate if This was the target for the retrofit design in this analysis. Higher investment, which goes with a smaller ΔT_{min} would of course save more energy, but the time required for recovery would also be longer.

The analysis led to a hot utility savings of 8.53MW. At a cost of $71,200 per MW of hot utility, this constitutes a savings of $607,336 per annum. The savings constitute about 60% of the retrofit target for the same investment. The design provided is by no means exhaustive. Other design scenarios could be developed.

It should also be pointed out that the greatest source of error is in the financial investment suggested. This is due to the fact that the constant- α curve is arbitrary. In practice, investment would be better determined from the number and types of exchangers that would actually be required for the retrofit. The analysis was based on simulation data for the plant. Further work will involve use of actual plant data.

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Table 1: Properties Of Topping Unit Streams (Bonny Medium, Data from TOR)

STREAM, [No.]	Type	T_S(°C)	T_t(°C)	CP (ΔH/ΔT)
92/95 (1a)	H	294.8	141.1	0.0249
95/96 (1b)	H	141.1	60.0	0.0206
72/73 (2a)	H	265.1	181.1	0.0430
73/74 (2b)	H	181.1	50.0	0.0366
103/106 (3a)	H	270.9	163.3	0.0934
106/107 (3b)	H	163.3	97.0	0.0844
100/103 (4)	H	325.6	270.9	0.0934
80/83 (5)	H	309.2	257.6	0.0959
60/63 (6)	H	229.0	170.5	0.1453
52/53 (7a)	H	185.6	60.0	0.0173
53/54 (7b)	H	60.0	40.0	0.0152
912/913 (8)	H	217.0	214.6	0.0488
312/313 (9a)	H	158.4	66.5	0.0097
313/314 (9b)	H	66.5	40.0	0.0084
200/201 (10)	H	47.9	36.0	0.0177
300/301 (11a)	H	87.8	55.0	0.0792
301/302 (11b)	H	55.0	40.0	0.0140
954/955 (12)	H	90.0	40.0	0.0005
40/41 (13)	H	138.9	40.0	0.1519
911/912 (14)	H	242.4	217.0	0.0465
910/911 (15)	C	214.6	242.4	0.0463
44/45 (16a)	C	40.0	106.4	0.0123
45/46 (16b)	C	106.4	114.3	0.0133
210/[211/212] (17)	C	164.0	183.0	0.0622
310/[311/312] (18)	C	147.5	158.1	0.1622
10/18 (19)	C	18.0	137.9	0.1501
19/26 (20a)	C	135.0	237.0	0.1596
26/29 (20b)	C	237.0	344.4	0.2653

Table 2: Duty, Area and Cost of Heat Exchangers, Coolers and Furnaces (Data from TOR)

Designation of Exchanger	**Duty (MW)**	**Area (m^2)**	**Cost (x$1000)**
Heat Exchangers			
01-E-61	3.59	123	53
01-E-01R	3.19	151	59
01-E-62	1.78	74	40
01-E-02R	2.70	85	43
01-E-63	4.10	385	103
01-E-03R	4.25	505	131
01-E-64A/B	4.10	292x2	152
01-E-04AR/BA	4.21	124x2	88
01-E-65	2.63	134.3	46
01-E-05	2.63	134	46
01-E-66A/B	2.53	124x2	90
01-E-06AR/BR	2.64	124.5x2	91
01-E-69A/Bx2	2.45	96x2	76
01-E-17R	2.06	111	46
	Total Area	3693	-
Cooling Exchangers			
01-E-67A/B	1.71	93x2	105
01-E-68	0.43	44	34
01-E-70	1.02	191	83
01-E-71	0.92	191	83
01-E-72	0.22	16.5	23
01-E-73	0.61	96	38
01-E-19	4.90	401	115
	Total Exch. Area	4322	1545
Cooling Fans			
01-EA-61	4.91	372	170
01-EA-62	5.58	74	168
01-EA-63	2.60	204	112
01-EA-64	6.68	963	170
01-EA-51M	27.27	2443	897
Furnaces			
01-F-01	18.20	-	-

Table 3: Comparison of Energy demand of individual streams with installed capacity of Exchangers

Stream No.	Energy Demand, $\Delta H=CP(\Delta T)$	Installed Heat Exchanger Duty
1	5.50	7.11
2	8.41	9.23
3	15.89	15.03
4	1.91	5.17
5	4.95	5.30
6	8.50	8.48
7	2.47	4.14
8	0.12	0.61
9	1.11	3.48
10	0.21	1.72
11	2.81	5.38
12	0.03	0.22
13	1.18	4.93
15	1.24	6.19
16	0.93	3.07
17	1.18	4.93
18	1.72	2.07
19	18.0	19.71
20	44.8	55.72
21	15.0	27.43

Table 4: Summary of Energy-Area-Cost calculations

ΔT_{min} (°C)	E_t (MW)	Target area, m^2 (A_t)	Constant- α area, m^2 (A_c)	Additional area, m^2 ($A_d=A_c-A_{ex}$)	Cost of A_d (x$1000) (Investment)	Energy Savings, MW ($E_{ex}-E_t$)	Savings (x$1000)
10°	14.67	4911	23975	20282	4279	16.52	1176.2
20°	16.69	3095	15111	11418	2420	14.50	1032.4
30°	18.72	2330	11375	7682	1637	12.47	887.9
40°	20.74	1823	8902	5209	1118	10.45	744.0
50°	22.76	1518	7413	3720	806	8.43	600.2
60°	24.78	1281	6249	2556	562	6.41	456.4
70°	26.80	1076	5253	1560	353	4.39	312.6
80°	28.83	922	4501	808	195	2.36	168.0
*	30.85	797	3890	197	67	0.34	24.2

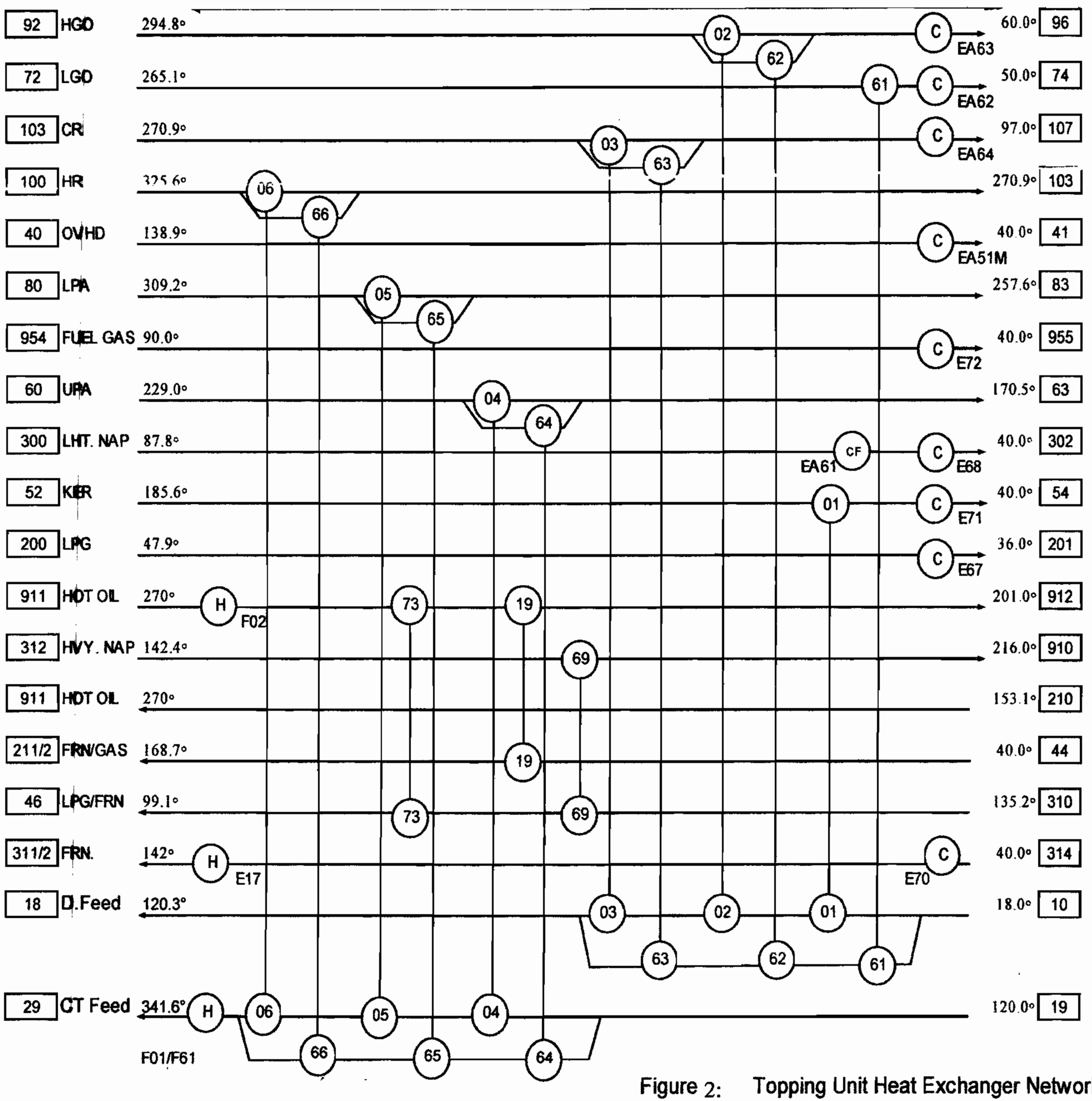


Figure 2: Topping Unit Heat Exchanger Network

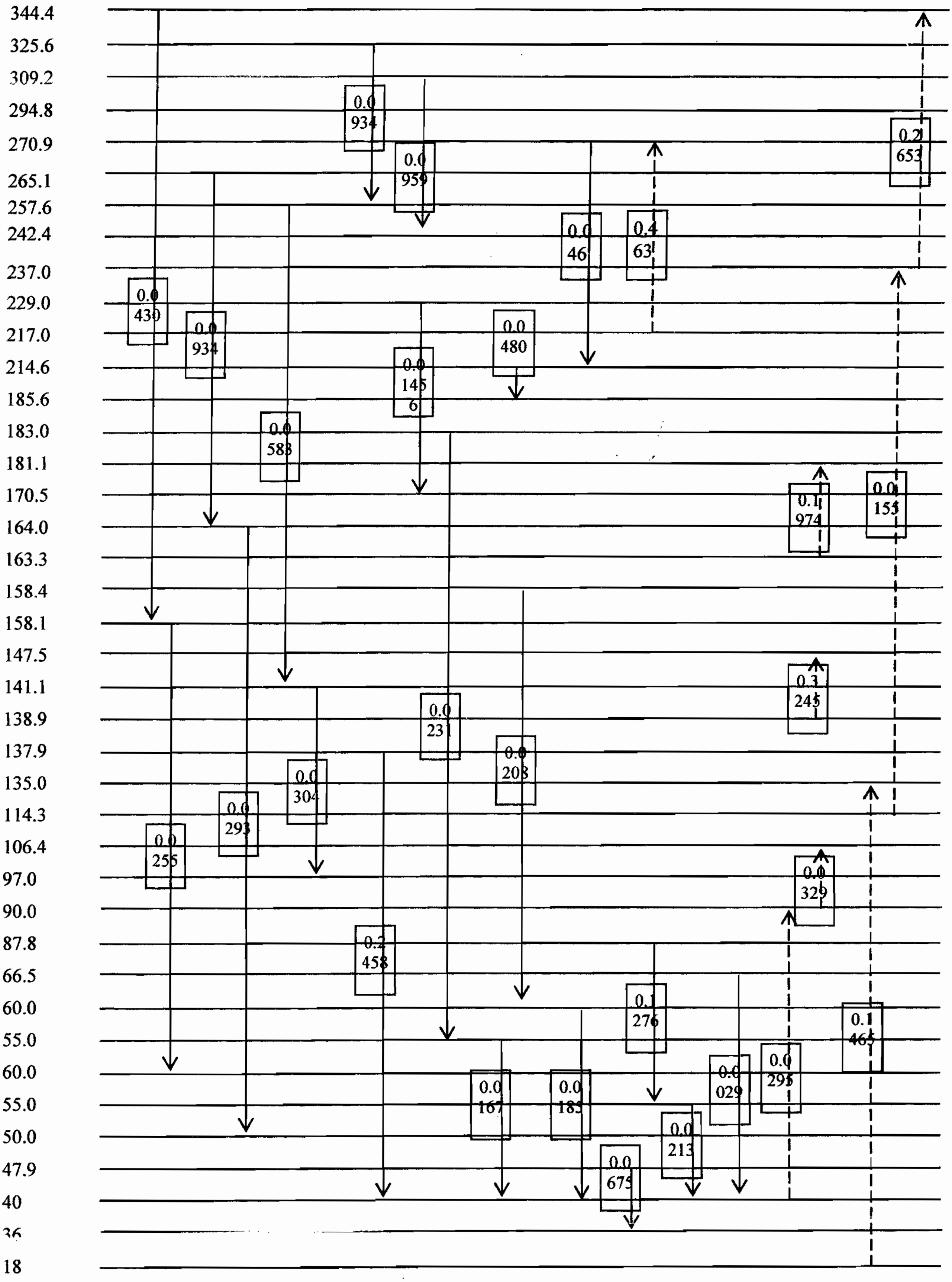


Figure 3: Temperature layout for Bonny Medium

Figure 4: Area-energy relations for existing and potential networks

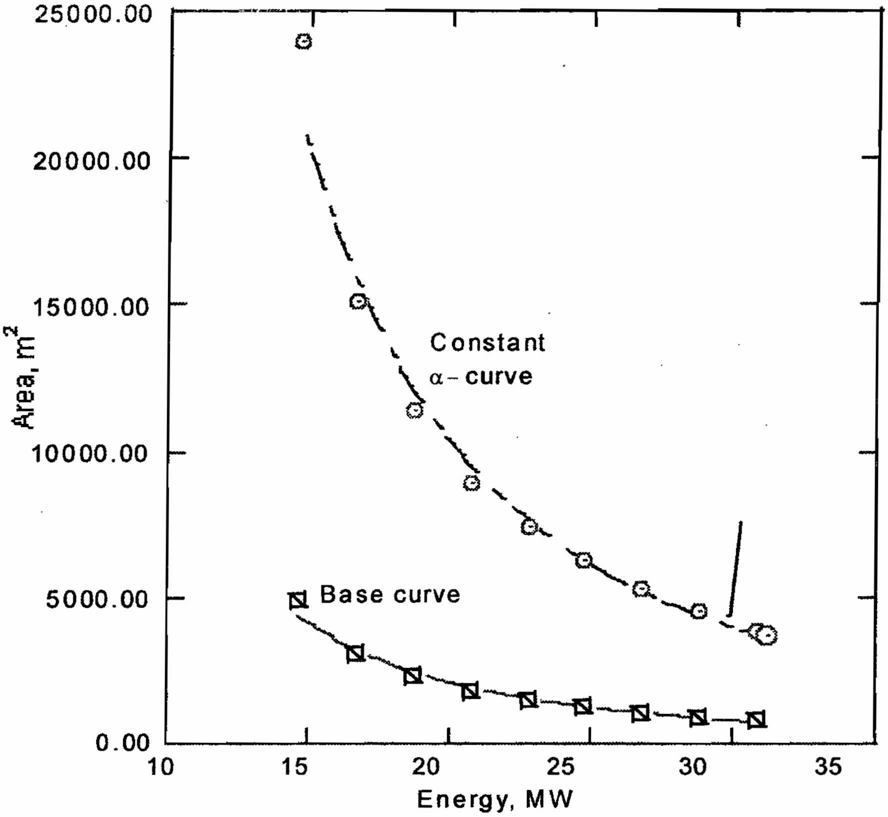
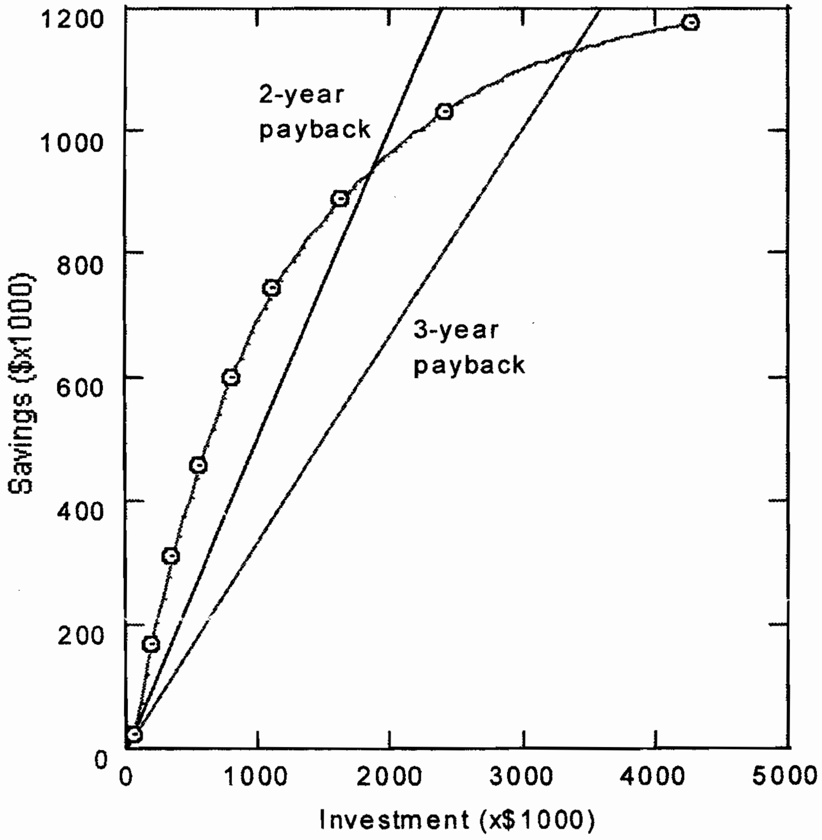


Figure 5: Investment-savings plot



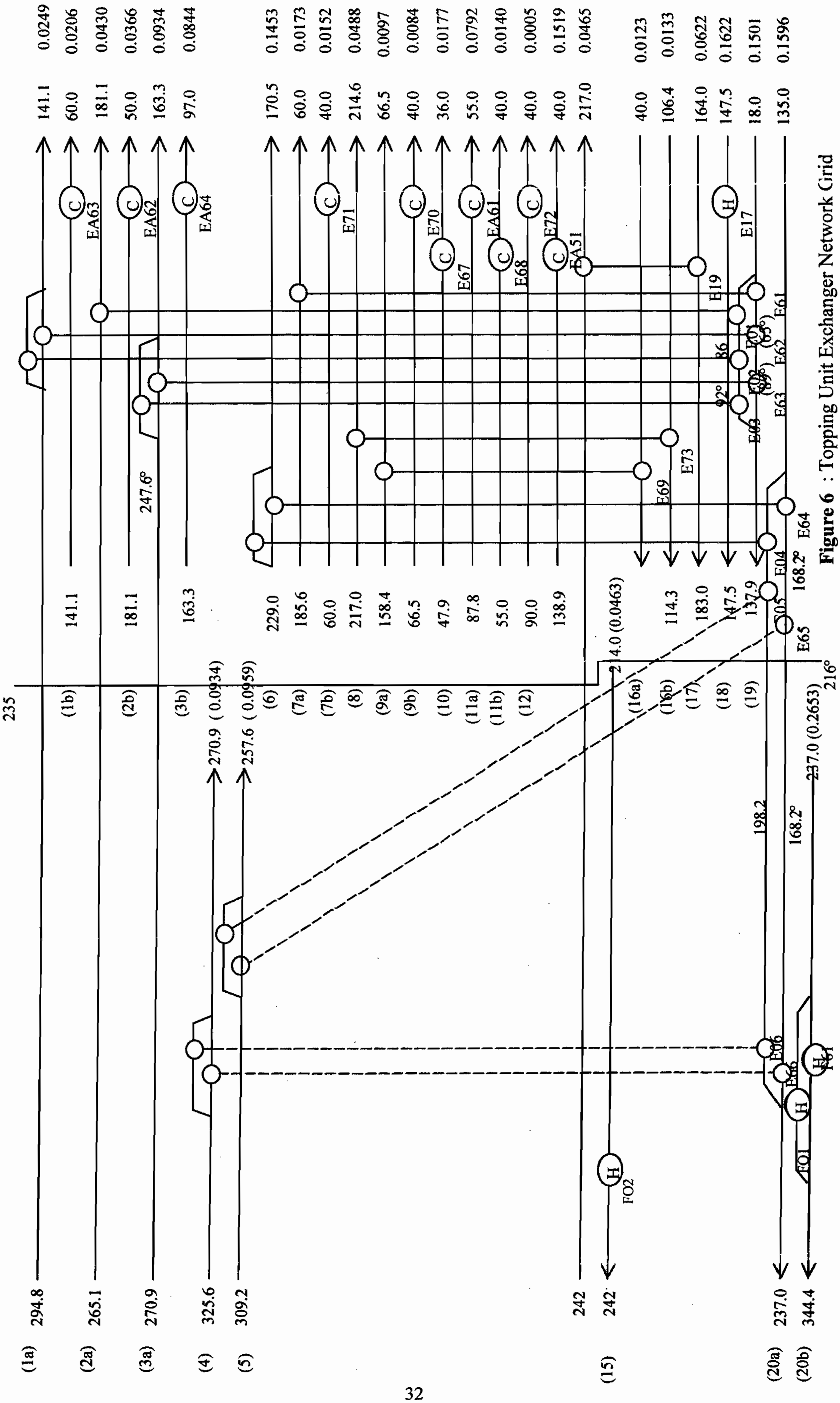


Figure 6 : Topping Unit Exchanger Network Grid

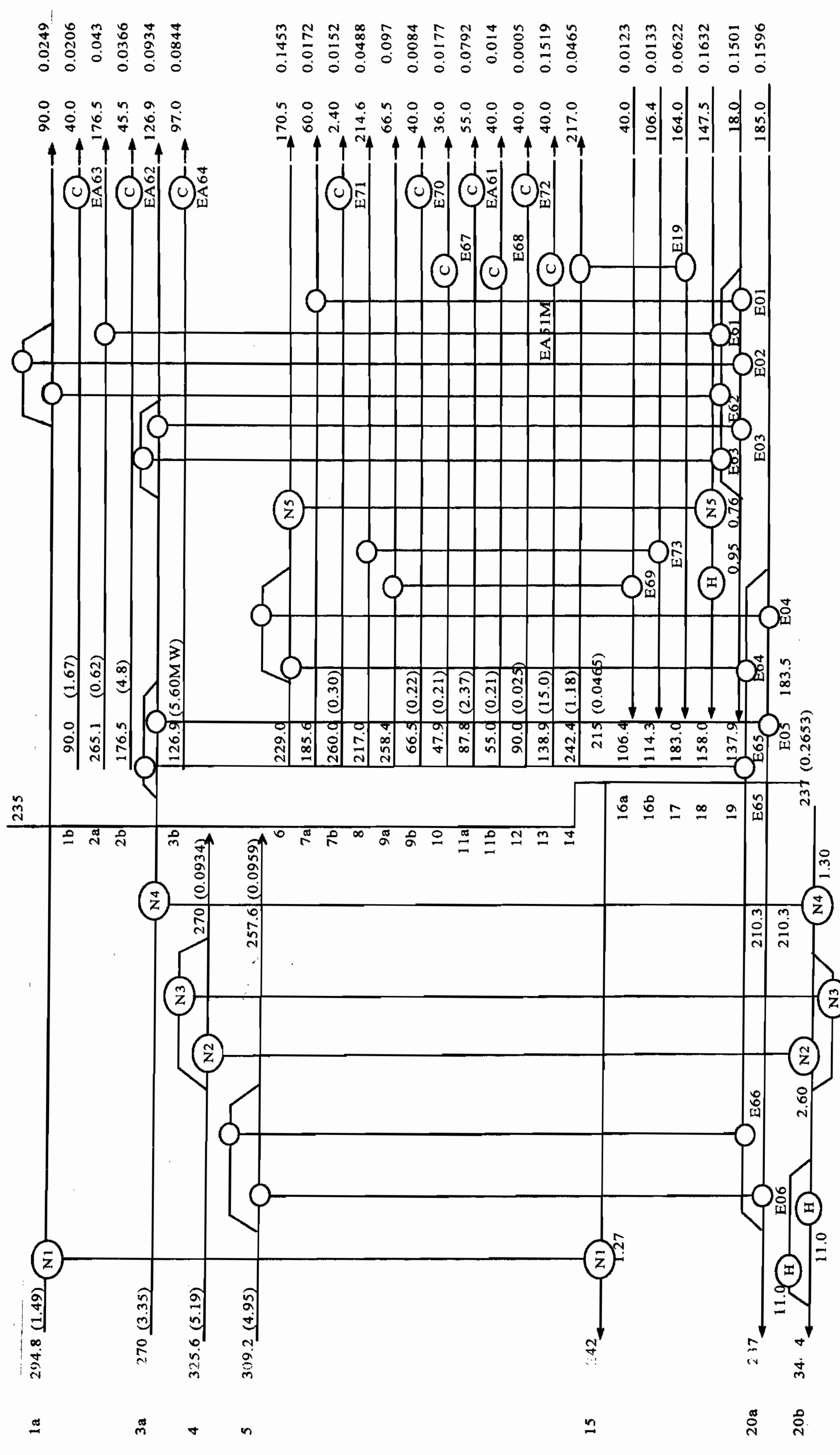


Figure 7: Improved Network - Bonny Medium