ENERGY
CONSERVATION

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REFINERY ENERGY PROFILE

User's Guide

By
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T. G. Golden

January 1979

Work Performed Under Contract No. EY-77-C-05-5262

Gulf Research & Development Company
Pittsburgh, Pennsylvania

MASTER

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Division of Industrial Energy Conservation

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OFFICE OF INDUSTRIAL PROGRAMS

USER'S GUIDE

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SECTION I

SUMMARY

Energy profiles are essentially detailed energy balances of refineries showing all inputs and losses for the total refinery and for each of the individual processing units. By showing the losses from each individual heater, exchanger, etc., the items with the greatest potential for saving energy are pinpointed for further evaluation. This User's Guide contains the step by step procedure that has been developed for preparing energy profiles at any refinery. The guide is written for people familiar with refinery equipment and operations and should provide sufficient guidance so that problems in preparing an energy profile at any refinery can be resolved.

The technique is presented as four parts (Sections 2, 3, 4, and 5 in this write up) covering preparation, data gathering, performing calculations and preparing the profiles. Section 2 on preparation gives the steps to take in starting the project and the procedures to follow in making preparations for gathering the raw data needed to calculate the various energy balances that are used in developing refinery energy profiles. Section 3 gives the procedures for gathering the raw data at a refinery. Section 4 gives the procedures for calculating the various energy balances. Section 5 gives the procedures for preparing the profiles once the various calculations have been completed.

The User's Guide is written as a procedure that will produce an accurate energy profile for an entire refinery. Rigorous calculation procedures are used that require the collection of substantial amounts of data and in some cases use commercially available computer programs. Since situations can arise where the data required for rigorous procedures or computer programs cannot be obtained, alternate calculation procedures are given which can be used when some sacrifice in accuracy is justifiable and acceptable.

An energy profile is essentially a tool for guiding energy conservation activities. Each user will have to decide how this tool can best be utilized as an energy conservation aid. For a user that has already reduced his energy losses from the more obvious areas, a complete, accurate energy profile can supply the data needed for identifying the less obvious areas. A user just beginning to develop an energy conservation program may begin by using the simplified calculation procedures given to more quickly determine an overall energy profile, or may begin by evaluating only known high loss areas such as heater stacks and air and water cooled heat exchangers. In other cases, a user may want to use the procedures to evaluate a single unit and even a single piece of equipment.

Any user of this procedure should first review the entire procedure and then decide how it can best be applied to his particular situation. The use to which the procedure is applied will determine the degree of accuracy that will be required. The accuracy requirement will dictate which calculation procedures should be used, and selection of the calculation procedures to be used will in turn determine the data collection requirements.

The technique is not presented here as a procedure for regular monitoring of total refinery energy consumption. The refining industry has already developed routine procedures for calculating and reporting their semi-annual overall net utility energy consumption based on data routinely collected, such as utility bills, etc. These procedures require only a fraction of the time required to develop a complete energy profile and should continue to be used for their intended purpose.

The final report for DOE contract DE-AC05-77CS05262 under which this procedure was developed, described the development of a refinery energy profile as carried out at Gulf's Alliance refinery, and may be of interest to review before beginning any work.

SECTION 2

PREPARATION

The procedures in this User's Guide have been written to produce an accurate energy profile for an entire refinery. However, the procedures can be used to prepare profiles for a single unit or for an individual piece of equipment. Alternate procedures are also included that in most cases can be used to reduce the time and effort required to develop a profile but also result in some sacrifice in accuracy. The user should review the entire procedure and decide how he wants to apply it to his particular situation. By determining how he will use the procedure and the degree of accuracy that is acceptable, the user can tailor the procedures to his purpose, particularly the data gathering procedures.

If a user decides to do a profile of an entire refinery or of several units, there are two methods that can be employed and need to be considered in carrying out the procedure. Method 1 would be to gather the data for all units during one time period, then do the calculations and develop the profiles. Method 2 would be to gather the data on one unit, do the calculations for that unit, and partially develop the profile before moving on to gathering data for the next unit. In Method 2, the complete profile would have to be developed after data have been gathered for all units and normalized (See Section 5.1.1). The advantages and disadvantages for both methods are listed below.

METHOD 1: Gather all data for the entire refinery.

Advantages

1. Best method for a Task Force approach where additional people and instrumentation are brought in.
2. Gives the best profiles for the entire refinery since variations are minimized.

Disadvantages

1. The data gathering must be carefully planned in order to minimize the chance of missing data.
2. Requires more time since refamiliarization with each unit is required in proceeding from preparation, to data gathering, to calculations.

METHOD 2: Gather the data and do calculations one unit at a time.

Advantages

1. The efficiency of data collection and profile development are increased as the work progresses.

2. If some data is missed or gives conflicting results, there is a better chance of rechecking the data.

Disadvantages

1. An overall refinery profile is more difficult to develop due to the variations which can occur over a longer period of time.

Other factors can enter in which tend to favor one method over another. For a highly integrated refinery, gathering all the data in one short time period might be preferable, but for a non-integrated refinery the unit at a time approach would probably be preferred.

The availability of people to do a profile is also a factor. If outside people are doing the profile, the Task Force approach of gathering all the data at once might be preferred. If a small group of refinery staff people are doing the profile, the unit at a time approach might be preferred.

2.1 Initial Preparations

Step 1: Study the refinery and separate it into units that can be profiled individually. As an example, Figure 2-1 gives a simplified flow diagram for a typical U.S. refinery showing the major types of units. Table 2-1 gives a sample "breakout" of units for such a refinery.

Step 2: Determine the elements in each unit that consume, generate, or transfer energy and determine the types of data that need to be gathered to evaluate each element. The criteria for selecting the elements are given in Section 4.0. Table 2-2 illustrates the types of data that need to be gathered for the various elements for calculating material and energy balances.

Table 2-3 lists typical elements concerned with consuming, generating, or transferring energy for a refinery crude unit. This list is presented here to illustrate the type of energy elements to be considered, not to imply that it is always necessary to make a formal listing to carry out the work.

FIGURE 2-1 - A TYPICAL U.S. REFINERY
(Simplified)

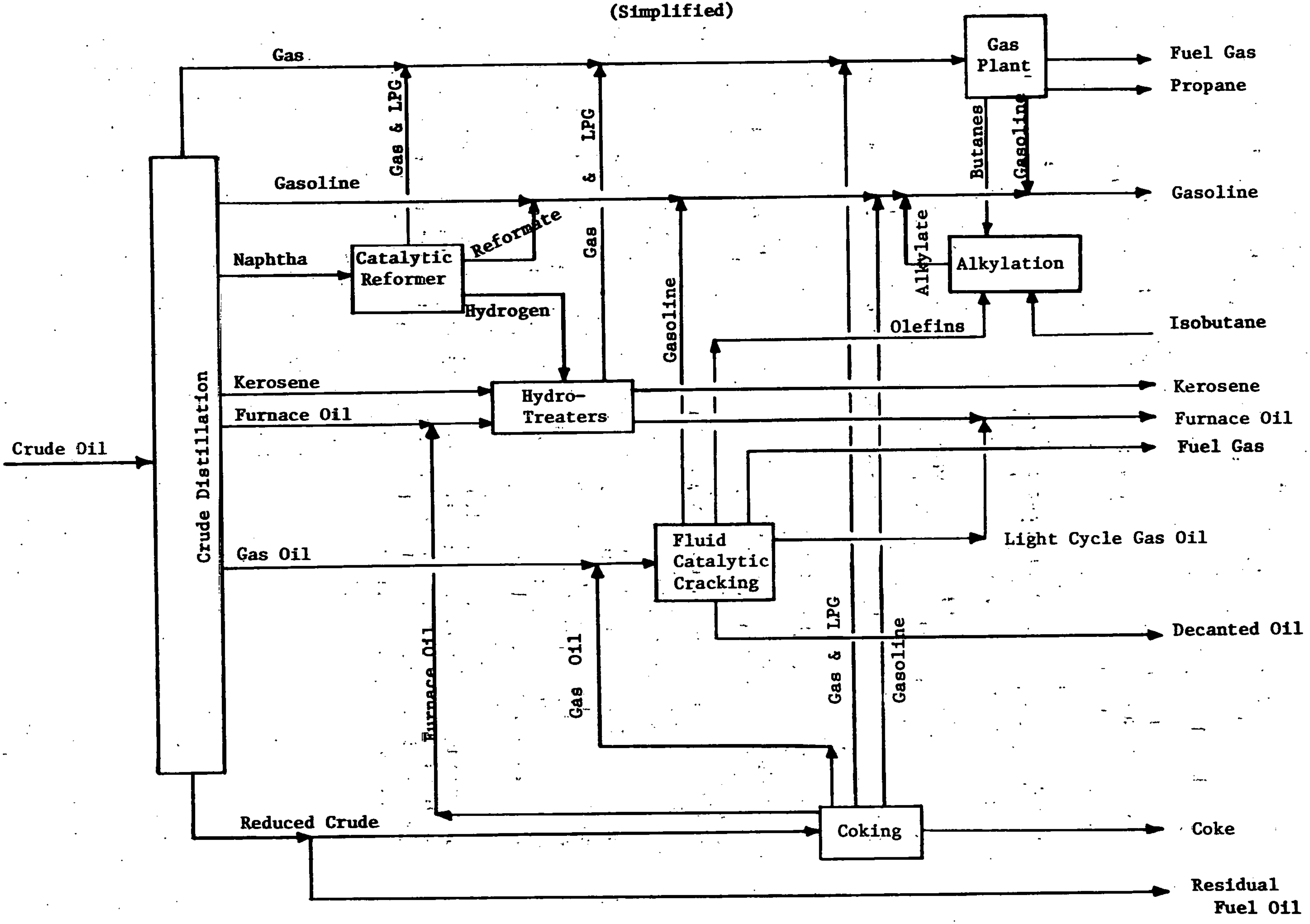


TABLE 2-1

SAMPLE BREAK-OUT OF UNITS

Name
Atmospheric & Vacuum Unit
Hydrotreater #1
Hydrotreater #2
Alkylation Unit
Delayed Coking Unit
Fluid Catalytic Cracking Unit
Catalytic Reforming Unit
Saturate Gas Unit
Utilities
Offsites

TABLE 2-2

TYPE OF DATA REQUIRED ON MAJOR ENERGY ELEMENTS FOR DETAILED ENERGY PROFILE

ITEM	TYPE OF ENERGY CALCULATION	TYPE OF STREAM	TYPE DATA FLOW$^{(4)}$	 ANALYSIS$^{(3)}$	 TEMPERATURE OUT	 TEMPERATURE IN	 PRESSURE OUT	 PRESSURE IN	OTHER DATA AND REMARKS
Furnaces & Boilers	Input	Fuel	X	X		X			
"	Output$^{(1)}$	Hydrocarbon	X	X	X	X	X$^{(2)}$	X$^{(2)}$	For each stream
"	Output	Steam	X		X	X	X	X	
"	Loss	Stack Gas		X	X				Air temperature and humidity
"	Radiation Loss	—							Configuration with respective area & temperature; ambient condition
Electric Power	Input	Power							Unit substations Kilowatts, design values on connected horsepower
Motors	Input	Power							(Amp, volts, power factor) or Watts on very large motors
Turbines	Input & Output$^{(1)}$	Steam	X$^{(5)}$		X$^{(5)}$	X	X	X	Design values$^{(1)}$
"	Input & Output	Steam			X$^{(5)}$	X	X	X	Steam chest pressure, Design values
Reactors	Heat of Reaction	Hydrocarbon	X	X	X	X	X$^{(2)}$	X$^{(2)}$	Compose flow from feed and/or product streams
"	Radiation	—							Configuration with respective area & temperature: ambient condition
Regenerators	Input	Air/Coke	X			X		X	
"	Output	Flue Gas		X	X		X		Steam injected
"	Radiation Loss								Configuration with respective area & temperature; ambient condition
Power Recovery	Input	Fluid	X	X		X		X$^{(2)}$	Design values$^{(1)}$
"	Output	Fluid	X	X	X	X	X	X$^{(2)}$	Design values$^{(1)}$
"	Output	Power							Kilowatts or (volts, amps, power factor)
Steam Reboilers	Input	Steam	X		X	X	X$^{(2)}$	X$^{(2)}$	
"	Output	Hydrocarbon	X	X	X	X	X$^{(2)}$	X$^{(2)}$	Design values$^{(1)}$
Coolers-Water	Loss$^{(1)}$	Hydrocarbon	X	X	X	X	X$^{(2)}$	X$^{(2)}$	
"	Loss$^{(5)}$	Water	X		X	X			
Coolers-Air	Loss	Hydrocarbon	X	X	X	X	X$^{(2)}$	X$^{(2)}$	Design values$^{(1)}$
Exchangers$^{(1)}$	Transferred	Fluid 1	X	X	X	X	X$^{(2)}$	X$^{(2)}$	Only one side required, Design values$^{(1)}$
"	" (1)	Fluid 2	X	X	X	X	X$^{(2)}$	X$^{(2)}$	
Inlet Streams to Unit	Import	Hydrocarbon	X	X		X		X$^{(2)}$	——
"	Import	Steam	X			X		X	
"	Import	Chemical	X			X			Specific heat
Outlet Streams from Unit	Export	Hydrocarbon	X	X	X		X$^{(2)}$		
"	Export	Steam	X		X		X		
"	Losses	Hydrocarbon	X	X$^{(5)}$	X				
"	Losses	Wastes	X	X	X		X$^{(2)}$		Heating value, composition estimate
Hot Surfaces	Radiation Loss								(Surface temperature, configuration, area and ambient conditions)

Notes:

(1) Additional data for alternate calculation if primary data cannot be taken.
(2) Required if a vapor phase is present.
(3) ASTM distillation, Lt. ends analysis, and API gravity for liquids. Component Vol. % for vapors.
(4) Where flow measurements cannot be made directly, additional information will be required
(5) Alternate calculations and data will be required if this data cannot be taken.

TABLE 2-3 (Sheet 1 of 2)

TYPICAL CRUDE UNIT MAJOR ENERGY ELEMENTS*

Service
Furnaces
Atmospheric Charge Heater
Vacuum Charge Heater
Electric Motor Drivers*
Raw Crude Pump
Desalted Crude Pump
Top Pumparound Pump
HFO Pumparound Pump
HFO Product Pump
Atmospheric Fractionator Bottoms Pump
Straight Run Debutanizer Charge Pump
#2 HO Product Pump
Vacuum Recycle Pump
Vacuum Residue Pump
HVGO Product Pump
LVGO Product Pump
Desalter Water Pump
Atmospheric Fractionator Overhead Fan
Miscellaneous Motors
Steam Turbine Drivers
Atmospheric Fractionator Bottoms Pump
Vacuum Recycle Pump
Boiler Circulation Pump
Water Coolers & Condensers
Atmospheric Fractionator Overhead Trim Cooler
LFO Product Cooler
HFO Product Cooler
LVGO Pumparound Cooler
1st Stage Intercondenser
2nd Stage InterCondenser
34d Stage InterCondenser
Air Coolers & Condensers
HFO Product Cooler
HFO Pumparound Cooler
HVGO Pumparound Cooler
Atmospheric Fractionator Overhead Condenser
LFO Product Cooler
Desalter Water Effluent Cooler

TABLE 2-3 (Sheet 2 of 2)

TYPICAL CRUDE UNIT MAJOR ENERGY ELEMENTS

Service
Heat Exchangers
TPA/Crude
HFO Prod/Crude
HFO PA/Crude
AGO/Crude
Vacuum Tower Bottoms
HVGO PA/Crude
Process & Misc.
Atmospheric Tower
Side Strippers
Ejectors
Miscellaneous
Import
Crude Charge
Process Slop
Sour Water
Clarified River Water
Fuel Gas
Heavy Polymers
Export & Products
Sour Water
Gas to SGU
Naphtha to SGU
HFO Products
HFO PA to SGU
LFO Products
AGO Products
#2 HO Products
HVGO Products
Vacuum Tower Bottoms

*Items such as motors may be grouped where total energy effects are minimal.

Step 3: Review the types of data that are currently being routinely recorded in the refinery. A considerable amount of data is generally available from unit log sheets, particularly flow, temperature, and pressure data. Daily operating reports may supply information on unit charge rates and yields and utilities consumption. Monthly utility bills will give purchased electric power and fuel consumption. Any currently available data may serve as a backup or, if necessary, may be the primary data used in calculating energy balances.

2.2 Preparations for Gathering Data

At this point, the user should have reviewed the entire procedure and decided what data is needed to give the degree of accuracy that is acceptable for the profile. The following procedures are designed for collecting the data necessary for calculating an accurate profile but can be modified if less accuracy is acceptable.

Step 1: For each unit determine where existing instrumentation is available for measuring the flow, temperature, pressure, and other applicable data required for each element as determined in Section 2.1, Step 2. Also determine the location of existing sample points.

Step 2: Mark the location of all data and sample points identified in Step 1 on the process flow sheet for each unit. Also mark the location of any points where data is needed, but existing instrumentation or sample points are not available. A flow diagram for a crude unit with the data points marked on it is shown in Figure 2-2. The major energy elements for the crude unit shown in Figure 2-2 were listed in Table 2-3.

FIGURE 2-2 CRUDE UNIT FLOW DIAGRAM - SECTION 1 OF 5

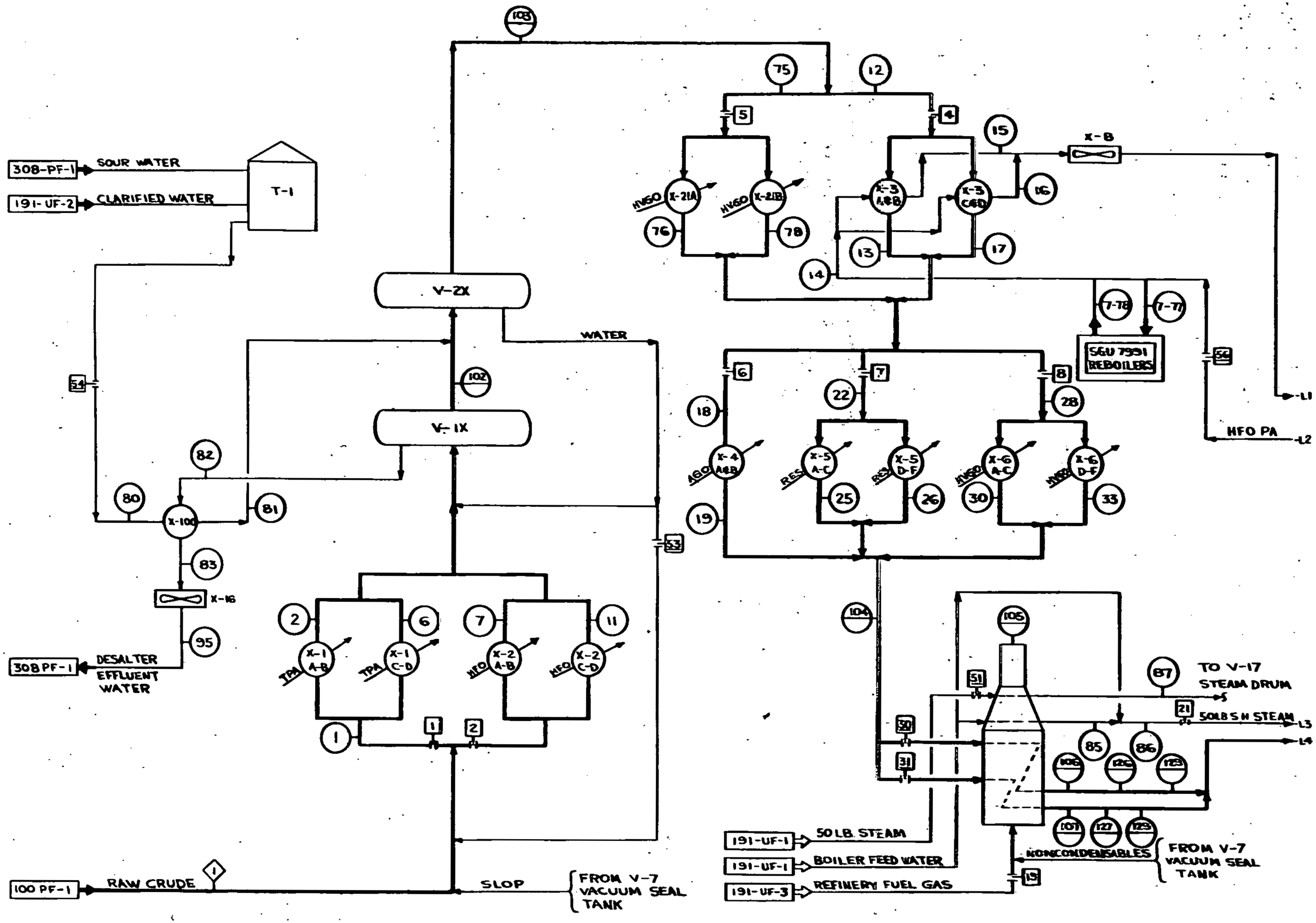


FIGURE 2-2 CRUDE UNIT FLOW DIAGRAM - SECTION 2 OF 5

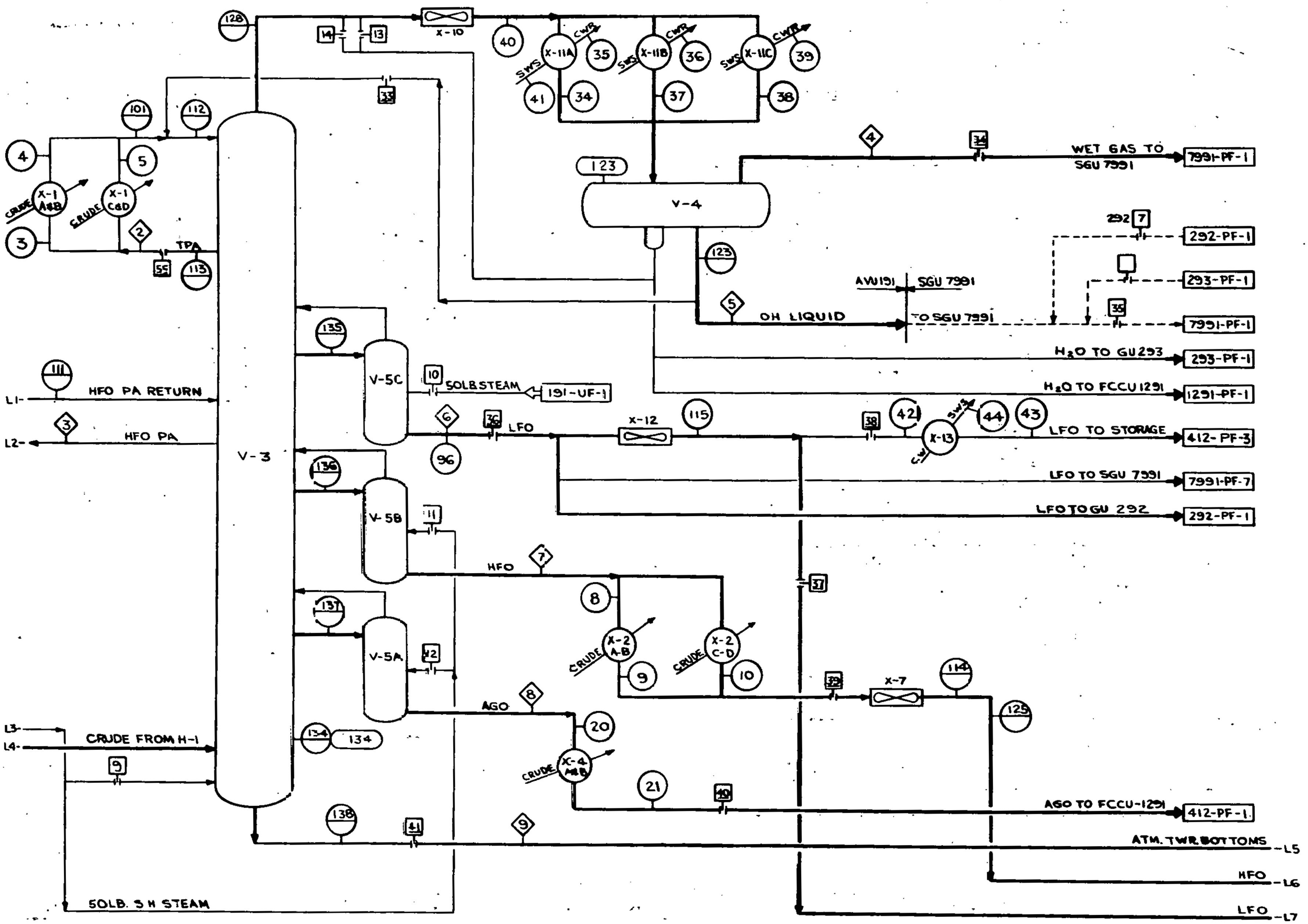


FIGURE 2-2 CRUDE UNIT FLOW DIAGRAM - SECTION 3 OF 5

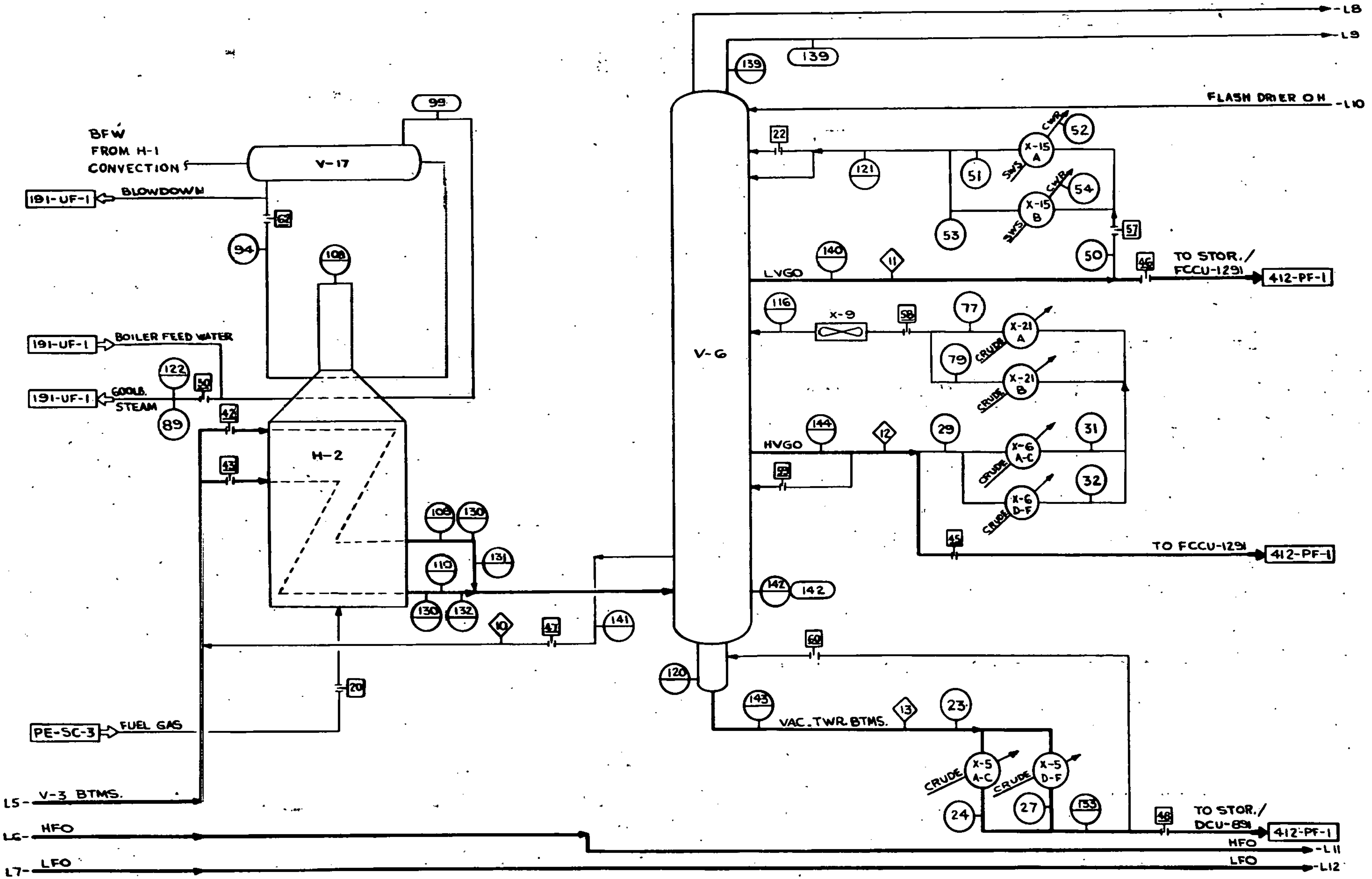


FIGURE 2-2 CRUDE UNIT FLOW DIAGRAM - SECTION 4 OF 5

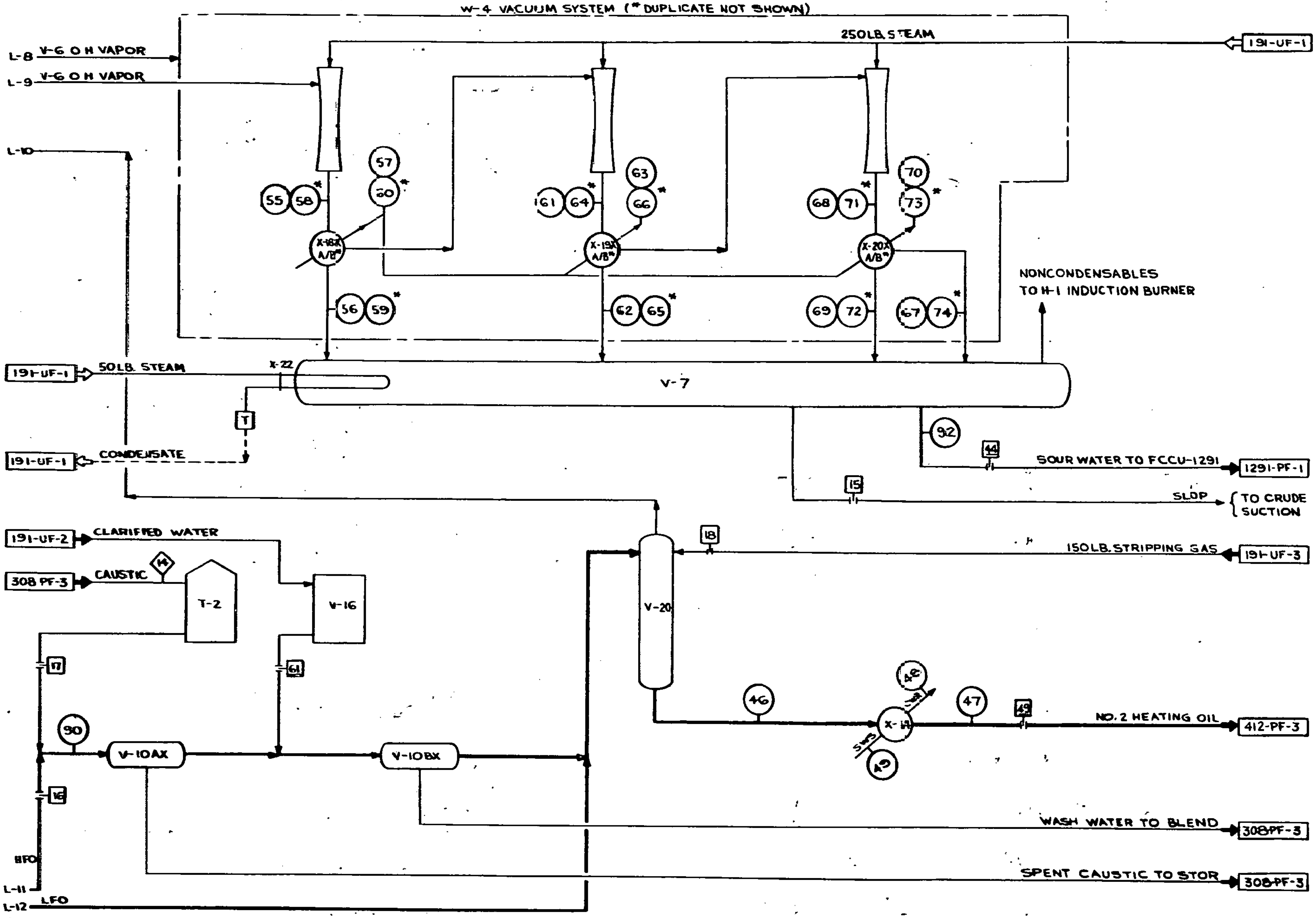
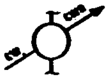


FIGURE 2-2 CRUDE UNIT FLOW DIAGRAM - SECTION 5 OF 5

EQUIPMENT LIST

TYPE	SYMBOL	ITEM	DESCRIPTION
HEATERS		H-1	CRUDE CHARGE HEATER
		H-2	VACUUM HEATER
TANKS		T-1	DESALTER WATER STORAGE TANK
		T-2	CAUSTIC STORAGE TANK
VESSELS & TOWERS	 OR 	V-1X	FIRST STAGE DESALTER
		V-2X	SECOND STAGE DESALTER
		V-3	ATMOSPHERIC FRACTIONATOR TOWER
		V-4	ATMOSPHERIC FRACTIONATOR OH ACCUMULATOR
		V-5A	AGO STRIPPER
		V-5B	HFO STRIPPER
		V-5C	LFO STRIPPER
		V-6	VACUUM TOWER
		V-7	VACUUM SEAL TANK
		V-10AX	FIRST STAGE NO.2 FUEL OIL TREATER
		V-10BX	SECOND STAGE NO.2 FUEL OIL TREATER
		V-16	CLARIFIED WATER SURGE DRUM
		V-17	STEAM DRUM
		V-20	NO.2 HEATING OIL FLASH DRUM
HEAT EXCHANGERS		X-1	CRUDE/TPA EXCHANGER
		X-2	CRUDE/HFO PRODUCT EXCHANGER
		X-3	CRUDE/HFO EXCHANGER
		X-4	CRUDE/AGO EXCHANGER
		X-5	CRUDE/VAC TWR BTMS EXCHANGER
		X-6	CRUDE/HVGO PA EXCHANGER
		X-21	CRUDE/HVGO EXCHANGER
AIR COOLERS & CONDENSERS		X-7	HFO PRODUCT COOLER
		X-8	HFO COOLER
		X-9	HVGO COOLER
		X-10	ATM. TWR. OH CONDENSER
		X-12	LFO PRODUCT COOLER
		X-16	DESALTER WATER COOLER
WATER COOLERS & CONDENSERS		X-11	ATM. TWR. OH TRIM COOLER
		X-13	LFO PRODUCT TRIM COOLER
		X-14	NO. 2 HEATING OIL PRODUCT COOLER
		X-15	LVGO COOLER
		X-18	FIRST STAGE INTERCONDENSER
		X-19	SECOND STAGE INTERCONDENSER
		X-20	THIRD STAGE AFTERCONDENSER
STEAM HEATERS		X-22	SEAL TANK BAYONET HEATER
EJECTORS		U-1X	FIRST STAGE EJECTOR
		U-2X	SECOND STAGE EJECTOR
		U-3X	THIRD STAGE EJECTOR

LEGEND

Ⓝ	TEMPERATURE DATA REFERENCE NO.
(N)	PRESSURE DATA REFERENCE NO.
[N]	FLOW DATA REFERENCE NO.
◈ N	STREAM COMPOSITION REFERENCE NO.
N	DATA REFERENCE NO. (OUTSIDE READING)
<u>N</u>	DATA REFERENCE NO. (CONTROL ROOM READING)
➡ REFERENCE	STREAM ENTERING OR LEAVING UNIT AS IMPORT OR EXPORT
⇨ REFERENCE	STREAM ENTERING OR LEAVING UNIT SHOWN SEPARATELY ON PROFILE FROM IMPORT OR EXPORT

Step 3: Prepare data sheets for recording the data to be collected. List all points where data is needed on the data sheets in a manner that will permit collecting the data in a systematic manner. This can include identifying instruments by number and location. Examples of three data sheet formats that may be used are shown in Figures 2-3, 4, 5.

Comment: Probably the most important step in preparing for gathering the data is to make sure that all data that could be needed in calculating energy balances is listed on a data sheet before the data gathering begins. This will help to insure that important data is not missed during the data gathering.

Step 4: Arrange, if possible, for additional instrumentation to be employed at points where data is required but existing instrumentation is not available. An example would be to use a portable flow meter to obtain readings from unmetered orifices. Plan to use a test instrument such as a thermocouple based instrument or a calibrated dial thermometer at points where dial thermometers are installed, since the existing dial thermometers may be inaccurate.

Step 5: Make arrangements for analyzing all samples that are to be collected. In general, most liquid hydrocarbon samples will need to have a gravity and a distillation analysis, and most gaseous samples will need a chromatographic analysis. In many cases the samples that are needed for a profile are already being routinely collected and analyzed by a refinery laboratory. Some samples may not be routinely analyzed by the refinery laboratory and special arrangements, such as sending samples to an outside laboratory, may have to be made.

FIGURE 2-3

REFINERY ENERGY PROFILE
INSTRUMENT READING DATA SHEET

UNIT____________________ DATE____________________

TEMP/FLOW/PRESS RECORDER OR INDICATOR METER LOCATION____________

CODE	METER NO.	LOC. CODE	SERVICE	METER FACTOR	READING		UNITS
					SCALE	DIRECT	

REMARKS:____

Form 1

FIGURE 2-4

REFINERY ENERGY PROFILE
OUTSIDE TEMPERATURE READING DATA SHEET

UNIT_________________________ DATE______________________

CODE No.	EQUIP. No.	LOC. CODE	STREAM I.D. AND FLOW DIRECTION	INST. CODE	READING °F	COMMENTS

REMARKS:____

____

____

Form 2

FIGURE 2-5

REFINERY ENERGY PROFILE
LABORATORY ANALYSIS DATA SHEET

UNIT____

SAMPLE DESCRIPTION						
CODE NO.						
DATE TAKEN						
DATE RUN						
SAMPLE TYPE						
°API 60/60						
ASTM DIST						
IBP						
10						
30						
50						
70						
90						
EP						
% RECOVERY						
COMPONENT ANALYSIS						
1. H_2						
2. METHANE						
3. ETHANE						
4. PROPANE						
5. I-BUTANE						
6. N-BUTANE						
7. I-PENTANE						
8. N-PENTANE						
9. HEXANES PLUS						

REMARKS:____

Form 3

SECTION 3

DATA GATHERING

Gather the data on one unit at a time. Attempt to schedule the data gathering so that the unit and, if possible, the entire refinery is running "normally". All data should be gathered for each unit in the shortest time possible to minimize any fluctuations. Record all data on the data sheets prepared for each unit. The following steps are recommended:

Step 1: In the control room, take spot readings for all data points listed on the data sheets from the recorders and indicators. If permitted to remove the strip charts from the recorders, date all strip charts and pull them the next day as a backup.

Step 2: Concurrently, if possible, take spot readings from all instruments listed on the data sheets that are located outside the control room on the unit itself. For accuracy, a test instrument should be used to obtain readings at all dial thermometer locations listed on the data sheets.

Step 3: Collect all samples for analysis, again concurrently, if possible, with gathering all data in Steps 1 and 2.

Note: On pieces of equipment where many data readings are needed, such as a fired heater where fuel flow, fuel analysis, stack temperature, stack oxygen reading and surface temperature readings are needed, all readings should be taken as close together in time as possible.

SECTION 4

PERFORMING ENERGY CALCULATIONS

From the temperatures, pressures, flow rates, laboratory analyses, etc., collected during the data gathering activities, the various energy values (Btu/hr) needed to determine the refinery energy profile are calculated. This section includes the detailed procedures required for calculating these energy values and gives examples of the calculations. The utilization of these values in developing the profile tables is given later in Section 5. Rigorous calculation procedures are given that follow standard engineering practice to give detailed and accurate values. Alternate procedures are also given when applicable for cases where adequate data may not be available for the preferred method, or where less accuracy is acceptable to reduce calculation time, or where the applicable computer programs are not available. Good engineering judgement must be exercised in deciding the appropriate procedure that best applies to the user's needs.

General Approach

The general approach in calculating profile energy values is to review each equipment item in the unit and determine if the item meets one of the criteria listed below. If so, calculate the energy values associated with the criteria following one of the procedures outlined in this Section. The criteria, with the applicable procedure numbers in parenthesis, are:

1. A stream enters the unit of the type:
    - Petroleum - oils, gases (4.2)
    - Chemical - caustic, acid, etc. (4.2)
    - Steam, boiler feedwater, condensate (4.5)
    - Combustion air (includes water vapor) (4.4.2)
    - Process water (cooling water not included) (4.2)
    - Flue gas - furnace stacks, catalyst regenerators (4.4)
    - Any other type process or waste stream (4.2)
2. A stream leaves the unit of the type:
    - (Same as No. 1 above)
3. Heat is added or removed by:
    - Burning a fuel - gas, oil, coal, coke, waste streams (4.4)
    - Consuming electric power - motors, lighting, misc. (4.6)
    - Transferring heat - heat exchangers, furnace coils (4.3, 4.5.3)
      - Radiation (4.7)
    - Chemical reaction (4.8.1)

4. Work is done by:

- Mechanical shaft (4.5.2, 4.6, 4.8.2)

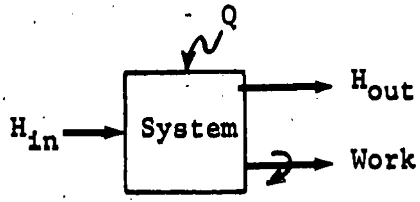
5. Potential heat is lost by:

- Imported fuel used and flared - purging, blanket, etc. (4.4.1)
- Stock loss (combustible portion) - gas flaring, tank breathing, leakage, etc. (4.8.3)

Note: Although the No. 5 criteria do not result from a first Law analysis (because no heat from it is used in the process), it is included because it represents a true energy loss by the refinery. This is discussed in more detail later in Section 4.8.3.

All profile energy calculations revolve around heat and material balances based on the First Law of Thermodynamics. The First Law simply states that for any process, the total enthalpy in, plus the heat added, is equal to the total enthalpy out, plus the work done, if elevation and velocity changes are assumed negligible. The First Law on a time basis, in equation and diagram form with elevation and velocity factors removed, is:

$$H_i + Q = H_o + \text{Work} \qquad (4\text{-}1)$$



where,

H_i = Sum of enthalpies of all entering streams
H_o = Sum of enthalpies of all leaving streams
Q = Heat added to system from external sources
Work = Work done by system

Note: Values for "Q" and "Work" may be negative, indicating reverse direction.

In the profile, individual equipment items are treated as systems as well as the entire unit, and equation 4-1 applied. Except for steam, adiabatic processes are not considered.

Sequence

The first step in the calculation procedure is to make a weight balance as outlined in Section 4.1. A reasonable weight balance must be obtained in order to get the energy to balance.

After the weight balance, there is no particular sequence in which the remaining calculations must be carried out. Consideration, however, should be given to starting next those procedures that might have some lag time, such as where computer programs are used. Other calculations may be completed during these intervals to increase calculation efficiency.

4.1 FLOW CALCULATIONS

Before starting any energy calculations, a flow balance should be made between the charge streams and product streams on a weight basis. In order to determine an accurate balance, meter factors should be corrected or recalculated for observed conditions.

4.1.1 Meter Factors

The most widely used flow meter in a refinery is the orifice meter. An orifice meter basically consists of an orifice plate with an appropriately sized concentric hole spaced between specially drilled flanges on a calibrated pipe run, a differential pressure transmitter (a bellows for local indicators), and a measuring indicating or recording meter. The pressure drop across the orifice is a function of the orifice/pipe dimensions and the physical properties of the fluid flowing through the pipe and is proportional to the square of the flow. This proportionality allows the use of a constant meter factor which is multiplied times the square root scale reading from the measuring meter to determine the flow. Meter factors are calculated originally from design fluid properties and conditions. If the existing properties and conditions are significantly different from design, new or corrected factors are required for accurate measurement.

Meter factors may be calculated manually using references such as Principles and Practices of Flow Meter Engineering by L. K. Spink, or with the use of a computer program. The program may be a proprietary in-house type, such as Gulf's TEHA 174B, or one of several commercially available programs. Sample input requirements for Gulf's TEHA 174B and output results are shown in Appendix A for oil, gas, and steam flow orifice meters.

4.1.2 Weight Balance

This procedure covers adjusting the charge or product flows so that the total of the charge flows agrees on a weight basis with the total of the products. Utility flows of water, steam, and fuel are not included.

Step 1: List and sum all feed stream flows to the unit in terms of lb/hr.

Step 2: List and sum all product stream flows from the unit in terms of lb/hr and check for a balance with the feedstreams.

Step 3: If an imbalance exists between the feed and product sums, review the individual meter reliability and determine if the imbalance can be pinpointed to certain meters. If so, correct these meter flows. For example, a certain stream meter may be known to be historically low or high.

Step 4: If an imbalance exists and cannot be pinpointed to any particular meters, decide which side (feed or product) is more accurate and prorate the imbalance back over each meter of the other side using the following relationship:

$$W_{ic} = W_i \times \frac{W_a}{W_c} \qquad (4.1\text{-}1)$$

W_i = Measured flow of each meter on corrected side, lb/hr.

W_{ic} = Adjusted flow of each meter on corrected side, lb/hr.

W_a = Sum of flows on accurate side, lb/hr.

W_c = Sum of flows on corrected side, lb/hr.

Example: Weight Balance

Determine weight balance on a crude unit. The charge side is considered more accurate in this example.

Step 1: Sum Feed Streams

Stream	By Volume	By Weight
Crude Composite 34.5°API	8289.2 BPH	2470.3 M lb/hr

Step 2: Sum Product Streams

Stream	Volume	Weight
Wet Gas, 2.03 Sp Gr	82.9 MSCFH	12.9 M lb/hr
Naphtha, 63.4°API	1875.3 BPH	476.2 M lb/hr
LFO, 41.2°API	1223 BPH	350.5 M lb/hr
HFO, 35.7°API	1658.8 BPH	491.0 M lb/hr
AGO, 28.5°API	389.1 BPH	120.4 M lb/hr
LVGO, 29.1°API	879.7 BPH	271.1 M lb/hr
HVGO, 22.5°API	1734.1 BPH	557.3 M lb/hr
Vac. Twr. Btms., 11.2°API	579.2 BPH	200.9 M lb/hr
Total		2480.3 M lb/hr

Imbalance = (2480.3 - 2470.3) M lb/hr = 10 M lb/hr or 0.4%.

Note: For all practical purposes the feed and product flow values are the same. To demonstrate the procedure, the products will be balanced to the feed.

Step 3: No particular product meter is obviously low, therefore, a correction will be applied to all the meters.

Step 4: The correction ratio is determined.

$$\frac{w_a}{W_c} = \frac{2470.3}{2480.3} = 0.996$$

then, New Wet Gas Flow = 0.996 x 12.9 M lb/hr
= 12.8 M lb/hr

and, New Wet Gas Flow = 0.996 x 82.9 MSCFH
= 82.6 MSCFH

likewise, the remaining product values are prorated.

Adjusted Product Flows

Stream	By Volume	By Weight
Gas	82.6 MSCFH	12.8 M lb/hr
Naphtha	1867.7 BPH	474.2 M lb/hr
LFO	1218.1 BPH	349.1 M lb/hr
HFO	1652.1 BPH	489.0 M lb/hr
AGO	387.5 BPH	119.9 M lb/hr
LVGO	876.2 BPH	270.0 M lb/hr
HVGO	1727.1 BPH	555.2 M lb/hr
Vac. Twr. Btms.	576.9 BPH	200.1 M lb/hr
Total		2470.3 M lb/hr

4.2 ENTHALPIES

A thermodynamic property called enthalpy is calculated and used for the heat content of a material. Enthalpies are preferred to heat capacities since heat capacities vary with temperature and do not correlate as well as enthalpies. Enthalpy is defined as the internal energy plus the product of the pressure and specific volume. Enthalpy is a relative value and a reference basis is arbitrarily chosen at which the enthalpy is assigned the value zero. The enthalpy basis used throughout this technique is the liquid phase at 60°F and 0 psig, except for non-hydrocarbon gases where the reference state is the gas phase, as normally used in such calculations.

Where differences in enthalpies are used, as in heat exchangers, the basis is immaterial and the enthalpy need not be converted to the profile basis. However, when streams cross a unit boundary, the enthalpies represent energy quantities as import or export heat and all must be on the same basis in order to have any consistency in the calculations. To convert to the profile reference basis the following relationship is used.

$$h_t = h_t' - h_{60}' \qquad (4.2\text{-}1)$$

Where h_t = Profile enthalpy, Btu/lb, at temperature, t°F, h = 0 at 60°F.

h_t' = Calculation enthalpy, Btu/lb, at temperature, t°F.

h_{60}' = Calculation enthalpy, Btu/lb at 60°F and liquid phase except non-hydrocarbon gas which is gas phase.

Likewise,

$$H_t \quad H_t' - H'_{60} \qquad (4.2\text{-}2)$$

Where H_t = Profile enthalpy, MM Btu/hr

= $h_t W$

W = lb/hr

Note: Throughout this profile, the enthalpy symbol is shown with a prime (H' or h') when the basis is not 60°F.

Two procedures are given for enthalpies. For separate calculations of a liquid hydrocarbon mixture, use the programmable calculator procedure 4.2.2. For all other applications, use the computer procedure 4.2.1.

An alternate third procedure, not listed, is the use of the enthalpy charts in Chapter 7 of the API Technical Data Book[1]: The Data Book procedure is not listed here because the charts are required from the Data Book, and the procedure with an example is documented adequately in the Data Book. Although this procedure will produce adequate results, users may find that it requires more time for the same degree of accuracy than the other procedures given. An exception would be for low pressure gases, where the part of the procedure dealing with the contribution of pressure and mixing energy may be ignored and the loss in accuracy may be acceptable.

4.2.1 Computer Method for Calculation of Enthalpies

This procedure covers the calculation of enthalpies of hydrocarbon streams whether a gas, liquid, or mixed phase stream and non-hydrocarbon gas stream, utilizing a digital computer. This procedure is recommended for all profile applications when accuracy is desired involving a gas phase or a change in phase or composition and also a liquid phase if already part of the calculation program, such as:

a) Import energy of a gas stream.
b) Export energy of a gas stream.
c) Heat rejected by an air cooled exchanger - cooling or condensing a gas phase.
d) Heat rejected by a water cooled exchanger - cooling or condensing a gas phase.
e) Recycle heat from a reactor feed-effluent exchanger.
f) Heat of Reaction from a reactor.
g) Heat absorbed by a gas stream from a compressor or blower.
h) Also, liquid hydrocarbon stream values when the reduced temperature (Temperature, °R/pseudocritical temperature) is greater than 0.8 or the reduced pressure (pressure, psia/pseudocritical pressure) is greater than 1.0. Otherwise, it is simpler to use the programmable calculator procedure.
i) Liquid hydrocarbon stream values when the stream data is being entered already to compose a total stream, and it is convenient to calculate the enthalpy.

Since it is not within the scope of the profile technique to develop a computer program or even to determine the most efficient one to use, it is not reasonable to give full details that will be applicable to any and all possible programs. Instead, some general requirements and considerations are given so that the user may determine an applicable program; and then a detailed procedure and example are given for the specific computer program used in this work.

4.2.1.1 General Procedure

To calculate mixed phase enthalpies, as required to duplicate this profile procedure, an equilibrium flash computer program is required that will determine the equilibrium vapor/liquid mixture and the enthalpy of the mixture. Although these calculations may be performed manually with the aid of a technical data book, they are simply too laborious for calculating all enthalpies for an entire refinery.

The equilibrium flash computer program may be a complex, sophisticated process simulator such as the Simulation Sciences Incorporated process simulator (SSI-100)[2] or a more simple program such as one of the Gas Processors Association programs (GPA Mod. II). The user must assess the computer facilities available, run time and cost, any lease or royalty payments required, and engineering time required to prepare and run the programs before determining the best programs. For the profile study, the process simulator was found to be the most advantageous; and several are commercially available.

The type calculation operations required are described below. Although all the operations are useful, some may be omitted if desired by preparing different and additional input data; and these are marked with an asterisk.

Vapor Enthalpy Curve - Calculates enthalpy of the stream in the vapor state at the temperature and pressure given, regardless of actual phase. The stream may be a defined real gas, a defined hydrocarbon liquid, a hydrocarbon mixture, or a mixed phase mixture of the three. Multiple calculations at equal intervals of temperature and pressure are possible.

Liquid Enthalpy Curve - Same as for Vapor Enthalpy Curve, except that the stream is considered in the liquid state regardless of actual phase.

Flash Enthalpy Curve* - Same as for Vapor Enthalpy Curve except that the actual vapor-liquid equilibrium state is calculated at the temperature and pressure given and the enthalpy is calculated at this state regardless of phase assumed in the input.

Isothermal Flash - Mixes any combination of separate streams (vapor, liquid, mixed phase) at separately specified flow temperature, pressure, and composition to produce a combined stream at a certain temperature and pressure that may be used as a feed stream to subsequent calculation operations. Calculates enthalpy and other properties of the separate feed streams and of the combined stream at the theoretical equilibrium state.

Adiabatic Flash* - Mixes or splits streams of the same phase adiabatically. Properties of the separate and combined streams are calculated.

Heat Exchanger* - Calculates duty of heat exchangers based on theoretical outlet conditions, or outlet temperature when duty is known. May be used instead of Isothermal Flash for certain problems where outlet state is not measured.

General Considerations for Setting Up Program Operations

The general approach to any of these enthalpy calculation problems is the same, although there may not be any two calculations that are identical due to process variations. The four main points to be considered are summarized below:

Point 1: If the stream on which the enthalpy is required is not defined in terms of flow and composition, compose the stream from defined feed, product or previously composed streams using the Isothermal and Adiabatic Flash operations.

Point 2: If the phase of the stream, temperature, and pressure are known, calculate the enthalpy at that phase by using the Vapor or Liquid Enthalpy Curve for gas or liquids, respectively. The theoretical equilibrium conditions may also be calculated (usually automatically) and compared to the measured conditions. Small variations between theoretical and measured conditions are expected and may be ignored, but the measured data may be in error if large differences occur.

Point 3: For possible mixed phase streams, calculate the enthalpy using the Isothermal Flash, Flash Enthalpy Curve, or Heat Exchanger operations that are best suited.

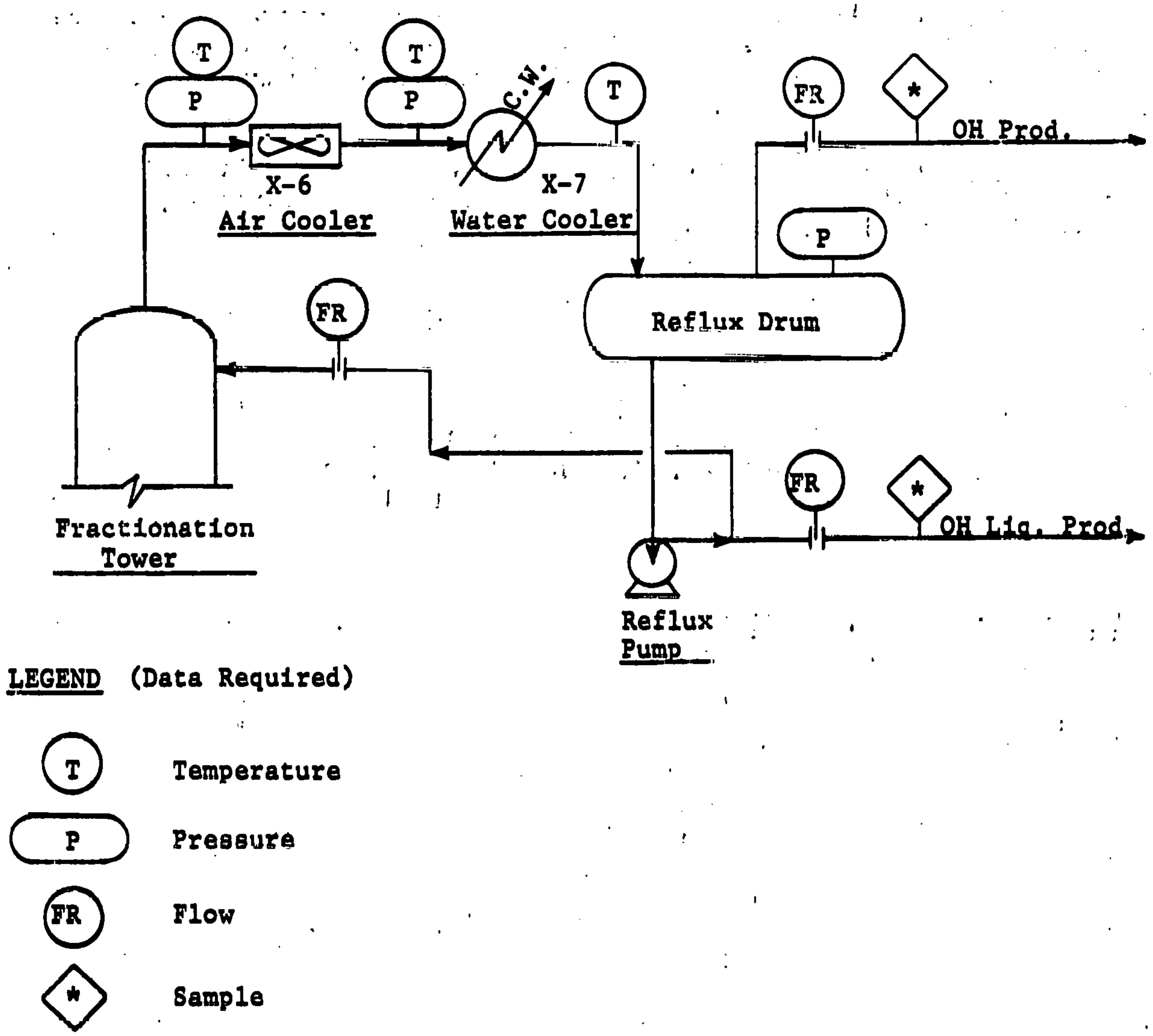
Point 4: For all Import and Export hydrocarbon streams, calculate an enthalpy at 60°F and 0 psig, in addition to the enthalpy at the measured conditions, using the Liquid Enthalpy Curve. This value at 60°F and 0 psig is subtracted from the calculated enthalpy at measured conditions to correct the enthalpy from the program reference base (usually ideal gas at °R) to the Profile reference base (liquid phase at 60°F, 0 psig) as shown by equation 4.2.2.

4.2.1.2 Details and Example for a Tower Overhead System

To list and demonstrate the entire procedure in detail, an example calculation of a typical fractionation tower overhead (OH) system (as shown in Figure 4-1), is given along with the detailed procedure steps. The procedure details the steps required to identify the gas stream components, to characterize the liquid hydrocarbon streams, to prepare the computer program input, and how to utilize the results.

FIGURE 4-1

TYPICAL FRACTIONATION TOWER OVERHEAD SYSTEM



Data for Stabilizer Example

X-6 In - 319°F, 25 psig
X-6 Out - 135°F, 20 psig
X-7 Out - 97°F, 15 psig
OH Gas - 42.25 MSCFH, Gas Chromatograph Analysis.
OH Liq. Prod. - 37 BPH, 35.7 °API, ASTM D86
Reflux - 207 BPH

Gas Stream Component Identification

The data required are a gas chromatograph analysis, temperature, and pressure of the vapor phase in the reflux drum; and the flow of each gas stream leaving. Since the gas chromatograph analysis is in volume percent, which is assumed the same as mole percent for a gas, no calculations are required to prepare the input. On wet gas samples, the condensation in the sample bomb may be ignored, if the sample is heated prior to analysis. Although the percent error of the energy value of the gas stream may be large, the quantity difference is not appreciable in comparison with the other streams; and the resulting exchanger duties are not significantly changed.

Step 1: Look up the component identification numbers in the computer program library for the program being used and assign sequential component numbers (See Table 4-1).

TABLE 4-1
STABILIZER OH GAS PRODUCT
COMPONENT ANALYSIS AND IDENTIFICATION
FOR COMPUTER FLASH CALCULATION

PROGRAM COMPONENT IDENTIFICATION			COMPOSITION OH GAS STREAM 1
COMPONENT NO.	LIBRARY* ID. NO.	NAME	(VOL. %)
1	1	Hydrogen	45.7
2	2	Methane	0.8
3	3	Ethane	16.9
4	4	Propane	8.5
5	5	I-Butane	0.3
6	6	N-Butane	3.9
7	26	Trans-2-Butene	1.3
8	7	I-Pentane	1.5
9	8	N-Pentane	2.3
10	10	Hexane	13.3
11	50	Hydrogen Sulphide	5.5
		TOTAL	100.0

---

*SSI-100

Characterization of the Liquid Hydrocarbon Mixture

This procedure covers the steps required to divide a liquid hydrocarbon stream into several fractions and to determine the boiling point, gravity, and K value for each fraction.

Step 1: From the lab data, obtain the API gravity and ASTM D-86 distillation.

API Gravity = 53.2 °API

Distillation, % by Vol.	IBP	10	30	50	70	90	EP
ASTM D-86, °F	114	212	260	290	308	330	352

Step 2: Convert the ASTM D-86 data to true boiling point (TBP) data. Computer programs are available that make this conversion simply and easily, such as Gulf's in-house program TEHA0118. For a manual conversion, use correlations and procedures from Figure 3A1.1 from the API Technical Data Book. A detailed example of a conversion is presented in the comments on Figure 3A1.1 of the Data Book.

Distillation, % by Vol.	IBP	10	30	50	70	90	EP
ASTM D-86, °F	114	212	260	290	308	330	352
TBP, °F	29	165	239	286	313	341	365

Step 3: Plot the TBP distillation curve, Figure 4-2, by plotting boiling point temperature in °F versus volume percent distilled.

Step 4: Determine the specific gravity and Watson K following steps 2 through 5 of procedure 4.2.2.

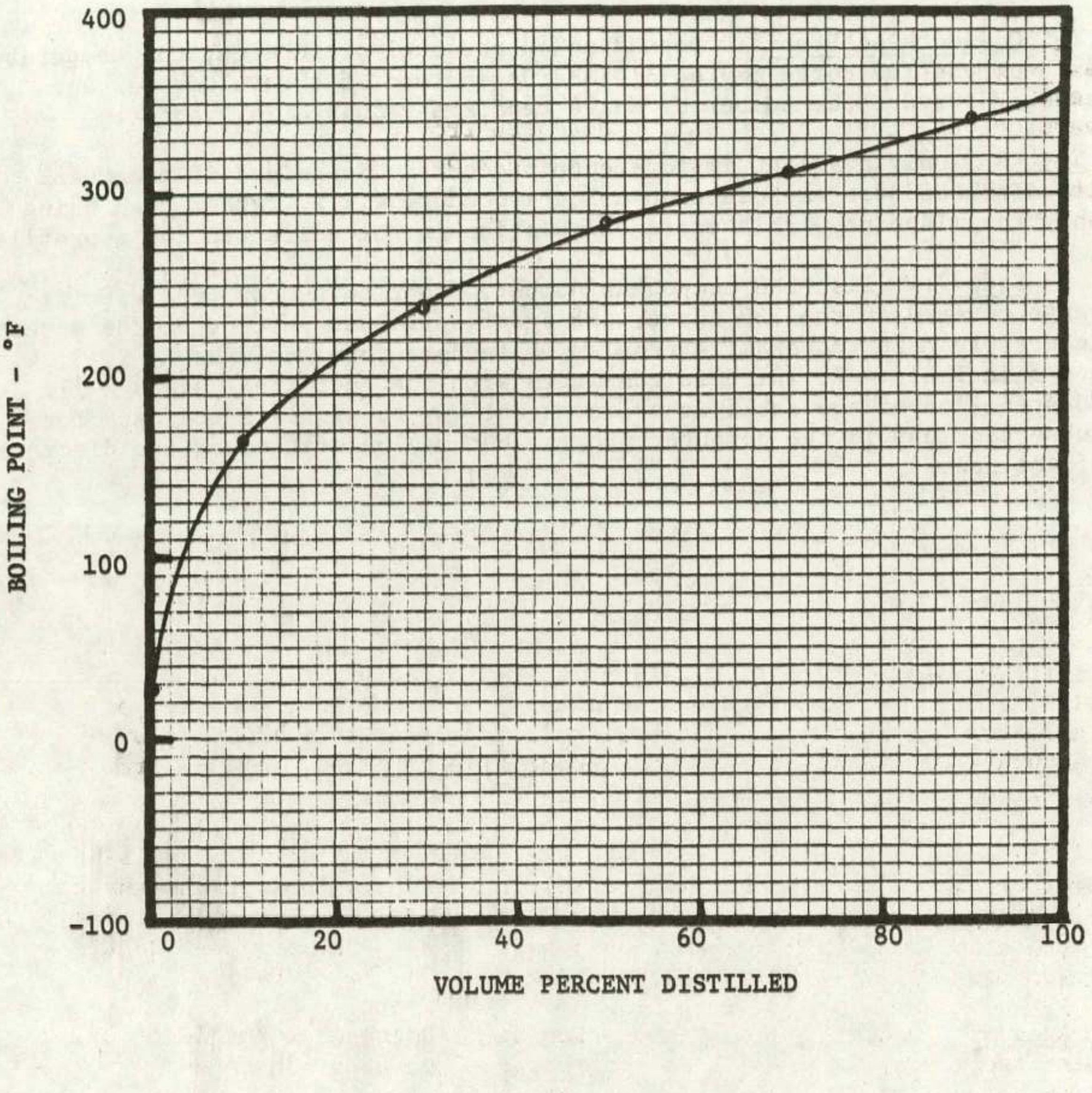
SpGr = 0.7661
K = 11.77

Step 5: Divide the TBP curve, Figure 4-2, into several sections along the volume percent axis located so the midpoints may be read easily from the curve. Although the whole curve may be considered as a single component, dividing it up into several sections will improve the accuracy of the flash program. About five to eight sections are adequate and the size of the sections do not have to be equal.

Generally, smaller sections are taken on the portion of the curve where the slope is changing rapidly. These sections of the curve form separate fractions of the total stream and are used as non-standard components in the flash program. Component numbers are assigned to the fractions according to particular program used.

Step 6: Read the temperature from the TBP curve at the midpoint of each section. These midpoint temperatures are used as the mean average boiling points (MeABP's) for the respective fractions. The volume percent of the fraction is the width of the volume percent range of the section.

FIGURE 4-2 TBP DISTILLATION CURVE
FOR STABILIZER OVERHEAD LIQUID



for example: Component no. = 12
Fraction No. = 1
Section = 0% to 4% on Vol.% scale
Vol.% = 4% - 0%
= 4%
MeABP = temperature from TBP curve at midpoint of the fraction (2%)
= 80°F

Comments on Step 6: Depending on personal preference, the temperature axis of the TBP curve may be divided up instead of the volume percent axis. However, the number of curve readings required is greater.

Only a slight improvement in accuracy is gained if the MeABP is calculated for each section using Procedure 4.2.2, rather than using only the midpoint. This extra calculation is not warranted for a profile.

Step 7: List the component number, fraction number, the specific range covered on the TBP curve, the fraction volume percent of the stream in a table. In the example problem, this data forms columns 1, 2, 3, 4, and 5 in Table 4-2, which is completed with the additional steps 8-11. Construction of the table is a convenient way to organize the data for subsequent use in the computer program but may be omitted at the discretion of the user.

TABLE 4-2

FRACTION PROPERTIES OF A STABILIZER OH LIQUID

COMPONENT NO.	FRACTION NO.*	TBP CURVE* SECTION RANGE (VOL. %)	FRACTION VOL. %	MeABP (°F)	FIRST* TRIAL SP GR	CORRECTED SP GR	CORRECTED GRAVITY (°API)
12	1	0-4	4	80	0.6919	0.6948	72.16
13	2	4-10	6	142	0.7174	0.7204	64.91
14	3	10-30	20	209	0.7431	0.7462	58.12
15	4	30-50	20	263	0.7626	0.7658	53.28
16	5	50-90	40	313	0.7797	0.7830	49.21
17	6	90-100	10	348	0.7913	0.7947	46.56
None	Total	0-100	100	---	0.7629	0.7661	53.20

---

*Listed for illustrative purposes only, not needed for program input.

Step 8: Assuming that the K values are the same for each fraction as the total stream K value from Step 4, calculate the specific gravity of each fraction (i) using equation (4.2-10). The equation is rearranged to solve for SpGr and listed here for easy reference.

$$\text{Sp Gr}_i = \frac{(\text{MeABP}_i + 459.67)^{1/3}}{K_i} \qquad (4.2\text{-}3)$$

For example: Fraction 1, 0% - 4% section

$$\text{Sp Gr}_i = \frac{(80 + 459.67)^{1/3}}{11.77}$$

$$= 0.6919$$

The specific gravities for the remaining fractions in the example are similarly calculated and listed in Table 4-2 as column 6.

Comment: Actually the K values for each fraction may vary. If a correlation between K, °API, and MeABP is known for the particular stream being characterized, it should be used. Otherwise, the K values are assumed equal to start with and are adjusted in the following steps as required.

Step 9: Calculate an overall specific gravity (SpGr_c) by summing the product of the fraction specific gravity (SpGr_i) and the volume percent (Vol. $\%_i$) for each fraction (i).

$$\text{Sp Gr}_c = \sum_{i=1}^{n} \frac{(\text{Vol.\%} \times \text{SpGr}_i)}{100} \qquad (4.2\text{-}4)$$

Step 10: Compare the calculated specific gravity from Step 9 with the measured specific gravity (SpGr) from Step 4. If they are equal, go to Step 11. Otherwise, correct the specific gravity from Step 8 (and thus the K value) of each fraction by the ratio of the total measured specific gravity to the total calculated specific gravity.

$$\text{New Sp Gr}_i = \frac{\text{Sp Gr}}{\text{Sp Gr}_c} \times \text{Sp Gr}_i$$

For example: Fraction 1, 0% - 4% section

$$\text{New Sp Gr}_i = \frac{0.7661}{0.7629} \times 0.6919 = 0.6948$$

The gravities of the remaining fractions in the example are listed in Table 4-2 as column 7.

Comment: Again, an assumption is made that the change in the K value on each fraction is such that the ratios of the specific gravities above are constant, unless test data shows otherwise. This is a reasonable assumption for a profile.

Step 11: Calculate the API gravity for each fraction using the following equation which is from Step 4 of Procedure 4.2.2 which is rearranged and listed here for easy reference.

$$\text{API Gravity}_i = \frac{141.5 - \text{Sp Gr}_i \times 131.5}{\text{Sp Gr}_i} \qquad (4.2\text{-}5)$$

For example: Fraction 1, 0% - 4% section

$$\text{API Gravity}_i = \frac{141.5 - 0.6919 \times 131.5}{0.6919}$$

$$= 72.16\ ^\circ\text{API}$$

The fraction gravities are added to Table 4-2, as column 8. This completes the data required to characterize the liquid stream.

Preparing Computer Program Input

After completing the characterization for all streams, construct a flow sheet, Figure 4-3, to keep up with stream identifications, stream data, and calculation sequences. The type of calculations available and input structure vary from one computer program to another, although there are many similarities. At this point, one must be familiar with the program to be used. To follow this example, reference must be made to the SSI-100 User's Manual[2].

The general procedure is to compose the total stream to the condensers with the downstream liquid and vapor products from the condensers as feed streams using the Adiabatic and Isothermal Flash operations and to calculate enthalpies using the Enthalpy Curve operation. This approach is used for all problems and is detailed for the tower overhead condensers in the following steps. Although many combinations of step alternates may be devised (limited only by the ingenuity of the user), this procedure will produce adequate results and generally will be one of the simplest. The steps apply to the program input development as well as the flow sheet construction.

Step 1: Mix the reflux stream (No. 2) and overhead liquid product stream (No. 3) using the Adiabatic mix unit operation to form the total liquid stream (No. 4). Label unit operation No. 1. This calculates the enthalpy (H'_4) of stream No. 4 also.

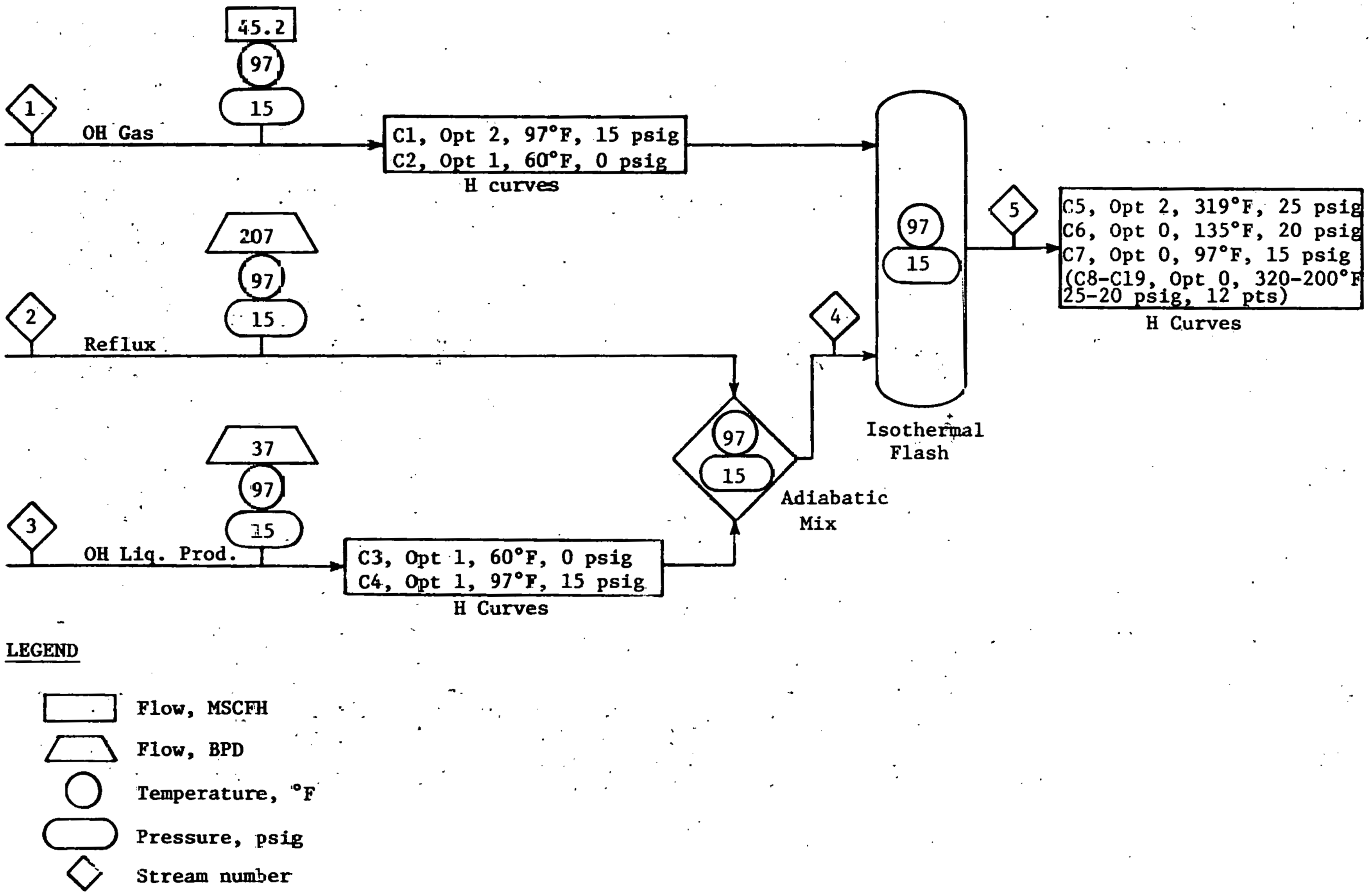
Comment: Entering the reflux and liquid product streams separately, rather than combined, allows additional operations to be performed on the individual streams, such as export calculations.

Step 2: Mix stream 4 from unit operation No. 1 with the overhead gas stream (No. 1) using the Isothermal Flash unit operation at the reflux drum temperature and pressure. Label unit operation No. 2. This composes the tower overhead stream (No. 5).

Comment: Additional streams (such as water) may be required for other problems. By combining the mix and split operations available, any stream may be composed.

FIGURE 4-3

COMPUTER PROGRAM INPUT FLOW SHEET
FOR STABILIZER OVERHEAD



Step 3: Set up Vapor Enthalpy Curve on the overhead gas stream (No. 1) at the actual temperature and pressure. Label C1 as part of unit operation No. 3. This calculates enthalpy with reference to 0°R.

Step 4: Set up Liquid Enthalpy Curve on the same overhead gas stream (No. 1) at 60°F and 0 psig. Label C2 as part of unit operation No. 3. This calculates enthalpy (H_{c2}) at the reference base.

Step 5: Set up Liquid Enthalpy Curve on the overhead liquid product (No. 3) at the actual temperature and pressure. Lable C3. This calculates enthalpy (H'_{c3}) with reference to 0°R.

Step 6: Set up Liquid Enthalpy Curve on the same liquid product (No. 3) at 60°F and 0 psig. Label C4. This calculates enthalpy (H'_{c4}) at the profile reference base with reference to 0°R.

Step 7: Set up Vapor Enthalpy Curve on the tower overhead (No. 5) at the actual temperature and pressure. Label C5. This calculates the enthalpy (H'_{c5}) with reference to 0°R.

Step 8: Set up Flash Enthalpy Curve on the same stream (No. 5) at the measured temperature and pressure after the air cooler. Label C6. This calculates the equilibrium enthalpy (H_{c6}) between the exchangers with reference to °R.

Comment: If preferred, an additional Isothermal Flash may be used instead of an Enthalpy Curve. The enthalpy results will be the same. Additional information is printed since an additional stream is identified.

Step 9: (Optional) Set up Flash Enthalpy Curve on the same stream (No. 5) at the outlet conditions of the water cooler. Label C7. This calculates the equilibrium enthalpy (H'_{c7})after the water cooler with reference to 0°R which is used as a cross check on the sample analysis.

Comment: If the temperature and pressure used in the Isothermal Flash of Step 2 are the same as this step, the equilibrium enthalpy ($H_5 = H'_{c7}$) will already be calculated and this step is not used. It is shown in example as an illustration.

Step 10: Set up Flash Enthalpy Curve on Stream No. 5 over a temperature range from the inlet temperature to the first cooler to the minimum temperature of interest for low level heat recovery in increments of 10°F to 50°F (for this example, 20°F increments down to 200°F). Label C8-C19 respectively, for the 12 pts. The enthalpies generated here are used later for determining energy available for potential recovery. (See Section 5.1.8.2).

Step 11: After constructing the flow sheet, Figure 4-3, develop the input to the computer program. This input typically falls in four categories: 1) General problem specifications; 2) component specification; 3) Stream definition; 4) calculations. Refer to the program User's Manual for details on input. (The input for SSI-100 for the overhead condenser example is shown as Figure A-4 in Appendix A).

Utilizing Flash Calculation Results

The output from the computer program is used to calculate the duty of the condensers and the export value for the gas and liquid products. The overhead condenser example is continued in the following steps in order to have continuity in the example, although the procedure is covered later in Procedure 4.3.1.

Step 1: Air Cooled Condenser - Using Procedure 4.3.1, subtract the outlet enthalpy from the inlet enthalpy to obtain the duty which is the heat rejected by the air cooler. List in the Heat Rejection Summary under Air Cooled Heat Exchangers. Using equation 4.3-1,

$$\begin{aligned} Q_6 &= \text{Heat Rejected by Air Cooler X-6} \\ &= H'_{c5} - H'_{c6} \\ &= (17.39 - 1.83)\ \text{MM Btu/hr} \\ &= 15.56\ \text{MM Btu/hr} \end{aligned}$$

Step 2: Water Cooled Condenser - Using Procedure 4.3.1, subtract the overhead gas enthalpy and the total liquid enthalpy from the inlet enthalpy to the water cooled condenser to obtain the duty which is the heat rejected by the water cooler. List in the Heat Rejection Summary under Water Cooled Heat Exchangers. Using equation 4.3-1,

$$\begin{aligned} Q_7 &= \text{Heat Rejected by Water Cooler X-7} \\ &= H'_{c6} - (H'_{c1} + H'_{4}) \\ &= [1.83 - (0.77 + (-0.01))]\ \text{MM Btu/hr} \\ &= 1.07\ \text{MM Btu/hr} \end{aligned}$$

Step 3: Product Gas Export - Subtract the overhead gas enthalpy at liquid conditions at 60°F and 0 psig from the overhead gas enthalpy at the temperature and pressure leaving the unit to obtain the export energy. List in Import/Export Summary as an export. Using equation 4.2-1,

$$\begin{aligned} H_1 &= \text{Overhead Gas Export} \\ &= H'_{c1} - H'_{c2} \\ &= (0.77 - 0.71)\ \text{MM Btu/hr} \\ &= 0.06\ \text{MM Btu/hr} \end{aligned}$$

Comment: This converts the enthalpy reference base from that used in the program to the reference base used in the profile of liquid at 60°F and 0 psig.

Step 4: Liquid Product Export - Subtract the overhead liquid product enthalpy and 60°F and 0 psig from the overhead liquid enthalpy at the temperature and pressure leaving the unit to obtain the export energy. List in the Import/Export Summary as an export.

$$\begin{aligned} H_3 &= \text{Overhead Liquid Export} \\ &= H'_{c4} - H'_{c3} \\ &= ((-0.01) - (-0.19)) \text{ MM Btu/hr} \\ &= 0.18 \text{ MM Btu/hr} \end{aligned}$$

4.2.2 Calculate Liquid Hydrocarbon Enthalpies with Programmable Calculators

This procedure covers the calculation of enthalpies of liquid hydrocarbon streams of unknown composition utilizing a programmable calculator. This procedure should be used when only a liquid phase is involved in the following profile applications: a) export energy; b) import energy; c) heat rejected by air coolers; d) heat rejected by water coolers.

Documentary detailed procedure steps and equations are first presented to characterize the stream using the Watson K value and then to calculate the enthalpy as based on the API Technical Data Book. These detailed steps are then programmed for the Hewlett-Packard (HP-97) programmable calculator, and the operating instructions included. The listing of the program developed (program no. 1) is included in Appendix B as Figure B-1.

Characterization Documentation

This section of the procedure determines the Watson characterization factor, K, for an undefined hydrocarbon mixture and is applicable for use with digital computers as well as programmable calculators.

For most liquid hydrocarbon streams, the specific gravity can be easily measured in a laboratory, but the K factor is not a measured quantity, but a correlation based on other properties. The method for determining K is based on a standard laboratory test known as ASTM D86 distillation. The API Technical Data Book[1] gives a graphical correlation between D86 and the mean average boiling point of the mixture. An equation has been fitted to the API correlation which allows the direct calculation of the mean average boiling point from the D86 data. K is then calculated from another API Technical Data Book formula relating K to the mean average boiling point and the specific gravity.

Step 1: Run an ASTM D86 distillation and an API gravity on a sample from the stream.

Step 2: Calculate the Volumetric Average Boiling Point (VABP) and slope(s) of the D86 distillation curve from the following formulas using the D86 data.

$$\text{VABP} = \frac{t_{10} + t_{30} + t_{50} + t_{70} + t_{90}}{5} \qquad (4.2\text{-}6)$$

$$s = \frac{t_{90} - t_{10}}{90 - 10} \qquad (4.2\text{-}7)$$

Where t_{10}, t_{20}, t_{50}, t_{70}, and t_{90} are the D86 temperatures in °F at which 10, 30, 50, 70 and 90 percent by volume have been distilled, respectively.

Step 3: Using the VABP and Slope, calculate the Mean Average Boiling Point (MeABP) from the following formula which is a mathematical representation of Figure 2B1.1 from the API Technical Data Book.

$$\begin{aligned}\text{MeABP} &= t - 3.24s + 0.001128\,ts - 0.001438ts^2 \qquad (4.2\text{-}8)\\ &\quad - 7.591 \times 10^{-5}\,ts^3 - 5.6.6 \times 10^{-7}\,t^2\,s\\ &\quad - 1.5259\,s^2\end{aligned}$$

Where t = VABP in °F, from equation 4.2-6

s = Slope of D86 curve, from equation 4.2-7

Note: MeABP calculated is in °F

Step 4: Convert gravity data from °API to specific gravity (SpGr) using formula 6-0.2 from the API Technical Data Book which is listed here as,

$$\text{SpGr, } 60°\text{F}/60°\text{F} = \frac{141.5}{131.5 + °\text{API}} \qquad (4.2\text{-}9)$$

Step 5: Calculate characterization factor, K, from MeABP and SpGr using the formula 2-0.2 from the API Technical Data Book which is listed here as,

$$K = \frac{(\text{MeABP} + 459.67)^{1/3}}{\text{SpGr, } 60°\text{F}/60°\text{F}} \qquad (4.2\text{-}10)$$

When the same liquid hydrocarbon stream is used in several calculations, it is convenient to tabulate the specific gravity and K value for quick reference, as illustrated in Table 4.3. The programmable calculator program is written so that the K value may be entered as data in subsequent calculations rather than all the distillation temperatures.

TABLE 4-3

CHARACTERIZATION OF LIQUID HYDROCARBON STREAMS ON A CRUDE UNIT

CODE NO.	NAME	ASTM D86 DISTILLATION,(3) °F					MeABP (3) °F	API GRAVITY	SPECIFIC GRAVITY (3)	WATSON K
		10%	30%	50%	70%	90%				
1	Crude	252	422	560	693	741	479	34.6	0.8719	11.5
2	TPA	244	312	324	336	350	321	49.0	0.7839	11.7
3	HFO PA	474	515	544	577	635	540	35.3	0.8783	11.8
6	LFO	396	412	428	446	474	428	41.2	0.8193	11.7
7	HFO	462	499	532	568	614	527	35.7	0.8463	11.8
8	AGO	636	670	694	716	748	688	28.5	0.8844	11.8
9	Atm. Twr. Btms.	--	--	--	--	--	--	22.0(1)	0.9218	11.9(2)
10	Vac. Twr. Recycle	--	--	--	--	--	--	22.6	0.9182	11.8(2)
11	LVGO	602	650	692	710	736	672	29.1	0.8811	11.8
12	HVGO	778	843	888	948	1016	883	22.5	0.9188	12.0
13	Residue	--	--	--	--	--	--	11.2	0.9916	11.8(2)

[1] Calculated from combination of streams 11, 12 and 13.

[2] Design values.

[3] Not required in table. Included for other reference only.

Step 6: Calculate the enthalpy (h) using equation 7B4.7-1 from the API Technical Data Book, which is reproduced here for easy reference as equation 4.2-11, but with constants for a 60°F reference base. The equation is applicable to liquid hydrocarbon streams in the region where the reduced temperature is less than 0.8 and the reduced pressure is less than 1.0. Due to the complexity, it is not reasonable to use the equation often without aid of a programmable calculator or digital computer. The equation is:

$$h = A_1\ (T - 519.67) + A_2\ (T^2 - 519.67^2) + A_3\ (T^3 - 519.67^3) \qquad (4.2\text{-}11)$$

Where:

h = Enthalpy, Btu/lb

$$A_1 = 10^{-3} \left[-1171.26 + (23.722 + 24.907\ \mathrm{Sp\ Gr})\ K] + \frac{(1149.82 - 46.535\ K)}{\mathrm{Sp\ Gr}} \right]$$

$$A_2 = 10^{-6} \left[(1.0 + 0.82453\ K)\ (56.086 - \frac{13.817)}{\mathrm{SpGr}} \right]$$

$$A_3 = (-10^{-9}) \left[(1.0 + 0.82453\ K)\ (9.6757 - \frac{2.3653)}{\mathrm{SpGr}} \right]$$

SpGr = Specific gravity, 60°F/60°F, equation 4.2-9.

K = Watson characterization factor, equation 4.2-10.

h = 0 at 60°F.

HP-97 Program for Liquid Hydrocarbon Enthalpies

This program is divided into two sets of subroutines. One set is used for the first enthalpy calculation on a new stream. The other set is used for calculations repeated on the same stream. Within each set, alternate subroutines are included to shorten the steps where sufficient data has been entered or calculated previously.

New Stream

Run either subroutine A or subroutine B, but not both. If K is known, use A; otherwise, use B.

Step 1 (Subroutine A): Enter ASTM D86 temperatures and gravity as follows:

INPUT		OUTPUT
Data	Operation Keys	
10% temp., °F	Stor, 1	
30% temp., °F	Stor, 3	
50% temp., °F	Stor, 5	
70% temp., °F	Stor, 7	
90% temp., °F	Stor, 9	
{API Gravity(°API<2.0) or SpGr}	A	°API or SpGr Watson K

Step 1 alternate (Subroutine B): Enter gravity and Watson K.

INPUT		OUTPUT
Data	Operation Keys	
{°API, (API>2.0) or SpGr}	Enter ↑	
Watson K	B	°API or SPGr Watson K

Step 2 (Subroutine C): Enter only the flow and temperature.

INPUT		OUTPUT
Data	Operation Keys	
Flow, Bph	Enter ↑	
Temperature, °F	C	Flow, BPH Temp., °F Enthalpy, MM Btu/hr

Repeat Calculation on Same Stream

- Run either Subroutine C or Subroutine D, but not both in the same sequence. If the flow rate is the same, use D; otherwise, use C.

Step 3 (Subroutine C): Enter only the temperature.

INPUT		OUTPUT
Data	Operation Keys	
Temp., °F	D	(space) Flow, BPH Temp., °F Enthalpy, MM Btu/hr

Step 4 (Subroutine E - Optional): Calculate the difference in the enthalpies of the two previous results from Step 2 or Step 3.

INPUT		OUTPUT
Data	Operation Keys	
None	E	ΔEnthalpy, MM Btu/hr

Example Calculation of Enthalpy using the HP-97 Programmable Calculator

Data

ASTM D86 Distillation

% by Vol.	10	30	50	70	90
°F	462	499	532	568	614

Gravity - 35.7 °API
Flow - 1658.8 BPH
Temp. - 167.5 °F

Calculation:

Step 1: Enter ASTM D86 data and API gravity. Press A. Results are:

SpGr = 0.8463

K = 11.76

Step 2: Enter flow rate and temperature. Press C. Results are:

H = 25.48 MM Btu/hr

4.3 HEAT EXCHANGER DUTIES

The duty of a heat exchanger is simply the quantity of heat exchanged or transferred from one stream to another. Heat exchanger duties are used in determining heat rejected to air and water coolers and recycle heat. In most cases, the duty can only be calculated from the hydrocarbon side of the exchanger because air and water rates are not metered. In the case of two measured streams exchanging heat, the duties may be calculated for both sides of the exchanger and averaged, if it is not evident the data of one stream is more accurate.

The preferred method of accurately calculating the duty of a heat exchanger is using Procedure 4.3.1 using enthalpies calculated from measured data. For water and for streams that enthalpy data may not be available, specific heats may be used in Procedure 4.3.2. On special cases, duties may be determined from a heat balance using Procedure 4.3.3. If data is insufficient to use either of these procedures, an estimate must be made using Procedure 4.3.4 which is based on using historical data, usually the design basis. Procedure 4.3.4 may be used, of course, for any calculations where the inherent loss in accuracy will not substantially affect the overall result (such as small, low temperature coolers) or the inaccuracy is not objectionable to the user in comparison to the time that would be saved.

4.3.1 Calculating Duties Using Enthalpies

The preferred method of calculating an exchanger duty is to subtract the outlet enthalpy from the inlet enthalpy using the best available data from one stream. The enthalpy values are calculated according to one of the procedures in 4.2. Since differences in enthalpy values are used, any enthalpy reference base may be used as long as it is the same for both values. This calculation is also included as part of the programmable calculator program in Procedure 4.2.2. The equation is:

$$Q = H_o - H_i \qquad (4.3\text{-}1)$$

Where Q = Heat Exchanger Duty, MM Btu/hr

H_i = Inlet Enthalpy of one stream, MM Btu/hr

H_o = Outlet Enthalpy of same stream, MM Btu/hr

Note: A negative value only indicates that heat is being removed from the stream and being added to the heat exchanger system. Since the direction of heat flow is usually obvious, the smaller value can be subtracted from the larger without regard to location.

Example:

Calculate the duty of a HFO Product Cooler given the following data.

Data:

Stream	HFO Product
Specific Gravity	0.8463
K	11.76
Flow Rate, BPH	1658.8
Temp. In °F	167.5
Temp. Out °F	139

Using the HP-97 program No. 1 in Appendix B:

Step 1: Enter specific gravity (0.8463) and K (11.76) (Note: This example assumes that K and the Specific Gravity have been determined previously):

Step 2: Enter flow rate (1658.8 BPH) and inlet temperature (167.5°F) Press "C". The result is:

Inlet Enthalpy, H_i = 25.48 MM Btu/hr

Step 3: Enter outlet temperature (139°F). Press "D". The result is:

Outlet Enthalpy, H_o = 18.4 MM Btu/hr

Step 4: Press "E". The result is:

Duty = 7.08 MM Btu/hr

4.3.2 Calculating Duties Using Specific Heats

Although enthalpies are generally preferred to specific heats, only specific heat data may be available for some streams, such as some chemicals. Also, specific heats may be used with water with reasonable accuracy. The equation to be used is:

$$Q = WC_p\ (t_i - t_o) \qquad (4.3\text{-}2)$$

Where,

Q = Exchanger Duty, MM Btu/hr

W = Flow rate, lb/hr

C_p = Constant pressure Specific Heat, Btu/lb-°F, taken at the mean average temperature, t_m

$t_m = \dfrac{t_i + T_o}{2}$

t_i = Inlet temperature, °F

t_o = Outlet temperature, °F

Example:

Calculate the duty of a Desalter Water Feed/Effluent Exchanger using specific heats.

Data:

Flow	=	400 BPH
Inlet Temperature	=	253 °F
Outlet Temperature	=	242 °F

Calculate:

W = 400 BPH x 350 lb/bbl = 140 M lb/hr

$C_p = 1.0$

$$Q = 140{,}000\ \frac{\text{lb}}{\text{hr}} \times 1.0\,\frac{\text{Btu}}{\text{lb-°F}} \times (253 - 242)\text{°F}$$

$= 1.54$ MM Btu/hr

4.3.3 Calculating Duties from Heat Balances

This procedure applys to determing a heat exchanger duty from a heat balance around a fractionation system. Although the procedure may be used to calculate any of the exchanger duties, import value, or export value, it is more appropriate for reboilers where adequate data is not available on either side; but all other energy quantities are defined. The reboiler may be fired heater or non-fired exchanger using either steam or hot oil heating medium.

Step 1: Define the system as small as possible so that all values are known except the exchanger in question.

Step 2: Calculate and sum up all energy inputs to the system.

Step 3: Calculate and sum up all energy outputs from the system.

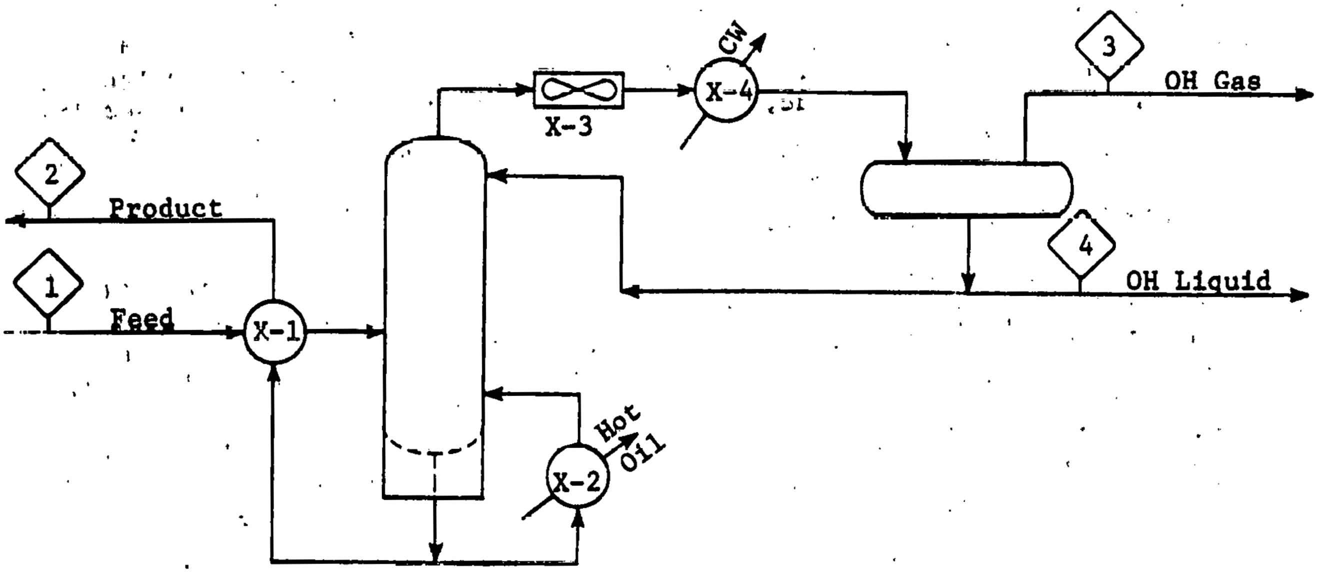
Step 4: Set the total energy input to the energy output and solve for the one unknown value.

Note: All energy values determined in steps 2 and 3 must be accurate for the value of the unknown to be accurate.

Example:

Calculate the reboiler duty (X-2) on the following typical fractionation tower from a heat balance around the tower system.

Step 1: System



Step 2: Sum of Energy Inputs

Feed H_1 = 13.9 MM Btu/hr
X-2 Reboiler, Q_2 = Unknown
Reflux pump, Q = Nil
Total Q_2 + 13.9 MM Btu/hr

Step 3: Sum of Energy Outputs

Btm's prod. H_2 = 26.0 MM Btu/hr
OH Gas H_3 = 0.1 "
OH Liq. H_4 = 0.2 "
X-3 Q_3 = 15.6 "
X-4 Q_4 = 1.1 "
Radiation Q = 0.3 "
Total 43.3 "

Step 4: Solution: Q_2 = (43.3 - 13.9) MM Btu/hr

= 29.4 MM Btu/hr

4.3.4 Estimating Duties from Design Data

For an exchanger where data is not available for calculating the duty using Procedure 4.3.1 or 4.3.2, an engineering estimate of the duty may be made based on a combination of measured data and design (or some past test run) data. Design data for heat exchangers are generally available from specification sheets which normally provide the design values for the duty, the inlet and outlet temperatures, and the flow rates of vapor and liquid entering and leaving the exchanger. Condensing curves may be available for some exchangers.

Which procedure to use depends on the type and reliability of the data. If there is reasonable assurance that the current stream composition is the same as design and a design condensing curve is available, Procedure 4.3.4.1 will produce the best results. If it is more reliable that the cooling water conditions are the same as design rather than the process side, Procedure 4.3.4.2 should be used. Otherwise, use Procedure 4.3.4.3.

4.3.4.1 Using Design Condensing Curve

This procedure covers estimating condenser duties where stream analyses are not available, by estimating the enthalpies from a design condensing curve. The assumption is made that the composition of the stream is the same as that on which the design condensing curve is based. Thus, a source of error is introduced. Even so, this procedure will yield more accurate results than just prorating as in Procedure 4.3.4.2; but will not be as accurate if the enthalpies are calculated from Procedure 4.2.

The condensing curve may be enthalpy versus temperature or duty versus temperature. The results will be the same.

Step 1: Read the enthalpy (or duty) from the curve at the measured inlet temperature.

Step 2: Likewise, read the enthalpy (or duty) from the curve at the measured outlet temperature.

Step 3: Subtract the outlet value from the inlet value and correct for the measured flow rate using one of these equations:

$$Q = (H'_{in} - H'_{out}) \frac{W}{W_d} \qquad \text{(for H vs. t)} \quad (4.3\text{-}3)$$

or

$$Q = (Q_{out} - Q_{in}) \frac{W}{W_d} \qquad \text{(for Q vs. t)} \quad (4.3\text{-}4)$$

Where,

Q = New duty, MM Btu/hr

Q_{out} = Duty from curve at new outlet temperature, MM Btu/hr

Q_{in} = Duty from curve and new inlet temperature, MM Btu/hr

H'_{in} = Enthalpy from design condensing curve at new inlet temperature, MM Btu/hr

H'_{out} = Enthalpy from design condensing curve at new outlet temperature, MM Btu/hr

W = Total measured flow, lb/hr

W_d = Total design flow, lb/hr

4.3.4.2 Using Water Side Estimates

If water side flow rate and temperatures can be measured, a water cooled exchanger duty may be calculated simply and accurately using Procedure 4.3.2 and may be preferred over Procedure 4.3.1 (using enthalpies on process side).

However, cooling water rates to individual exchangers are seldom metered; but may be estimated based on design data. One method for estimating the cooling water flow (assuming a clean exchanger) is using the following equation:

$$W = W_d \sqrt{\frac{\Delta p}{\Delta Pd}} \qquad (4.3\text{-}5)$$

Where W = Estimated cooling water flow, lb/hr

W_d = Design cooling water flow, lb/hr

Δp = Measured pressure drop, psi

Δp_d = Design pressure drop, psi

The estimated flow rate is used in the equation of procedure 4.3.2, and the duty calculated normally.

Example:

Estimate the duty of a sponge oil cooler using cooling water data:

Data:

Design Flow W_d = 336,000 lb/hr
Inlet temperature t_{in} = 82°F
Outlet temperature, t_{out} = 97°F
Assume $\Delta p = \Delta p_d$ (measured Δp not available)

then $Q = WC_p \, (t_{out} - t_{in})$

$= 336{,}000 \text{ lb/hr} \times \frac{\text{Btu}}{\text{lb-°F}} \times (97 - 82) \text{ °F}$

$= 5.0 \text{ MM Btu/hr}$

Note: This compares with 5.9 MM Btu/hr as calculated using procedure 4.3.1. Thus, some inaccuracy can be expected when estimating the flow rate (or assuming design), especially where the exchanger may be fouled. For this reason, estimated flow rates should not be used for and accurate profile on large coolers unless process data is not available.

4.3.4.3 Prorating Design

This procedure covers estimating any type heat exchanger duty based on design duty, flow, and temperatures, but would primarily be used where condensation or evaporation takes place and previous procedures cannot be used.

The estimating procedure is to prorate the design duty based on the ratio of design to measured flow rate and the ratio of design to measured temperature differential across the exchanger using the following equation:

$$Q = Q_d\left(\frac{W}{W_d}\right) \times \left(\frac{\Delta t}{\Delta t_d}\right) \qquad (4.3\text{-}6)$$

where Q and Q_d = Prorated and design duty respectively, MM Btu/hr

W and W_d = Measured and design flow respectively, lb/hr

Δt and Δt_d = Measured and design temperature difference respectively, °F

Note: For truly rough but quick approximations, the flow ratio and Δt ratio can be replaced with only the ratio of the measured to design unit charge rate.

Comments: Several assumptions must be made which limit the reliability of this method. The first two have the most effect on accuracy. The first assumption is that the composition of the stream being used is the same as design. The composition may have changed because of a different charge or operating conditions. Another assumption is that the change in temperature is such that the average specific heat of the mixture is the same, which requires one measured temperature to be higher and one measured temperature to be lower than design by a certain ratio. However, this is generally not the case. Usually, the temperatures are both higher or are both lower than design.

A third assumption is that the inlet and outlet state remains the same as design, which is usually the case. A fourth assumption is that the slope of a hypothetical condensing curve is linear between the new and design temperature points for both inlet and outlet, which is reasonable.

Example: <u>Condenser Duty from Design</u>

Calculate the duties of the crude overhead condensers and compare with values using procedure 4.3.1.

Data:

	Design	Measured
Combined duties, MM Btu/hr	183.5	(Unknown for the example)
Total Flow Mlb/hr	606.4	643.2
Temp. in, °F	319	300 (after water inj.)
Temp. out, °F	120	139
Δt, °F	199	161

Calculation, using equation 4.3-6:

$$Q = 183.5 \text{ MM Btu/hr} \times \frac{643.2}{606.4} \times \frac{161}{199}$$

$$= 157.5 \text{ MM Btu/hr}$$

This estimated value is 20% less than the 196.3 MM Btu/hr calculated using computer generated enthalpies from procedure 4.2.

4.4 FUELS AND FURNACES

This procedure covers the calculation of the combustion energy released by burning a fuel in a furnace (process heater, boiler, incinerator, etc.), the sensible and latent heat in the fuel and combustion air, the stack heat losses, and potential fuel savings for reduced excess air and stack temperature.

The preferred method of performing several detailed and accurate furnace calculations is to use a computer program. The program may be a proprietary in-house type, such as Gulf's TEHA 0122, or one of several commercially available programs. Sample input requirements for Gulf's TEHA 0122 and a sample printout are shown in Appendix A as Table A-4 and Figure A-5.

If a computer program cannot be used, follow the procedures listed in this section. A programmable calculator will shorten the calculation time considerably. A program has been written for the Hewlett-Packard calculator (HP-97) for furnaces on fuel gas, and it is included as part of this procedure. The HP-97 program follows the steps presented here except constant specific heats are used. The results are comparable to, but slightly less accurate than the computer program. The HP-97 operating instructions and an example calculation are included here after the documentary equations. The program listing and data for the component cards are given in Appendix B as Figure B-2, Figure B-3 and Table B-1.

4.4.1 Fuel Input

In the profile, energy input from fuel is only the heat released during combustion as based on the Higher Heating Value (HHV). Any sensible or latent heat is counted with imports and is calculated in the following procedure. The Higher Heating Value of the fuel is the heat released in combustion of the fuel based on starting at 60°F, burning the fuel, and cooling the products of combustion back to 60°F, with all the water vapor condensed out. Heating values are available in most combustion reference manuals. Heating values of some common fuel gas components are given in Appendix B in Table B-1.

<u>Step 1</u>: Calculate energy released by combustion of each component of the fuel and sum for the fuel energy input. The equations are:

for gases, $$Q_f = \sum(HHV_i \times Vol.\%_i \times V_f)\ 10^{-6} \qquad (4.4\text{-}1)$$

where Q_f = Total fuel energy input from combustion, MM Btu/hr

HHV_i = Higher Heating Value of component$_{(i)}$ in terms of Btu/SCF.

$Vol.\%_i$ = Volume percent of component$_{(i)}$ in fuel.

V_f = Fuel volume flow rate, SCFH

for liquids, $Q_f = \sum(HHV_i \times Wt.\%_i \times W)\ 10^{-6}$ (4.4-2)

where HHV_i = Higher Heating Value of component$_{(i)}$ in terms of Btu/lb.

$Wt.\%_i$ = Weight percent of component$_{(i)}$ in fuel.

W = Fuel flow rate, lb/hr.

4.4.2 Import Heat in the Fuel and Combustion Air

The sensible and latent heat of the fuel and combustion air is calculated as an input. The latent heat in the fuel is calculated to be consistent with the liquid enthalpy base. Both the sensible and latent heat of the water vapor is calculated as an input, also.

Step 1: Calculate the liquid enthalpy of the fuel using procedure 4.2. For programmable calculators, the equations listed below may be substituted. The equation for sensible heat is:

$$Q_s = W_f Cp\ (t - 60) \times 10^{-6} \qquad (4.4\text{-}3)$$

where Q_s = Sensible heat above 60°F, MM Btu/hr

W_f = Fuel flow rate, lb/hr

Cp = Constant pressure specific heat, Btu/lb.°F

$= \sum[W_i\ (Cp)_i]$

t = Temperature, °F

Equation 4.4-3 and equation 4.4-4 may be written on a volume or mole basis as long as the units are consistent. The equation for latent heat is:

$$Q_L = \sum(W_i \times \lambda_i) \times 10^{-6} \qquad (4.4\text{-}4)$$

where Q_L = The latent heat, MM Btu/hr

W_i = Fuel component flow rate, lb/hr

λ_i = Latent heat of vaporization of fuel component, if any, at 60°F. See Table A-5 in Appendix A, or API Technical Data Book procedure 7C1.

Step 2: From the fuel analysis and stoichiometric equations, calculate the theoretical amount of oxygen required to burn the fuel. The stoichiometric equations for common fuel components are:

$$C_xH_y + (x + 1/4\ y)\ O_2 \longrightarrow x\ CO_2 + (1/2\ y)\ H_2O \qquad (4.4\text{-}5)$$

$$CO + 0.5\ O_2 \longrightarrow CO_2 \qquad (4.4\text{-}6)$$

$$H_2S + 1.5\ O_2 \longrightarrow SO_2 + H_2O \qquad (4.4\text{-}7)$$

$$S + O_2 \longrightarrow SO_2 \qquad (4.4\text{-}8)$$

The amount of oxygen required for each component is calculated and summed according to:

$$O_2 = \sum(\text{Mole }\%_i \times M_{O_2}) - \text{Mole }\%\text{ of }O_2\text{ in fuel} \qquad (4.4\text{-}9)$$

O_2 = Total O_2 required from air per mole of fuel

Mole$\%_i$ = Mole percent of fuel component$_{(i)}$

M_{O_2} = No. of moles O_2 per mole of fuel component from above stoichiometric equations 4.4-3 to 4.4-6.

Step 3: Calculate the theoretical amount of each stack gas component. The equation for CO_2 is:

$$CO_2 = \sum(\text{Mole}\%_i \times M_{CO_2}) + \text{Mole }\%\text{ of }CO_2\text{ in fuel} \qquad (4.4\text{-}10)$$

where CO_2 = Moles of CO_2 generated per mole of fuel

Mole $\%_i$ = Mole percent of fuel component$_{(i)}$

M_{CO_2} = Moles of CO_2 generated for each component (i) from stoichiometric equations 4.4-5 and 4.4-6 above.

Likewise, the equation for the number of moles of SO_2 generated per mole of fuel is:

$$SO_2 = \text{Mole }\%_{H_2S} + \text{Mole }\%\text{ S} \qquad (4.4\text{-}11)$$

where, Mole $\%_{H_2S}$ = Mole percent of H_2S in fuel

Mole% S = Mole percent of S in fuel

Step 4: Calculate the actual moles of excess oxygen supplied from:

$$EO = \frac{\text{Vol.}\%EO\ (3.77\ O_2 + CO_2 + SO_2 + \Phi \times H_2O)}{100 - 4.77\ \text{Vol.}\%\ EO} \qquad (4.4\text{-}12)$$

where EO = Moles of excess O_2 supplied per mole of fuel

Vol.% EO = Volume percent Oxygen in stack gas from analysis. Either wet or dry basis. See Φ below.

O_2 = Moles O_2 from equation 4.4-9.

CO_2 = Moles CO_2 from equation 4.4-10

SO_2 = Moles SO_2 from equation 4.4-11

H_2O = Moles H_2O from equation 4.4-18

Φ = 0, If O_2 analysis is on dry basis (water condensed out)

= 1, If O_2 analysis is on wet basis.

Step 5: Calculate total combustion air from the following equation:

$$W_{air} = \frac{28.96 \text{ lb air}}{\text{Mole air}} \times \frac{O_2 + EO}{0.2095 \text{ Mole } O_2\text{/Mole air}} \times \frac{V_f}{379.5 \text{ SCF/Mole}} \quad (4.4\text{-}13)$$

where W_{air} = Total combustion air, lb/hr

O_2 = Moles O_2 per mole fuel from equation 4.4-9.

EO = Moles excess O_2 per mole fuel from equation 4.4-12.

V_f = Fuel flow, SCFH

Step 6: Calculate percent excess air from,

$$EA\% = \frac{EO}{O_2} \times 100 \quad (4.4\text{-}14)$$

where EA% = Percent excess air
EO = Moles of excess O_2 per mole fuel from equation 4.4-12.
O_2 = Moles of O_2 per mole of fuel from equation 4.4-9.

Step 7: Calculate import heat of dry air using procedure 4.2. Equation 4.4-3 may be substituted for the programmable calculators.

Step 8: From psychometric charts, determine the moisture in the combustion air and calculate the sensible and latent heat from,

$$H_{aw} = W_{air} \times Air_w \times h_{aw} \times 10^{-6} \quad (4.4\text{-}15)$$

where H_{aw} = Enthalpy of water vapor in the combustion air, MM Btu/hr

Air_w = lb water/lb air from psychometric charts

h_{aw} = Enthalpy of water vapor at inlet temperature, Btu/lb, eq. 4.5-1

Note: The sum of equation 4.4-3 and equation 4.4-4 may be substituted for equation 4.4-15 for the programmable calculator with λ = 1059.1 Btu/lb.

Step 9: Sum fuel enthalpy from Step 1, dry air enthalpy from Step 7, and air water enthalpy from Step 8 to give the total Import heat in the fuel and combustion air. The equation is:

$$Q_I = H_f + H_a + H_{aw} \quad (4.4\text{-}16)$$

where Q_I = Total import heat of fuel and air, MM Btu/hr

H_f = Enthalpy of fuel from Step 1, MM Btu/hr or the sum of the sensible and latent heat from equations 4.4-3 and 4.4-4, MM Btu/hr.

H_a = Enthalpy of dry air from Step 7, MM Btu/hr.

H_{aw} = Enthalpy of the water vapor in the air from equation 4.4-15.

4.4.3 Heat Rejected from the Stack

The heat rejected from a furnace stack is calculated as the sensible heat of the flue gas above 60°F and the latent heat of all the water vapor in the flue gas, since the input is based on higher heating value.

Step 1: Determine nitrogen in flue gas. Since air is essentially 20.95% O_2 and 79.05% N_{O_2}, the equation is,

$$N_2 = 4.77 \quad (O_2 + EO) \quad + \frac{\text{Mole\% Fuel}_{N_2}}{100} \qquad (4.4\text{-}17)$$

where N_2 = Moles of nitrogen in flue gas per mole of fuel

O_2 = Moles of theoretical O_2 supplied per mole of fuel from equation 4.4-9.

EO = Moles of excess O_2 supplied per mole of fuel from equation 4.4-12.

Fuel_{N_2} = Mole percent of nitrogen component in fuel.

Step 2: Determine water generated from combustion of the fuel. The equation is,

$$H_2O = \frac{(\text{Mole\%}_i \times M_{H20})}{100} \qquad (4.4\text{-}18)$$

where H_2O = Moles of combustion water generated per mole of fuel

M_{H20} = No. of Moles of H_2O generated from component (i) from stoichiometric equations 4.4-5 and 4.4-7.

$\text{Mole\%}_i$ = Mole percent of fuel component (i)

Step 3: Determine total water in flue gas by summing water from combustion air, water from combustion, and any fuel water as shown by,

$$W_{H20} = W_{air}\ Air_w + \quad H_2O + \frac{\text{Fuel}_{H_2O}}{100}\ V_f \times \frac{18.02}{379}\ \frac{\text{lb } H_2O}{\text{SCFH Fuel}} \qquad (4.4\text{-}19)$$

where W_{H20} = Total water in the gas, lb/hr

W_{air} = Total combustion air from equation 4.4-13, lb/hr

Air_w = lb water/lb air used in equation 4.4-15

H_2O = Mole combustion water generated from equation 4.4-18 mole/mole

Fuel_{H_2O} = Mole percent of water in fuel

V_f = Fuel flow, SCFH

Step 4: Calculate the enthalpy of each component of the flue gas using procedure 4.1 and the equations listed below. For programmable calculators, equation 4.4-3 may be substituted for the enthalpy (H_i).

Oxygen

$$W_{O_2} = EO \times V_f \times \frac{32.0}{379.5} \qquad (4.4\text{-}20)$$

$$H_{O_2} = W_{O_2} \times h_{O_2} \times 10^{-6} \qquad (4.4\text{-}21)$$

Nitrogen

$$W_{N_2} = N_2 \times V_f \ \frac{28.013}{379.5} \qquad (4.4\text{-}22)$$

$$H_{N_2} = W_{N_2} \times h_{N_2} \times 10^{-6} \qquad (4.4\text{-}23)$$

CO_2

$$W_{CO_2} = CO_2 \times V_f \ \frac{44.01}{379.5} \qquad (4.4\text{-}24)$$

$$H_{CO_2} = W_{CO_2} \times h_{CO_2} \times 10^{-6} \qquad (4.4\text{-}25)$$

SO_2

$$W_{SO2} = SO_2 \times V_f \ \frac{64.064}{379.5} \qquad (4.4\text{-}26)$$

$$H_{SO2} = W_{SO2} \times h_{SO2} \times 10^{-6} \qquad (4.4\text{-}27)$$

H_2O

W_{H20} = Value from equation 4.4-17.

$$H_{H20} = W_{H20} \ (h'_{H20} + 1059.1 \text{ Btu/lb}) \times 10^{-6} \qquad (4.4\text{-}28)$$

Step 5: Sum all the values in Step 4 for the total flue gas enthalpy which is the heat rejected by the furnace stack. The equation is,

$$H_s = H_{O_2} + H_N + H_{CO_2} + H_{SO2} + H_{H20} \qquad (4.4\text{-}29)$$

where H_s = Heat rejected by stack, MM Btu/hr

H_x = Values calculated in Step 4.

4.4.4 Potential Fuel Savings from Reducing Excess Air and Stack Temperature

At least two additional sets of calculations are made on each furnace to provide data for the graph made later in Procedure 5.7.1. Additional points may be calculated when using a computer to improve the accuracy a minor amount. More than two points per curve are not necessary when using the HP-97 program as described in Procedure 4.4.5 because constant specific heats are assumed anyway. The first calculation is made while lowering the excess air to some target level. The second calculation is made while lowering the stack temperature to some target level and lowering the excess air to the same level used in the first calculation. The user must determine the target levels which may be achieved. A family of curves at different levels of excess air may be developed on the same graph if desired.

The potential savings calculations are based on maintaining a constant total heat absorption and obtaining the heat savings by reducing the fuel. In some cases, such as when adding waste heat boilers, the total fuel savings will not all be gained in the furnace on which calculations are being made, but the remainder will be gained by the boilers or elsewhere.

Step 1: Determine radiation loss from furnace following procedure 4.7.1 or based on manufacturer's design data. Convert to a percent of present input. For this procedure, the loss is assumed to be the same percent in each case.

Step 2: From the input and stack loss values calculated for the existing base case, calculate the absorbed duty and furnace efficiency.

$$EFF_1 = \frac{Q_{a1}}{Q_{t1}} \times 100 \qquad (4.4\text{-}30)$$

$$Q_{a1} = Q_{t1}\left(1 - \frac{\text{Rad. \%}}{100}\right) - H_{s1} \qquad (4.4\text{-}31)$$

$$Q_t = Q_{f1} + Q_{I1} = \text{Total input, MM Btu/hr}$$

where

Q_{a1} = Absorbed duty for base case, MM Btu/hr

Q_{f1} = Fuel combustion energy, equation 4.4-1, MM Btu/hr

Q_{I1} = Air and fuel import, from equation 4.4-16, MM Btu/hr

H_{s1} = Air and stack loss, from equation 4.4-29, MM Btu/hr

Rad.% = Radiation loss from Step 1 as percent of Q_t.

EFF_1 - Furnace efficiency for base case, based on HHV, %.

Step 3: Set percent oxygen in the stack (sets excess air) and/or stack temperature to new target levels. For the profile example, 10% excess air and 350°F stack were used.

Step 4: Using the new stack oxygen and/or new stack temperature, repeat Procedure 4.4.2 starting with Step 4 and repeat Procedure 4.4.3.

Note: The values determined in Step 4 are only hypothetical and are used only to determine a new efficiency as shown below.

Step 5: Calculate new efficiency for conditions used in Step 4 and at the same fuel rate as the base case, using the following equation:

$$EFF_2 = \left(1 - \frac{\text{Rad. \%}}{100} - \frac{H_{S2}}{Q_{f1} + Q_{I2}}\right) \times 100 \qquad (4.4\text{-}33)$$

where EFF_2 = Furnace efficiency for the new case, %.

Rad. % = Radiation loss percent from Step 2, %

H_{S2} = Stack loss, MM Btu/hr, from equation 4.4-29 from Step 4 above

Q_{f1} = Fuel combustion energy of base case from equation 4.4-1, MM Btu/hr

Q_{I2} = Air and Fuel Import for above Step 4 case, MM Btu/hr.

Step 6: Assuming constant heat absorption, calculate the new actual total input by,

$$Q_{t3} = \frac{Q_{a1}}{EFF_2} \times 100 \qquad (4.4\text{-}34)$$

where Q_{t3} = Total input for new conditions, MM Btu/hr

Q_{a1} = Absorbed duty from base case, MM Btu/hr, equation 4.4-31.

EFF_2 = New efficiency, equation 4.4-33, %.

Step 7: Determine the new fuel combustion heat by prorating the new input using the equation,

$$Q_{f3} = \frac{Q_{t3} - \left(\dfrac{EO_{(2)}}{O_{2(1)} + EO_{(1)}}\right)(H_{a1} + H_{aw1})}{1 + \dfrac{H_{f1}}{Q_{f1}} + R} \qquad (4.4\text{-}35)$$

where $$R = \frac{(H_{a1} + H_{aw1})}{Q_{f1}\left(1 + \frac{EO_{(1)}}{O_{2(1)}}\right)}$$

Q_{f3} = New fuel combustion heat at new stack temperature and O_2 used in Step 4, MM Btu/hr.

$EO_{(2)}$ = Moles of excess O_2/mole of fuel from Step 4 above, equation 4.4-12.

$EO_{(1)}$ = Same as above but from base case.

$O_{2(1)}$ = Moles of theoretical O_2 supplied per mole of fuel from equation 4.4-9 for the base case.

H_{a1} = Enthalpy of total combustion air (dry) from Procedure 4.4.2, Step 7 for the base case, MM Btu/hr.

H_{aw1} = Enthalpy of water vapor in the total combustion air from the base case, equation 4.4-15, MM Btu/hr.

H_{f1} = Enthalpy of the fuel from the base case, Procedure 4.4.2, Step 1, MM Btu/hr.

Q_{f1} = Fuel combustion heat for base case, equation 4.4-1, MM Btu/hr.

Step 8: Calculate the potential savings in fuel at the new conditions from the base case. The savings is based on only the difference in fuel combustion heat release rather than difference in total input. The equation is:

$$Q_f = Q_{f1} - Q_{f3} \qquad (4.4\text{-}36)$$

Q_f = Potential fuel savings from reducing excess air and/or stack temperature from base case, MM Btu/hr. Based on a constant total heat absorption and varying radiation loss at a constant percent of input.

Q_{f1} and Q_{f3} are as defined in above Step 7.

Step 9: Repeat this procedure for the next point as required, starting with Step 3.

4.4.5 HP-97 Program for Furnace Calculation

This program calculates the energy released from combustion of a fuel gas, Import heat of the fuel and combustion air, the heat lost from the stack, and potential savings from reducing excess air and stack temperature. The calculations follow those presented above in Procedures 4.4.1 - 4.4.4, except constant specific heats are assumed. Two program cards and one data card per component are required and are listed in Appendix B as Figure B-2, Figure B-3, and Table B-1.

Fuel Input and Import Heat

Step 1: Load only program card No. 1 (Input).

Step 2: Press "E" to clear storage registers of any previous data and to set amount of printout. If "0" is displayed, all printout is made. If "1" is displayed, printout of data marked with an asterisk below will be suppressed. Repeat operation to change from "0" to "1" or "1" to "0".

Step 3: Enter percent of one component. They may be in any order. Press "A". The program will cycle. Enter data card for the component as prepared from Table B-1.

INPUT		OUTPUT
Data	Operation Keys	
Component %	A	Print component % *
Component data card	None	Print component No. *
		Display total %

Step 4: Repeat Step 3 for each component.

Note: If more than one furnace calculation is to be made for the same fuel, steps 3 and 4 do not need to be repeated.

Step 5: Enter fuel temperature, combustion air temperature (inlet to air preheater), and water vapor in air (lb water/lb air).

INPUT		OUTPUT
Data	Operation Keys	
Fuel temp., °F	Enter ↑	
Air Temp., °F	Enter ↑	
Water in air, lb/lb	B	
		print water in air, lb/lb*
		print air temp., °F *
		print fuel temp., °F *

Step 6: Enter fuel flow and stack oxygen content as percent volume on a dry basis (water condensed in sampling). Press "C".

INPUT		OUTPUT
Data	Operation Keys	
Fuel flow, MSCFH	Enter ↑	
Stack O_2, %	C	Print % O_2
		Print Fuel flow, MSCFH
		(Space)
(Fuel Input for Profile) ⟶		Print Combustion heat (HHV) MM Btu/hr
		(Space)
		Print fuel sensible heat, MM Btu/hr*
		Print fuel latent heat, MM Btu/hr*
		Display percent excess air, %
		Print air sensible heat, MM Btu/hr*
		Print air water S.H., MM Btu/hr*
		Print air water L.H., MM Btu/hr*
(Combustion air and fuel Import heat for profile) ⟶		Print total air and fuel import Heat, MM Btu/hr
		(Space)
		Total input to furnace, MM Btu/hr

Heat Rejected

Step 7: Load program card No. 2 (Stack loss)

Step 8: Press "E" to set amount of printout and to clear particular registers. If "0" is displayed, all printout is made. If "1" is displayed, printout of data marked with an asterisk is suppressed. Repeat "E" operation to change from "0" to "1" or "1" to "0". A zero "0" must be displayed at least once.

Step 9: Enter stack temperature and radiation loss as a percent of the total input from Step 6. Radiation loss may be calculated from procedure 4.7.1 or estimated from design data. Press "A".

INPUT		OUTPUT
Data	Operation Keys	
Stack Temp., °F	Enter ↑	
Radiation loss, %	A	
		Print stack temp., °F
		Print O_2 S.H., MM Btu/hr*
		Print N_2 S.H., MM Btu/hr*
		Print CO_2 S.H., MM Btu/hr*
		Print SO_2 S.H., MM Btu/hr*
		Print H_2O S.H., MM Btu/hr*
		Print H_2O L.H., MM Btu/hr*
(Heat Rejected for Profile)		Print stack loss, MM Btu/hr
		(Space)
		Print furnace efficiency, %/100

Potential Heat Recovery

Step 10: Enter new stack temperature and stack oxygen percent by volume on a dry basis. Press "B".

INPUT		OUTPUT
Data	Operation Keys	
Stack temp., °F	Enter ↑	
Stack O_2, %	B	Print % O_2 in stack, %
		Print stack temp., °F
		Print O_2 S.H., MM Btu/hr*
		Print N_2 S.H., MM Btu/hr*
		Print CO_2 S.H., MM Btu/hr*
		Print SO_2 S.H., MM Btu/hr*
		Print H_2O S.H., MM Btu/hr*
		Print H_2O L.H., MM Btu/hr*
(Heat Rejected for Profile) →		Print stack loss, MM Btu/hr*
		(Space)
		Print furnace efficiency, %/100
		Print fuel combustion heat, MM Btu/hr
		Total input heat, MM Btu/hr
(Value for graph) →		Fuel savings, MM Btu/hr

Step 11: Repeat step 8 and Step 9 for other combinations of stack temperature and percent oxygen as desired.

Example: Furnace Calculation Using the HP-97 Calculator

Calculate the combustion energy of the fuel to a furnace, the heat input by the fuel and combustion air enthalpy and the heat rejected out the stack. Also, determine the potential fuel savings if the oxygen in the stack is, first reduced to 2.0% at the same stack temperature and then, to 2.0% at a 350°F stack temperature by the use of an air preheater.

Data:

Fuel: Composition: Hydrogen 10% by Vol.
Methane 75% by Vol.
Ethane 10% by Vol.
Propane 5% by Vol.

: Temperature = 100°F

: Flow = 500 MSCFH

Air : Temperature = 80°F

: Water vapor in air = .0157 lb/lb

Stack : Temperature = 600°F

: Oxygen = 4.0% by Vol. (dry basis)

Other : Assume radiation loss = 2.0% of input

The steps given in procedure 4.4.4 for the HP-97 calculator are followed:

<u>Step 1</u>: Load program card 1.

<u>Step 2</u>: Press "E" until "1" is displayed for minimum printout.

<u>Step 3</u>: Enter 10. Press "A". Enter Hydrogen component card.

<u>Step 4</u>: Repeat Step 3 for each remaining component. "1.0" should be displayed when all components are in.

<u>Step 5</u>: Enter fuel temperature (100.0) and air temperature (80.0). Key lb water/lb dry air (.0157) and press "B".

<u>Step 6</u>: Enter fuel flow (500.0). Key stack oxygen (4.0) and press "C". The results are:

Oxygen = 4.0%
Fuel = 500 MSCFH
(Space)
Heat input from combustion of fuel = 546.2 MM Btu/hr
(Space)
(Import heat from fuel and air) = 546.2 MM Btu/hr
(Space)
Total Input = 557.9

<u>Step 7</u>: Load program card 2.

<u>Step 8</u>: Press "E" until "1" displays.

<u>Step 9</u>: Enter stack temperature (600.0). Key % radiation (2.0). Press "A". The results are:

Stack temperature = 600°F
Total stack loss = 136.8 MM Btu/h
Furnace efficiency (%/100) = 0.735

<u>Step 10</u>: Enter same stack temperature (600.0), but key a new stack oxygen at 2.0%. Press "B". The results are:

Percent O_2 in stack = 2.0%
Stack temperature = 600.0°F
New total stack loss = 115.6 MM Btu/hr
(Space)
New furnace eff. (%/100) = 0.773
New fuel combustion heat = 521.1 MM Btu/hr
New total input to furnace = 530.5 MM Btu/hr

Energy savings in fuel between this and first case. = 27.4 MM Btu/hr

Step 11: Enter new reduced stack temperature (350.0). Key in same reduced oxygen (2.0). Press "B". The results are:

Percent O_2 in stack = 2.0%
Stack temperature = 350.0°F
New total stack loss (Space) = 86.5 MM Btu/hr
New furnace eff. (%/100) = 0.825
New fuel combustion heat = 488.2 MM Btu/hr
New total input to furnace = 497.0 MM Btu/hr
Energy savings in fuel between this and first case. = 60.9 MM Btu/hr

4.4.6 Combustion Heat from Coke

In a Fluid Catalytic Cracking (FCC) Unit, coke is a byproduct of the catalytic reaction and is deposited on the catalyst. The coke, which must be removed to maintain the effectiveness of the catalyst, is burned off the catalyst in the regenerator. The heat released in burning the coke off the catalyst is a fuel input to the FCC unit (and to the refinery) and the amount of heat released must be calculated to determine the fuel input. The procedure used to determine the combustion heat of the coke is to first use the flue gas analysis and combustion air rate to calculate the amount of coke in the form of carbon and hydrogen that is burned off the catalyst. Then the amount of heat released in burning the carbon and hydrogen to CO_2, CO, and H_2O is calculated from the heats of combustion. In this procedure, an example calculation is included with each step. The example data used is:

Combustion Air Rate (measured)	691,879 lb/h4
Air Temperature	80°F
Relative Humidity	74%

Dry Flue Gas Analysis, Mole Fraction

N_2 = 0.840
O_2 = 0.005
CO_2 = 0.105
CO = 0.050

Step 1: Calculate the Moles of N_2 and O_2 in the Combustion air. From published reference tables and the water content of air at 74% relative humidity and 80°F is 0.01643 lbs H_2O/lb dry air. The formula for converting the air rate to a dry basis is:

$$\frac{\text{Air Rate lb/hr}}{1 + \text{lb } H_2O/\text{lb dry air}} = \text{lb/hr dry air}$$

$$\frac{691{,}879}{1 + 0.01643} = 680{,}695 \text{ lb/hr dry air}$$

Using MW air = 28.96
Mole Frac N_2 = 0.79
Mole Frac O_2 = 0.21

$$\text{Component Flow Rate (Mole/hr)} = \frac{\text{Dry Air Flow Rate (lb/hr)}}{\text{Mole. Wt. of Air (lb/mole)}} \times \begin{pmatrix}\text{Component}\\ \text{Mole Fraction}\end{pmatrix}$$

$$N_2 \text{ Flow Rate} = \frac{680{,}695 \text{ lb/hr}}{28.97 \text{ lb/mole}} \times 0.7 = 18562.3 \text{ mole/hr.}$$

$$O_2 \text{ Flow Rate} = \frac{680{,}695 \text{ lb/hr}}{28.97 \text{ lb/mole}} \times 0.21 = 4934.3 \text{ mole/hr.}$$

Step 2: Calculate the total flue gas rate and the rate of each component. Since the N_2 is unchanged in the combustion process, the same amount of H_2 is in the flue gas as is in the combustion air. Therefore:

$$\text{Mole/hr of Dry Flue Gas} = \frac{\text{Mole/hr of } N_2 \text{ in combustion air}}{\text{Mole fract. } N_2 \text{ in Flue Gas}}$$

$$= \frac{18562.3}{0.84} = 22098.0 \text{ mole/hr}$$

The flow rate of each component is the product of this total and the component mole fraction. The equation is,

$$\begin{pmatrix}\text{Mole/hr of Flue}\\ \text{Gas Component}\end{pmatrix} = \text{Mole/hr Dry flue gas} \times \begin{pmatrix}\text{Mole Fract. of}\\ \text{of Component in}\\ \text{Dry Flue Gas}\end{pmatrix}$$

Component	Dry Flue Gas Mol/hr		Mole Fract.		Component Flow Rate Mole/hr
O_2	22098	x	0.005	=	110.5
CO_2	22098	x	0.105	=	2320.3
CO	22098	x	0.050	=	1104.9
N_2	22098	x	0.840	=	18562.3
			TOTAL	=	22098.0

Step 3: Calculate moles of carbon and H_2 in coke.

Carbon

Since there is one mole of carbon in each mole of CO_2 or in each mole of CO, the moles of carbon in the coke are the same as the sum of the moles of CO_2 and CO in the flue gas. As calculated above, the CO_2 and CO flue gas rates are:

$$\begin{array}{rcll} CO_2 & = & 2320.3 & \text{mole/hr} \\ \underline{CO} & = & \underline{1104.9} & \text{mole/hr} \\ \text{Total} & = & 3425.2 & \text{mole/hr} \end{array}$$

Therefore, the carbon in the coke is 3425.2 mole/hr.

Hydrogen

The H_2 in the coke cannot be calculated directly since the quantity of H_2O in the flue gas is not known. The H_2O must be calculated from an oxygen balance. The oxygen consumed in burning the carbon is calculated as follows:

$$\begin{pmatrix}\text{Mole/hr } O_2\\ \text{to } CO_2 \text{ \& } CO\end{pmatrix} = \begin{pmatrix}\text{Mole/hr } CO_2\\ \text{in flue gas}\end{pmatrix} + \begin{pmatrix}0.5 \text{ x mole/hr } CO\\ \text{in flue gas}\end{pmatrix}$$

$$= 2320.3 + 0.5 \text{ x } 1104.9$$

$$= 2872.7 \text{ mole/hr } O_2 \text{ to } CO_2 \text{ and } CO$$

The O_2 balance can then be calculated from the following equation:

$$\begin{array}{ccccccc}\begin{pmatrix}\text{Mole/hr } O_2\\ \text{in Combustion Air}\end{pmatrix} & - & \begin{pmatrix}\text{Mole/hr } O_2\\ \text{in Flue Gas}\end{pmatrix} & - & \begin{pmatrix}\text{Mole/hr } O_2\\ \text{to } CO_2 \text{ \& } CO\end{pmatrix} & = & \begin{pmatrix}\text{Mole/hr } O_2\\ \text{to } H_2O\end{pmatrix}\\ 4934.3 & - & 110.5 & - & 2872.7 & = & 1951.1 \text{ Mole/hr } O_2 \text{ to } H_2O\end{array}$$

The H_2 in the coke is then calculated as follows:

$$\begin{pmatrix}\text{mole/hr}\\ \text{of } H_2 \text{ in coke}\end{pmatrix} = \begin{pmatrix}\text{mole/hr } O_2\\ \text{to } H_2O\end{pmatrix} \text{ x } 2$$

$$= 1951.1 \text{ x } 2$$

$$= 2902.2 \text{ mole/hr } H_2 \text{ in coke}$$

<u>Step 4</u>: Calculate the heat released in burning coke. The heat released in burning the coke off the catalyst is the sum of the heat released in burning the carbon in the coke to CO_2 and CO and the hydrogen in the coke to H_2O. The equation for each calculation is:

Mole/hr x Mol. Wt. x HHV = Btu/hr

		=	Btu/hr
Carbon to CO_2	2320.3 x 12 x 14,100	=	392.6 MM Btu/hr
Carbon to CO	1104.9 x 12 x 3,960	=	52.5 MM Btu/hr
Hydrogen to H_2O	3902.2 x 2 x 60958	=	475.7 MM Btu/hr
	TOTAL		920.8 MM Btu/hr

The total Heat Input from combustion of the coke to the FCC (and to the overall refinery) is 920.8 MM Btu/hr.

4.5 STEAM SYSTEM

This section covers procedures for calculation of flows and energy values of steam, boiler feedwater, and condensate being consumed and/or produced by individual equipment items in a unit. Several items in the procedures that may differ from those used conventionally are noted in the following rules:

Rule 1: Steam, boiler feedwater, and condensate are considered consumed or produced by an equipment item if the equipment changes pressure levels or phases of the steam stream. However, in some cases, such as superheating steam, the pressure level may be the same; but the energy level changes and is still calculated.

Rule 2: All steam, boiler feedwater, or condensate consumed/produced in the unit is considered input/exported, respectively, from the unit even though it may be used internally within the unit.

Rule 3: Since the profile is based on gross values, the steam input energy to an item is the inlet enthalpy of the steam rather than the net difference between inlet and outlet enthalpies. The outlet energy value is considered an export as a recovered output. This may seem unusual at first, but this method yields more useful data for further evaluation later than the convention method of only considering net consumption.

Rule 4: To be consistent with the hydrocarbon enthalpies, the steam enthalpy obtained from the Steam Tables[3,4] is adjusted from the 32°F reference base to the 60°F reference base by the following equations:

$$h = h' - 28.1 \text{ Btu/lb} \qquad (4.5\text{-}1)$$

where h = profile enthalpy, $h = 0$ for saturated water at 32°F, Btu/lb

h' = Steam Tables[3,4] enthalpy, $h = 0$ for water at 60°F & 0 psig.

then

$$H = hW \qquad (4.5\text{-}2)$$

where H = Profile enthalpy, Btu/hr
h = Profile enthalpy, Btu/lb
W = Stream flow, lb/hr

Since all steam calculations essentially follow the same procedure, a general procedure is given first. Then detailed example calculations of the more common equipment values are given for each of the four classifications; Turbines, process, heat recovery, and miscellaneous.

General Procedure

Steam calculations follow the same general procedure as listed in the beginning of this Section 4. Each steam user is analyzed by making a weight balance and an energy balance by applying equation 4-1. The appropriate material and energy values are calculated and then tabulated in a weight balance table and energy balance table.

Step 1: Determine the equipment items that use or produce steam, boiler feedwater, or condensate. Typical equipment items are:

- Turbines and reciprocating engines.
- Heat exchangers
- Fractionation towers
- Ejectors
- Boilers
- Process heaters

Step 2: Define the system for each equipment item by drawing a diagram of it with all the steam system streams entering and leaving shown on it. Heat transferred and mechanical work are also indicated. This may only need to be a mental process for simple, well understood systems.

Step 3: Determine the quantities of steam, boiler feedwater, and condensate that are being consumed or produced at each of the pressure levels of interest (600 lb, 250 lb, 50 lb, etc.). Steam, boiler feedwater, or condensate are consumed if the stream changes pressure level or phase. Tabulate these quantities according to pressure levels for each equipment item in a Weight Balance. See Table 5-1 in Section 5 for a typical Weight Balance. The individual equipment items are grouped together according to the following classifications:

- Steam turbines and engines
- Process - stripping, heating
- Heat recovery and steam generation
- Miscellaneous

Step 4: Calculate the energy inputs and outputs from each system defined in Step 3. Each system's inputs and outputs should balance to form the following equation, which is equation 4-1, written specifically for steam:

$$\text{Gross input} + \text{Heat recovered} = \text{Total export} + \text{Energy transferred} + \text{Heat rejected} \qquad (4.5\text{-}3)$$

where

Gross input = Inlet enthalpies of steam, boiler feedwater, condensate that were found consumed in Step 3.

Heat recovered = The net energy received from the process by heat transfer through furnace coils and heat exchangers to preheat boiler feedwater, generate steam, or superheat steam.

Note: In some cases, the heat recovered valued may be calculated from equation 4.5-3 as the remaining value.

Total export = Sum of enthalpies (Btu/hr) of steam, boiler feedwater, and condensate produced in Step 3.

Rejected = Enthalpies of steam, boiler feedwater, or condensate either leaking or being vented to the atmosphere.

+ Mechanical losses on steam driven equipment

+ Heat lost by radiation and convective cooling

Note: The equipment manufacturer should be consulted for estimates of equipment losses. These losses may be assumed to be a certain percent of the rated power.

Transferred to process = Actual net energy input to the process by injection, heat transfer, or work done.

Note: Heat transferred may be calculated from equation 4.5-3 as the remaining value.

Tabulate these energy quantities according to the categories in equation 4.5-1 for each equipment item in an Energy Balance Table. See Table 5-2 in Section 5 for a typical energy balance. The individual equipment items are grouped into the same categories as on the weight balance table.

Step 5: Determine the energy values to be used in the unit profile, Heat Input and Heat Rejection Summary and Energy Balance Table. Since the equipment item systems defined in Step 2 are part of the unit, and the profile is on a gross basis, the Heat Transferred and Heat Recovered categories all occur internally and therefore are not part of the unit input or output. The Heat Transferred is of interest because this is the conventional input on a net basis.

The total export energy quantity is split up to show the amount of energy left over in the steam input. The terms are:

Steam generated = Energy recovered total
Steam and condensate = Total export - Steam generated

These two energy values are listed in the Energy Balance Table as a recovered energy. See Procedure 5.3.1.

The remaining two categories of gross input and heat rejected are listed in the Heat Input and Heat Rejection Summary as an Input and Rejection, respectively, with the same equipment sub-categories.

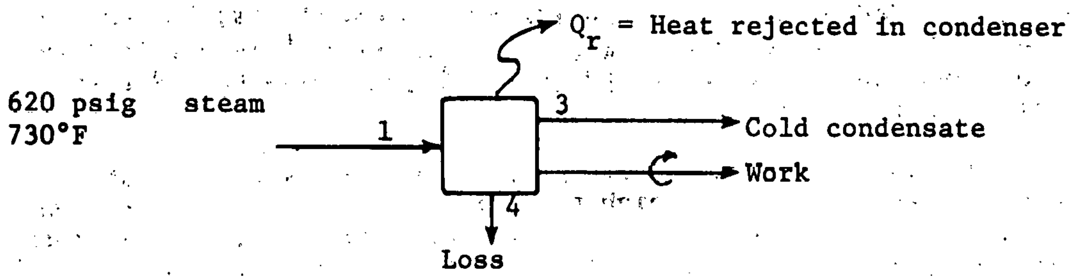
4.5.1 Steam Turbines

Steam turbines are used to drive pumps, compressors, and blowers. If the turbine exhaust goes to a steam surface condenser, the turbine is considered a condensing turbine and the heat rejection calculation is different. Otherwise, the turbine is non-condensing (or topping, or back pressure). Example calculations are given for both the condensing and the non-condensing and also for the case of a slow rolling turbine on stand by.

Example 1: Condensing Turbines

A turbine driving a compressor uses 50.0 M lb/hr of 600 lb. steam. The exhaust goes to a surface condenser at 25 in. Hg vacuum. The hot well temperature was measured at 132°F. The exhaust temperature is not known and is assumed saturated (t2).

System Diagram



Weight Balance Values

600 lb steam consumed = W_1

= 50.0 M lb/hr

Gland leakage recovered = W_4

= 400 lb/hr estimated

Note: Actually the steam losses from the turbine are from both the high pressure and low pressure end, but for profile purposes may be considered as a percent of the rated power, or even ignored. The manufacturer should be consulted for estimates of losses if they are considered.

Condensate returned = Cold condensate produced

= W_3

= $W_1 - W_4$

= (50,000 - 400) lb/hr

= 49,600 lb/hr

Energy Balance Values

Heat input = Heat of 600 lb inlet steam
= H_1'
= $(h_1' - 28.1)\ W_1$
= (1366.5 - 28.1) Btu/lb x 50,000 lb/hr
= 66.9 MM Btu/hr

Heat rejected = Direct loss + Heat rejected in condenser
= .05 x Hp + $(h_2' - h_3')\ W_3$
= 0.5 MM Btu/hr (1119.5 - 99.9) Btu/lb x 49,600 lb/hr
= 50.6 MM Btu/hr

Notes: 1) The condenser duty should not be counted as a loss twice. If it is desired to keep all heat rejected to cooling water together, the condenser should be considered outside the system and not counted here. The turbine exhaust would be considered "transferred" to the process, and the heat rejected by the condenser would be accounted for in water cooler losses.

2) The direct losses are heat energy in the steam lost (through the shaft seals at the high pressure end, the low pressure end, and governor), bearing friction, and radiation. Since it is nearly impossible to measure these losses, they are lumped together as a percentage of the rated horsepower, or assigned a value depending on the turbine size, condition, and steam pressure levels. The manufacturer should be consulted for accurate estimates of this type.

Heat export = Heat in cold condensate
= H_3'
= $(h_3 - 28.1)\ W_3$
= (99.9 - 28.1) Btu/lb x 49,600 lb/hr
= 3.6 MM

Heat transferred = Heat equivalent of the shaft work
= Heat input - heat export - heat rejected
= (66.9 - 3.6 - 50.6) MM Btu/hr
= 12.7 MM Btu/hr

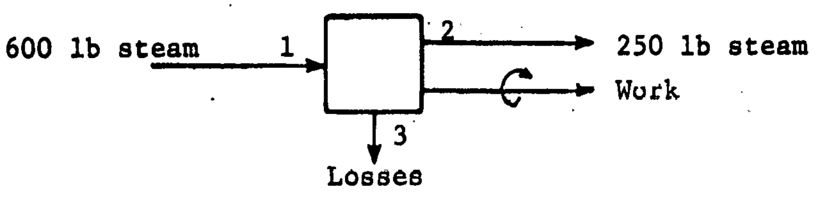
Note: Heat transferred is not used in the profile except to balance the steam energy balance and to show the net input.

Example 2: Non-Condensing Turbines

If the inlet flow is measured, the values for a non-condensing turbine are calculated the same way as shown in example 4.5.1-1 above, except there is no condenser loss and the exhaust remains useful steam. In this example, the flow is not known.

A turbine driving a pump uses 600 lb steam and exhausts to the 50 lb header.

System Diagram



Weight Balance Values

If the flow cannot be measured, it is estimated from the following equation:

$$W_i = \frac{P}{P_d} \times W_d$$

where

W_i = Steam consumed, lb/hr
P = Measured steam chest pressure, psia
P_d = Design steam chest pressure, psia
W_d = Design steam rate for the turbine, lb/hr

Note: If the turbine has any hand valves open, then the design case should be used that has the same number open.

then, Steam consumed $= \frac{565}{615} \times 14{,}800$ lb/hr

$=$ 13.6 M lb/hr of 600 lb steam

Steam loss $= W_2$

$=$ 100 lb/hr

Steam produced = W_2
= $W_1 - W_3$
= (13.6 - 0.1) M lb/h4
= 13.5 M lb/hr

Energy Balance Values

Heat input = Enthalpy of entering steam
= H_1,
= $(h_1 - 28.1)$ Btu/lb x 13,600 lb/hr
= 18.2 MM Btu/hr

Heat rejected = Losses
= $.05 \times HP_d$
= .05 x 400 hp x 2545 Btu/hp-hr
= .1 MM Btu/hr

Heat export = Enthalpy of exhaust steam
= H_2,
= $(h_1 - 28.1)$ x 13,600 lb/hr
= 17.2 MM Btu/hr

Note: This assumes that the exhaust steam is recovered. If the exhaust is to the atmosphere, then it is counted as a loss.

Heat transferred = Heat equivalent of work
= $\frac{P}{P_d} \times HP_d \times 2545$ Btu/hp-hr
= $\frac{565}{615} \times 400$ hp x 2545 Btu/hp-hr
= 0.9 MM Btu/hr

where HP_d = Design turbine horsepower.

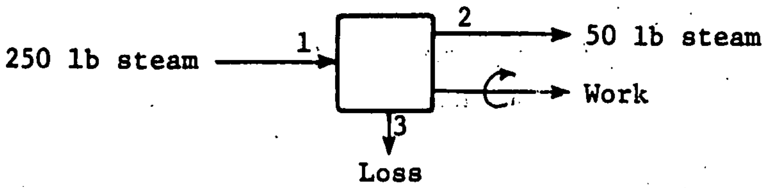
Note: When the exhaust temperature cannot be measured, the heat export is calculated from a heat balance by,

Heat export = Heat input - Heat transferred - Losses

Example 3: Slow Rolling Turbine (Standby)

The inlet valve to a turbine is only slightly open to allow the turbine to slowly roll for emergency start up. The design normal steam rate is 5350 lb/hr.

System Diagram



Weight Balance Values

As a rule of thumb, the steam flow to a turbine that is only slow rolling is estimated at twelve percent of rated load.

250 lb steam consumed = 0.12 x 5350 lb/hr
= 0.6 M lb/hr

condensate loss = Steam loss (assume 2% of rated load unless leaks are excessive.)
= .02 x 5,320 lb/hr
= 0.1 M lb/hr

50 lb steam produced = 250 lb steam consumed - steam loss
= (0.6 - 0.1) M lb/hr
= 0.5 M lb/hr

Energy Balance Values

Heat input = Heat of 250 lb steam consumed
= H_1,
= $(h_1 - 28.1)\ W_1$
= (1272.6 - 28.1) Btu/lb x 642 lb/hr
= 0.8 MM Btu/hr

Heat rejected = Heat in steam loss + bearing friction loss + radiation loss
= h (2% x rated flow + 2% x rated flow + 2% x rated flow)
= (1272.6 - 28.1) Btu/lb x 5350 lb/hr (.02 + .02 + .02)
= 0.4 MM Btu/hr

Note: The above values are insignificant, but the calculations are shown to demonstrate the procedure.

Heat export = Heat in 50 lb steam exhaust

= $H_{2'}$

= $(h_2 - 28.1)\ W_1$

Note: Since neither the exhaust flow nor the temperature was measured, the export heat is assumed to equal the remaining heat.

Heat export = (0.8 - 0.4) MM Btu/hr

= 0.4 MM Btu/hr

Heat transferred to process = Heat equivalent of work done

= Heat input - Heat export - Heat rejected

= 0.0

Note: The slow rolling turbine work is negligible.

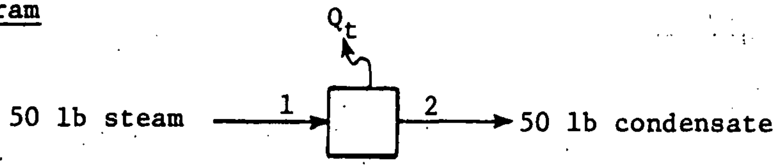
4.5.2 Process Uses

The most common process use for a steam is heating in heat exchangers or tank coils. Other uses are stripping, eductor steam, attrition steam, etc. Procedures, including example calculations, are given for heating and stripping.

Example 1: Heating

A steam reboiler on a tower uses 10,000 lb/hr of 60 lb. steam. The condensate is recovered at saturated conditions.

System Diagram



Weight Balance Values

50 lb steam consumed = 10.0 M lb/hr = W_1

Condensate returned = 10.0 M lb/hr = W_2

Energy Balance Values

Heat input = Heat in 50 lb steam consumed

= $H_{1'}$

= $(h_1 - 28.1)\ W_1$

= (1205.6 - 28.1) Btu/lb x 10,000 lb/hr

= 11.8 MM Btu/hr

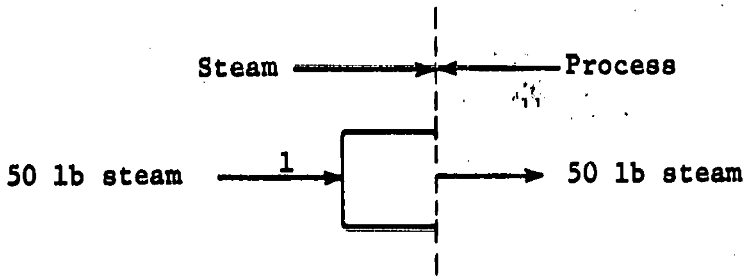
Heat export = Heat in condensate (if recovered)
= H_2,
= $(h_2 - 28.1)\ W_2$
= (276.5 - 28.1) Btu/lb x 10,000 lb/hr
= 2.5 MM Btu/hr

Heat transferred to Process = Heat input - Heat export
= (11.8 - 2.5) MM Btu/hr
= 9.3 MM Btu/hr

Example 2: Stripping Steam

A fractionation tower uses 20,700 lb/hr of superheated steam at 45 psig and 745°F.

System Diagram - (open system)



Weight Balance Values

50 lb steam consumed = 20.7 M lb/hr = W_1
condensate loss = 20.7 M lb/hr = W_1

Energy Balance Values

Heat input = Heat of 50 lb steam consumed
= H_1,
= $(h_1 - 28.1)\ W_1$
= (1403.1 - 28.1) Btu/lb x 20,700 lb/hr
= 28.5 MM Btu/lb

Heat transferred to Process = Steam input
= 28.5 MM Btu/hr

4.5.3 Steam Generation and Waste Heat Recovery

In a refinery, steam is generated by utilizing waste heat sources as well as in a fired boiler. The waste heat source may be a process stream or flue gas from a process heater or catalyst regenerator. The calculation procedure is the same, regardless of the source of the heat.

Steam generation occurs in three phases:

- Preheating the boiler feedwater
- Generating saturated steam
- Superheating the saturated steam

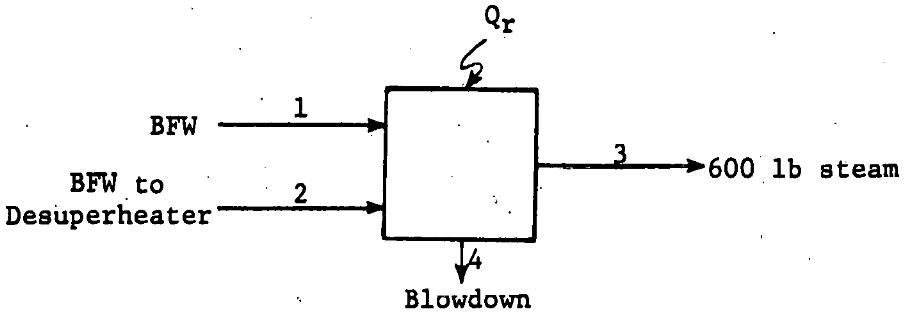
In the profile, all of these phases are ultimately labeled, "Steam Generation". If two or more phases occur in the same piece of equipment, such as a boiler, they are combined as one. Examples are given below with the phases combined and separated (preheating and superheating).

Example 1: Steam Generation

This example is also applicable to boilers as well as waste heat recovery. The only difference is that the heat recovered (Q_r) may be labeled as heat absorbed.

In a heater convection section, 600 lb steam is generated from 63,280 lb/hr of preheated BFW from another heater stack. Addition of BFW to the desuperheater increases the total steam production to 64,000 lb/hr.

System Diagram



Weight Balance Values

Steam produced = W_3
= 64,000 lb/hr

BFW loss = Blowdown (assume 2% of BFW inlet)
= .02 x 63,280 lb/hr
= 1,266 lb/hr

BFW to desuperheater

= W_3 + Blowdown - W_1
= ((64,000 _ 1,266 - 63,280) lb/hr
= 1,986 lb/hr

BFW consumed = (53,280 + 1,986) lb/hr

= 65,266 lb/hr

Energy Balance Values

Heat input = Heat in BFW + BFW to desuperheater

= $H_1 + H_2$

= $(h'_1 - 28.1)\ W_1 + (h'_2 - 28.1)\ W_2$

= (385.3 - 28.1) Btu/lb x 63,280 lb/hr

+ (203.3 - 28.1) Btu/lb x 1,986 lb/hr

= 23.0 MM Btu/hr

Heat rejected = Heat in blowdown

= H_4

= $(h'_4 - 28.1)\ W_4$

= (470.1 - 28.1) Btu/lb x 1,266 lb/hr

= 0.6 MM Btu/hr

Heat export = Heat of 600 lb steam

= H_3

= $(h'_3 - 28.1)\ W_3$

= (1353.7 - 28.1) Btu/lb x 64,000 lb/hr

= 84.8 MM Btu/hr

Heat recovered (to steam generation) = Q_R

= Heat export + Heat rejected - Heat input

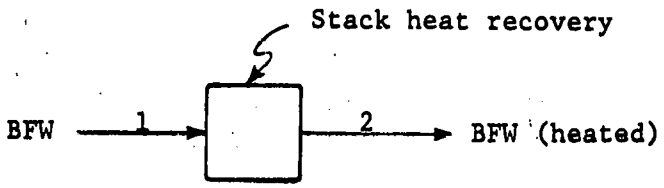
= (84.8 + 0.6 - 23.3) MM Btu/hr

= 62.1 MM Btu/hr

Example 2: Preheating BFW

In a process heater, 64,000 lb/hr of Boiler Feedwater is heated from 235°F to 412°F in the convection section. The BFW then goes to another heater where steam is produced.

System Diagram



Weight Balance Values

The flow rate of a BFW stream is only counted once. Since the BFW does not leave the unit boundary, but is used later in generating steam, it is not considered consumed until it is changed to steam in the other heater.

BFW consumed = 0.0

BFW produced = 0.0

Energy Balance Values

Since the BFW is not considered consumed above, the enthalpies in and out are not counted as input and export in heat calculations either, but are used in determining the heat recovery.

Heat recovered = Enthalpy gain by BFW
(to "Steam Generation")

$$= (h'_2 - h_1) \times W_1$$

$$= (385.3 - 203.3) \text{ Btu/lb} \times 63{,}280 \text{ lb/hr}$$

$$= 11.5 \text{ MM Btu/hr}$$

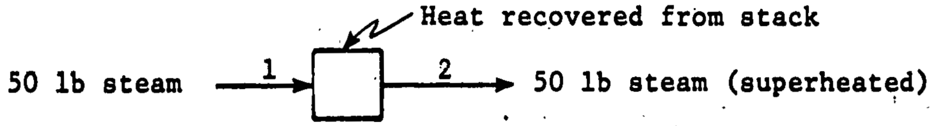
Heat export = Heat recovered

$$= 11.5 \text{ MM Btu/hr}$$

Example 3: **Superheating Steam**

In a process heater, 38,909 lb/hr of 50 lb. steam is superheated in the convection section from 520°F to 745°F. The superheated steam is used later in the unit for stripping. No BFW was used in the desuperheater.

System Diagram



Weight Balance Values

Since the stream leaving is still counted as 50 lb. steam and is the same quantity, there is no consumption.

Steam consumed = 0.0

Steam produced = 0.0

Energy Balance Values

Since there is no consumption of 50 lb. steam, the enthalpies in and out are not counted as input and export in heat calculations, but are used in determining the heat recovery.

Heat recovery (to "Steam Generation") = Enthalpy gain by 50 lb. steam

= $(h'_1 - h'_2) \times W_1$

= (1403.1 - 1205.6) Btu/hr x 28,909 lb/hr

= 7.7 MM Btu/hr

Heat export = Heat recovered

= 7.7 MM Btu/hr

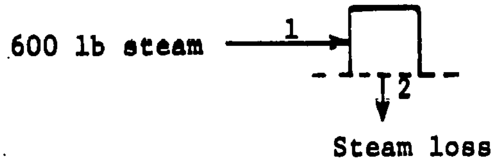
4.5.4 Miscellaneous

Other uses of steam that do not fit into one of the previous classifications are all lumped together under miscellaneous. Example calculations are given below of the two common applications of direct loss and steam flash drum.

Example 1: Direct Loss

A steam leak is estimated to leak 1,000 lb/hr of 600 lb. steam to the atmosphere.

System Diagram - (open system)



Weight Balance Values

600 lb. steam consumed W_1 = 1 M lb/hr

Condensate loss = W_2 = 1 M lb/hr

Energy Balance Values

Heat input = Heat in steam leaking

= H_{1},

= $(h_1 - 28.1)\ W_1$

= (1378.9 - 28.1) Btu/lb x 1,000 lb/hr

= 1.4 MM Btu/hr

Heat rejected = Heat input

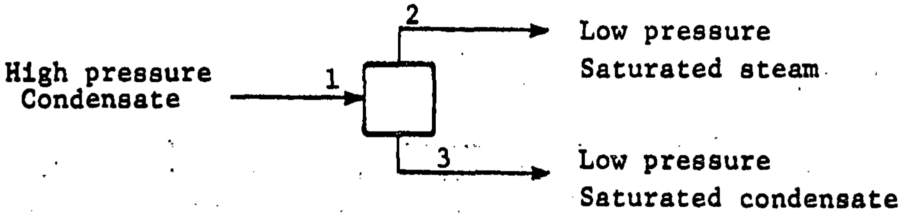
= 1.4 MM Btu/hr

Example 2: Steam Flash Drum

In a refinery steam system, high pressure condensate is collected and then flashed to a lower pressure to produce saturated steam and condensate at the flash drum pressure. Since steam generation occurs, a profile calculation is made to account for the material and heat transformation even though the process is adiabatic.

For this example, assume 268.3 M lb/hr of high pressure condensate is being flashed to 59 psig. The steam enters the 50 lb. steam system and the condensate given to the boilers.

System Diagram



Weight Balance Values

In this example, the high pressure condensate flow was determined by summing all the separate condensate flows from the different units that feed the drum. Then,

High pressure condensate = W_1 = 268,300 lb/hr

To determine the flow rates of the flash steam and low pressure condensate, a material balance equation and an enthalpy balance equation are written around the drum. The equations are:

$$W_1 = W_2 + W_3$$

$$H_1 = W_2 (h'_2 - 28.1) + W_3 (h'_3 - 28.1)$$

The inlet enthalpy is determined in the same manner as the inlet flow by summing all the condensate export enthalpies from the different units that feed the drum. This sum has been determined to be 90.4 MM Btu/hr. Since both the flash steam and condensate products are saturated, the unit enthalpies are looked up in the Steam Tables. Substituting in yields the equations:

$$268.3 \text{ M lb/hr} = W_2 + W_3$$

and

$$90.4 \text{ MM Btu/hr} = W_2 (1181.6 - 28.1) \text{ Btu/lb} + W_3 (312.5 - 28.1) \text{ Btu/lb}$$

Since there are two equations and two unknowns, these are solved simultaneously to yield:

Flash steam produced = W_2 = 26.3 M lb/hr

Low pressure condensate produced = W_3 = 241.5 M lb/hr

<u>Energy Balance Values</u>

Heat input = Enthalpy of high pressure condensate
= 90.4 MM Btu/hr

Heat export = Enthalpy of flash steam <u>only</u>
= $W_2\ (h'_2 - 28.1)$
= 26,300 lb/hr (1181.6 - 28.1) Btu/lb
= 30.3 MM Btu/hr

Note: Since the remaining condensate proceeds on to the boiler, it is not included in the export value, nor will the condensate be an import to the boiler.

4.6 ELECTRIC POWER

Electric power is a form of energy that may be directly measured. However, since the electric power input to a unit is relatively small in comparison to the total energy input to the unit (less than 2% on the average), measurements and calculations are not made on each consumer. Instead, only the total to the unit is measured and prorated over the user categories of interest.

This section includes procedures to determine the distribution of the power to the units as well as within the unit. If a unit's consumption of electric power is not distinctly separable from the remaining units, it may be necessary to determine the entire refinery's electrical distribution at one time.

4.6.1 Plant Distribution

Electric power is generated by utility companies and distributed at a higher voltage than is used by the units individual consumers. If the refinery generates power, it is still distributed at the highest voltage used, or higher. Therefore, substations are spaced around the plant close to the load centers. These substations feed one or more motor control centers. The total power input is always measured and usually the input to each substation or motor control center is also measured or can be measured with meters. These measurements are used in determining the power to the unit.

Step 1: Measure the total electric power input to the plant entering the master substation. This is preferably done with kilowatt-hour meters over a 24-hour period, but voltage and amperage readings may be used also. See conversions in Section 4.6.3.

Step 2: Measure the power input to each of the lowest measurable branches (motor control centers, substations, etc). Some values may have to be estimated from transformer size or connected load.

Step 3: Sum all measurements in Step 2 for a total. This total should be only slightly less (approximately 2%) than the measured total in Step 1. Some transmission loss can be expected. For purchased power, this loss is included with the unit input. For plant generated power, the loss would best be credited against the generator.

Step 4: Adjust the individual feeder measurements in Step 2 so that the sum is equal to the measured total in Step 1. Some values may be questionable and a correction made only to them. Otherwise, prorate the difference by,

$$\text{Adjusted feeder input} = \frac{\text{measured feeder input} \times \text{measured total}}{\text{sum of feeder totals}} \qquad (4.6\text{-}2)$$

Note: If the entire plant electric balance is not being made at one time, this step and the measurements of the feeders in Step 3 not connected to the unit may be omitted and only incur a minor error.

<u>Step 5</u>: Determine the unit input by summing the feeder inputs to it. If a feeder goes to more than one unit, then the portion to the unit is estimated by,

$$\text{Feeder Input to Unit} = \text{Feeder Total} \times \frac{\text{Unit load connected to Feeder}}{\text{Total load connected to Feeder}} \qquad (4.6\text{-}2)$$

The connected loads may be estimated using design data as demonstrated in the following procedure, 4.6.2. The plant and unit inputs are tabulated in a Refinery Power Balance.

4.6.2 <u>Unit Distribution</u>

This procedure uses the unit input total as determined in the preceding procedure 4.6.1 and prorates it over several categories. The difference in results obtained from this procedure and the more accurate procedure of measuring the power consumption to each user is insignificant. The categories are:

1. Pump Motors - Drives for pumps, blowers, and compressors that are handling a process fluid, boiler feedwater, or condensate.

2. Fan Motors - Drives for air cooler fans, cooling tower fans. Also other drives where it is evident that the transmitted power does not enter into the process; such as, cooling water pumps, waste water pumps, etc.

3. Miscellaneous - Lighting, instruments, etc.

The procedure is listed first and then an example.

<u>Step 1</u>: From design power summary sheets or motor specification sheets, sum the rated brake horsepower (bhp) for each motor in the first category above. If the design bhp is not available, use the motor name plate horsepower.

<u>Step 2</u>: Likewise, sum the bhp for each motor in category two.

<u>Step 3</u>: Likewise, total the remaining design power use for category three. A percentage of the total in the order of 2% to 3% may be assumed if no data is available.

Step 4: Sum the subtotals from each of the three categories. Divide the total into each category subtotal to determine the fraction of the input for each category. If a percentage value was assumed for miscellaneous uses (No. 3), this percent is subtracted from the total, and the remainder is used for pumps and fans.

Step 5: Multiply the measured power input to the unit times the design input fraction of each category determined in Step 4. This gives the input from electric power and is tabulated in the Heat Input and Heat Rejection Summary according to the above three categories.

Step 6: Determine the losses as listed below and tabulate in the Heat Input and Heat Rejection Summary under direct rejection.

Pumps: $\text{Loss} = \text{Input}\left(1 - \frac{\text{Efficiency}}{100}\right)$

Fans: Loss = Input

Misc.: Loss = Input

The efficiency above is the combined efficiency of the electric motor and the mechanical efficiency only of the driven equipment. Although the efficiency for each motor will be different, an overall average may be estimated by reviewing the design specifications. The losses should represent, motor winding resistance, motor and pump bearing friction, etc., that are not transmitted to the process fluid or steam system fluid.

Example:

The kilowatt-hour meter on the electrical feeder to a unit measures 25818 KWH over a 24-hour period.

Step 1-3: Tabulate design loads.

Pumps = 1119.5 Hp

Fans = 125.0 Hp

Misc. = Unknown

Total = (1244.5 + Misc.) Hp

Assume misc. = 2% of total, then

$$\text{Total} = \frac{1244.5}{1-.02} = 1269.9 \text{ Hp equivalent}$$

Step 4: Calculate fraction of each.

$$\text{Pumps Fraction} = \frac{1119.5}{1269.9} = 0.88$$

$$\text{Fans Fraction} = \frac{125.0}{1269.9} = 0.10$$

Misc. Fraction " = 0.02

Step 5-6: Using equation 4.6-3, the measured total is,

$$\text{Total Unit Input} = \frac{25818}{24\text{-hr.}} \text{ KWH} \times 3413 \text{ Btu/}_{\text{KWH}}$$

$$= 3.67 \text{ MM Btu/hr}$$

and the input to each category is:

$$\text{Pumps input} = 0.88 \times 3.67 \text{ MM Btu/hr}$$

$$= 3.2 \text{ MM Btu/hr}$$

$$\text{Pumps loss} = 3.2 \text{ MM Btu/hr} \times \left(1 - \frac{95}{100}\right)$$

$$= 0.2 \text{ MM Btu/hr}$$

$$\text{Fans input} = \text{Loss}$$

$$= 0.1 \times 3.67 \text{ MM Btu/hr}$$

$$= 0.4 \text{ MM Btu/hr}$$

$$\text{Misc. input} = 0.02 \times 3.67 \text{ MM Btu/hr}$$

$$= 0.1 \text{ MM Btu/hr}$$

4.6.3 Conversions

The following conversions are used in the profile to convert electrical energy or work to its heat equivalent.

$$\text{BTU/hr} = \frac{N_{KWH}}{N_{hr}} \times 3413 \text{ Btu/KWH} \qquad (4.6\text{-}3)$$

$$\text{BTU/hr} = \text{Volts} \times \text{Amps} \times \sqrt{3} \times \text{Power Factor} \times 3413 \text{ Btu/KWH} \qquad (4.6\text{-}4)$$

$$\text{BTU/hr} = \text{Horsepower} \times 2545 \text{ Btu/Hp-hr} \qquad (4.6\text{-}5)$$

where N_{KWH} = Kilowatt hours measured over a period

N_{hr} = No. of hours in period

power factor = ratio of $\frac{\text{watts}}{\text{volts} \times \text{amps}}$, although it is different for each motor, the overall power factor may be used.

4.7 RADIATION AND CONVECTION LOSSES

This procedure covers estimating the heat loss by radiation and convection from equipment and piping on a unit. Since the calculation conditions that must be assumed to apply the empirical heat transfer equations presented only approximate the actual conditions, the results should only be used as estimates. For a well insulated plant, the small radiation loss (approximately 1% - 3% of input) does not warrent the major effort that would be required to calculate every loss. Instead, only the large, hot areas (such as heaters, hot storage tanks, long hot piping runs, and regenerators) are measured and calculated. The remaining areas can be estimated by roughly estimating the remaining area and applying an average heat loss factor. The average heat loss factor can be determined by spot checking some surfaces and using the equation given here or by using the design value.

If the remaining energy values in the profile are calculated accurately, any radiation loss not accounted for will be in the imbalance. If the imbalance is large, and the plant is not well insulated, closer attention may be given to the radiation loss calculation. Employment of infrared imagery for detection of deteriorated insulation and uninsulated piping may be warranted.

The procedure for estimating the heat losses from equipment where the surface temperature is known is to use the program developed for the HP-97. The listing of the program is included in Appendix B, as program No. 3. Documentary equations, operating instructions, and example calculations are given here. This procedure is intended to serve as an initial screening process. Further analyses will be required for design or economic studies.

Documentary Equations

The equation for heat loss from a surface to the air is based on the sum of the convection loss using the Langmuir equation[5] and the radiation loss using the Stefan-Boltzmann formula[5]. The equation is,

$$Q_r = \left[0.296\,(t_s - t_a)^{5/4}\sqrt{\frac{\bar{V} + 68.9}{68.9}} + .174 \times 10^{-8}\,\epsilon\left(T_s^4 - T_a^4\right)\right] A \times 10^{-6} \tag{4.7-1}$$

where Q_r = Heat loss from surface to air by radiation and convection, MM Btu/hr

t_s = Surface temperature, °F

T_s = Absolute surface temperature, °R

t_a = Air temperature, °F

T_a = Absolute air temperature, °R

$\bar{V}$ = Air velocity, ft/min.

ϵ = Emissivity of surface.

A = Surface Area, ft^2

HP-97 Program for Radiation and Convection Losses
Program No. 3

This program calculates the heat loss to the air from hot flat plates or cylinders by means of radiation and convection and is based on equation 4.7-1.

Step 1: Load program No. 3. No data cards are required.

Step 2: Press "E" to clear program of any previous data and to set the amount of printout. If "0" is displayed, all printout is made. If "1" is displayed, printout of data listed that is marked with an asterisk will be suppressed. Repeat "E" operation to change from "0" to "1" or "1" to "0". A zero, "0", must be displayed at least once.

Step 3: Enter air velocity perpendicular to the surface and air temperature as shown.

INPUT		OUTPUT
Data	Operation Keys	
Air Velocity, Mph	Enter ↑	
Air temperature, °F	A	Print air temp., °F*
		Print air velocity, Mph*

Note: This step does not have to be repeated for a new problem if data remains the same, even if "E" is pressed.

Step 4: (cylinders): For cylinders only, enter surface temperature, diameter, length, and emissivity of surface as shown.

INPUT		OUTPUT
Data	Operation Keys	
Surface temp., °F	Enter ↑	
Diameter, ft.	Enter ↑	
Length, ft.	Enter ↑	
Emissivity,	B	Print emissivity*
		Print length, ft.*
		Print diameter, ft^2.*
		Print surface temp., °F
		Print convection loss, Btu/ft^2 *
		Print radiation loss, Btu/ft^2 *
		Print total loss, Btu/ft^2
		Print total loss, MM Btu/hr

Step 4: (Flat Surfaces): For flat surfaces only, enter surface temperature, height, width, and emissivity as shown.

INPUT		OUTPUT
Data	Operation Keys	
Surface temp., °F	Enter ↑	
Height, ft.	Enter ↑	
Width, ft.	Enter ↑	
Emissivity	C	Print emissivity* Print width, ft* Print length, ft* Print surface temp., °F Print convection loss, Btu/ft^2* Print radiation loss, Btu/ft^2* Print total loss, Btu/ft^2 Print total loss, MM Btu/hr

Step 5: Repeat steps 2, 3 and 4 for a new surface. The totals will be accumulated.

Step 6: Press "D" for the grand total.

OUTPUT

Print total heat loss of all surfaces, MM Btu/hr

Example Radiation Loss Calculations Using the HP-97 Calculator

Example 1: Cylinders

Calculate the heat loss from uninsulated vessel 10 ft. in diameter by 50 ft. long that has an average surface temperature of 140°F. The wind is blowing at 10 mph at 70°F.

Step 1: Load program 1.

Step 2: Press E. "0" is displayed. Press "E" again for minimum printout. A "1" is displayed.

Step 3: Enter air velocity (10). Key in air temperature (70) and press "A".

Step 4: Enter surface temperature (140), diameter (10), length (50) and key in emissivity (.7). Press "B". The results are:

Surface temperature, °F = 140
Heat loss, Btu/ft^2 = 284
Heat loss, MM Btu/hr = 0.49

Example 2: Flat Surfaces

Calculate the loss from a section of a heater wall, 60 ft. wide x 30 ft. high with a surface temperature of 170°F on the average. The wind is blowing at 10 mph and at 70°F.

Step 1-3: Assume previous calculations on the unit have been run and this is part of them. Go to 4.

Step 4: Enter surface temperature (170), height (30), width (60), surface emissivity (0.7). Press "C". The results are:

Surface temp., °F = 170.0
Heat loss, Btu/ft^2 = 443.0
Heat loss, MM Btu/hr = 0.80

Step 5: Total previous calculations. Press "D". The result is,

Total heat loss, MM Btu/hr = 1.29

4.8 MISCELLANEOUS

This section covers the calculation of energy values for those miscellaneous items that do not occur in every unit, such as heat of reaction, power recovery, and lost potential combustion energy.

4.8.1 Heat of Reaction

The rigorous method of calculating heat of reaction involves the heat of formation of the molecular species of the individual components of the feed and products. In a refinery, most feed and product streams contain undefined petroleum mixtures of which the heats of formation are not known. The heat of reaction may be approximated with sufficient accuracy for purposes of developing a profile by making the following assumption: For calculation purposes, the reaction takes place isothermally and the heat of reaction heats (or cools) the reactor products from the reactor inlet conditions to the reactor outlet conditions. The heat of reaction is then approximated from:

$$Q_r \cong H'_{Prod(0)} - H'_{Prod(i)} + \text{Losses} \qquad (4.8\text{-}1)$$

where Q_r = Heat of reaction, MM Btu/hr

$H'_{Prod(0)}$ = Enthalpy of product at outlet conditions, MM Btu/hr

$H'_{Prod(i)}$ = Enthalpy of product at feed inlet conditions, MM Btu/hr

Losses = Reactor radiation loss (See Procedure 4.2.6) + Heat absorbed by non-reacting streams, MM Btu/hr.

If the difference is positive, the heat of reaction is exothermic and is considered a heat input to the unit and refinery. If the difference is negative, the heat of reaction is endothermic and is considered a loss.

In a simple example where the enthalpies of the product stream have been calculated at reactor inlet and outlet conditions are:

	Enthalpy, MM Btu/hr
Product Stream, Reactor Inlet Conditions	100.0
Product Stream, Reactor Outlet Conditions	110.00

then the heat of reaction is then approximated as (assuming losses are negligible):

$$Q = H'_{Prod(0)} - H'_{Prod(i)}$$

$$Q = 110 \text{ MM Btu/hr} - 100 \text{ MM Btu/hr}$$

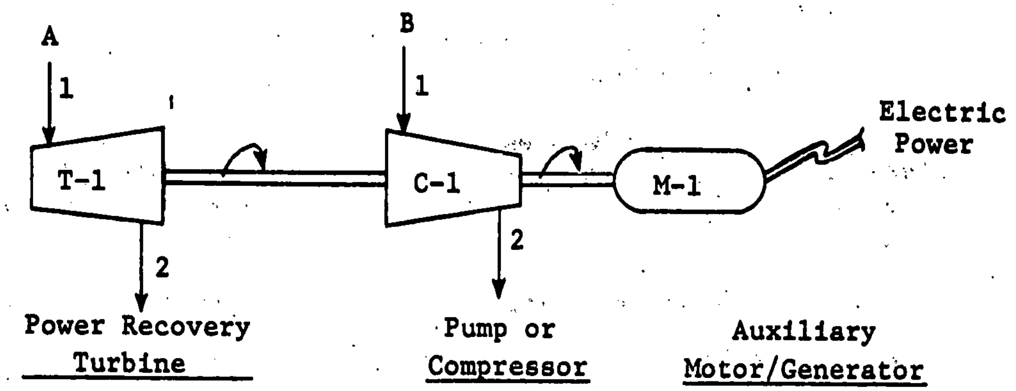
$$= 10 \text{ MM Btu/hr}$$

Since the heat of reaction is positive, it is considered a heat input to the unit.

4.8.2 Power Recovery Turbines

Gas or liquid process streams that must be reduced to lower pressures can be a potential source of energy for recycle provided that the inlet pressure and/or flow rate are sufficient to warrant the use of power recovery turbines. Such turbines can recover energy from liquid streams to supplement pump motors and from gas streams to supplement compressor motors.

The energy recycled from a power recovery turbine to the process may be calculated in two ways. One is to calculate the change in enthalpy of the stream passing through the turbine, then apply an overall efficiency for the turbine and pump or compressor to determine the amount of energy actually being transferred. The other is to calculate directly the amount of energy being transferred to the process stream being pumped or compressed. Both methods of calculation will be illustrated in the following procedures and example calculations included. A diagram is shown below of a typical power recovery system.



Using Stream Through Power Recovery Turbine (A)

Not all the energy given up by stream "A" is recycled to stream "B" since all mechanical equipment has some mechanical losses. Then, the recycled energy is calculated by,

$$\Delta H_A = H'_{A1} - H'_{A2} \qquad (4.8\text{-}2)$$

$$Q_r = \Delta H_A \times \frac{EFF}{100} \qquad (4.8\text{-}3)$$

where,

ΔH_A = Heat released by A

Q_r = Recycle energy, MM Btu/hr

H'_{A1} = Enthalpy of stream "A" at point 1.

H'_{A2} = Enthalpy of stream "A" at point 2.

EFF = Mechanical efficiency of T-1 and C-1.

$= EFF_{T\text{-}1} \times EFF_{C\text{-}1}$

Example:

In the Fluid Catalytic Cracking (FCC) unit, the hot flue gas from the regenerator is passed through a power recovery turbine called the expander which in turn helps drive the air blower that supplies the combustion air to the regenerator. The remaining power is supplied by a motor (which can also act as a generator).

Data:

Flue gas analysis
Inlet conditions - 1210°F, 17.0 psig
Outlet conditions - 995°F, 1.0 psig

The inlet and outlet enthalpies are calculated using Procedure 4.1. For this example, the power conversion efficiency is estimated at 90%. Then from equation 4.8-2 and equation 4.8-3, the recycled energy is found by,

$$\Delta H = (351.4 - 306.5) \text{ MM Btu/hr} = 44.9 \text{ MM Btu/hr}$$

$$Q_r = 44.9 \text{ MM Btu/hr} \times 0.90 = 40.4 \text{ MM Btu/hr}$$

Using Stream Through the Driven Equipment

The recycled energy may be calculated more accurately than the preceding method by calculating the energy gain from stream "B" and subtracting off the auxiliary power. Note: If M-1 is generating power, it is added to the energy gain by "B". The equations are:

$$\Delta H_B = H'_{B2} - H'_{B1} \qquad (4.8\text{-}4)$$

$$Q_r = \Delta H_B - Q_M \frac{EFF_M}{100} \qquad (4.8\text{-}5)$$

where

ΔH_B = Total heat gained by stream "B", MM Btu/hr

H'_{B1} = Inlet enthalpy of "B", MM Btu/hr

H'_{B2} = Outlet enthalpy of "B", MM Btu/hr

Q_r = Recycled energy, MM Btu/hr

Q_M = Heat equivalent of power to motor, eq. 4.6-3, MM Btu/hr

EFF_M = Efficiency of motor, %

Example:

The preceding expander example is continued.

Data:

Air to Blower (Dry Basis)	680,695 lb/hr
H_2O in Air to Compressor	11,184 lb/hr
Inlet Temp.	80°F
Inlet Press.	0 psig
Discharge Temp.	374°F
Discharge Press.	36 psig

The enthalpies of the air are calculated using Procedure 4.2 and the enthalpies of the water vapor are taken from steam tables. Then from equation 4.4-4, the total energy gain is found.

$$\Delta H_B = 680{,}695 \text{ lb/hr } (76.44 - 4.57) \text{ Btu/lb} + 11{,}184 \text{ lb/hr } (1193.7 - 1068.5) \text{ Btu/lb}$$

$$= 50.3 \text{ MM Btu/hr}$$

The electrical consumption of the motor was measured as 3200 KWH/Hr. This is converted to the heat equivalent using equation 4.6-3 at 0.97 power factor to 10.6 MM Btu/hr. Then using equation 4.8-5 and a motor efficiency of 90%, the recycle energy is:

$$Q_r = (50.3 - 10.6 \times 0.9) \text{ MM Btu/hr}$$

$$= 40.8 \text{ MM Btu/hr}$$

<u>Power Recovery Train Loss</u>

The total mechanical losses (assuming no leakage) are determined by subtracting the total energy gain from the total energy input, that is by:

$$\text{Loss} = \Delta H_A + Q_M - \Delta H_B \qquad (4.8\text{-}6)$$

where ΔH_A = Energy input from "A", eq. 4.8-2, MM Btu/hr

Q_M = Heat equivalent of power to motor, same as in eq. 4.8-5, MM Btu/hr

ΔH_B = Energy gain by "B", eq. 4.8-4, MM Btu/hr

Example: The preceding expander example.

$$\text{Loss} = (44.9 + 10.6 - 50.3) \text{ MM Btu/hr}$$

$$= 5.2 \text{ MM Btu/hr}$$

Note: Rather than make a new category for the single item of power recovery turbine, the loss would be credited against the motor in the heat Input and Heat Rejection Summary.

4.8.3 Potential Combustion Heat Lost

Part of the total oil charge to the refinery and part of the imported fuel are ultimately lost to the environment by flaring, leakage, flaring, etc., at various stages in the refining process. The combustible portions of these losses are a potential energy source, since heat would be released if they were burned. Since these potential energy sources are lost forever and cannot be used by anyone, they represent an energy consumption by the refinery and are listed in the profile. The energy value used for the profile is the heat that would be released by combustion of the loss if used as a fuel by anyone. The losses are accounted for in the profile as an input, and a loss in one of the following categories:

- Oil Charge Loss - As an input representing the combustible losses that entered the refinery as part of the oil charge (crude, intermediate feedstocks, additives).
- Fuel Gas - As an input representing the lost fuel from any imported fuel that is not considered part of the oil charge above.
- Oils and Gases Lost - As an output which is equal to the sum of the oil charge loss and fuel loss inputs above.

A procedure is given for calculating the energy value of each of the above potential heat source categories.

Oil Charge Lost

The procedure for calculating the Oil Charge Lost is to utilize the refinery's stock loss accounting procedure. In general, refineries calculate the amount of stock lost by,

$$\text{Stock loss} = \begin{pmatrix}\text{Total weight}\\ \text{of Oil Charge}\end{pmatrix} - \begin{pmatrix}\text{Total weight}\\ \text{of Products}\end{pmatrix}$$

Most refineries have established procedures for calculating each factor in the above equation. Stock lost is normally broken down into two categories, identifiable losses and unidentifiable losses. Identifiable losses (either measured or estimated) are flare losses, storage evaporation losses, etc., and methods for calculating identifiable losses are normally available. The difference between the total stock loss and identifiable losses is the unidentifiable losses.

The procedure for calculating the Oil Charge Lost and converting from a weight basis to a BTU basis for the refinery energy profile is as follows:

<u>Step 1</u>: Determine typical stock loss values by averaging several of the refinery's stock loss reports that are prior to the data taking period, during it, and after it. Several months may be necessary to produce typical values. Convert the loss values to an hourly rate by dividing the total of the loss for the summed periods by the number of hours in the summed periods.

<u>Step 2</u>: Select from the identifiable losses those categories that have a fuel value. Salt and water from crude, for example, would not be included.

<u>Step 3</u>: Calculate the fuel value of each category selected in Step 2, including unidentifiable losses, using appropriate conversion factors. The following conversion factors may be used for each category if no historical values are available.

Loss Category	Weight Conversion Factor (f)	Fuel Value Factor (HHV)
Gas to Flare	0.057 lb/ft^3	1200 Btu/ft^3
Waste Oil Loss	300 lb/bbl	6.25×10^6 Btu/bbl
Storage Loss	300 lb/bbl	6.25×10^6 Btu/bbl
Propane Venting	---	2509 Btu/lb
Unidentifiable Stock Loss	300 lb/bbl	6.25×10^6 Btu/bbl

The equation for calculating the fuel values is,

$$Q_i = W_i \times \rho_f \times HHV_i \times 10^{-6}$$

where Q_i = oil charge loss for one category, MM Btu/hr

W_i = quantity loss, lb/hr

ρ_f = density factor, lb/ft^3 or lb/bbl

HHV_i = higher heating value of category, Btu/ft^3 or Btu/bbl

<u>Step 4</u>: Sum all the energy loss values calculated above, both identifiable and unidentifiable, and tabulate as an input in the Energy Balance Table for the Offsites Unit unless it is evident that portions of the loss can be assigned to particular operating units.

Imported Fuel Lost

Step 1: Determine fuel usage and losses that fit into the category of the following type usage:

- gas to flare pilots
- purge gas to flare
- blanket gas to storage tank and surge drums
- purge gas to vessels (vented to flare)

If any of the fuel gas that is used for the above originated from part of the oil charge, the value must be deleted from the Oil Charge Lost category or not counted here.

Step 2: Calculate the combustion energy of the fuel following Procedure 4.4.1 and tabulate as a fuel input on the Energy Balance Table for the unit that is using the fuel.

Oils and Gases Lost

This is simply the total of the Oil Charge Loss value input and fuel lost value input and is tabulated as a loss in the Energy Balance Table.

SECTION 5

PREPARING PROFILES

After completing the calculation of the energy values of the input and output categories as outlined in Section 4, the results are grouped together in a series of tables, graphs, and diagrams to form a profile for each unit and also the entire refinery. The working series of tables, as discussed later in Procedure 5.1, may be completed on one unit before proceeding to take data on another unit; but before the entire profile for the unit can be completed, the data must be taken for all the units. After taking all the data, a "normalization factor" is derived for each unit to bring all the units to a common crude charge basis. The calculation of the normalization factor is given in Procedure 5.1.1.

After calculation of the normalization factors, the individual unit profiles are completed as discussed in Procedure 5.1. Selective energy values from the individual unit profiles are then combined to form the overall refinery profile as discussed in Procedure 5.2.

5.1 INDIVIDUAL UNIT PROFILE

The energy profile for the individual unit is made up of a series of tables, diagrams, and graphs that are used to give various levels of detail. The energy values are first grouped together in the following initial series of detailed tables according to the procedure shown in parentheses:

- Steam Weight Balance Table (Procedure 5.1.1)
- Steam Heat Balance Table (Procedure 5.1.2)
- Heat Input and Heat Rejection Summary Table (Procedure 5.1.3)
- Import and Export Energy Summary Table (Procedure 5.1.4)

The unit profile is then completed by summarizing the data from the tables above in the following:

- Energy Balance Table (Procedure 5.1.6)
- Energy Profile Diagram (Procedure 5.1.7)

An additional series of tables and graphs may be developed and included as part of the profile that point out amounts of energy potentially recoverable from major sources of energy losses. These should include, but are not limited to, the following:

- Potential Heat Recovery Table (Procedure 5.1.8)
- Potential Energy Savings from Heater Stack Graph (Procedure 5.1.9)
- Energy Available for Potential Recovery from Air and Water Cooled Heat Exchanger Graph (Procedure 5.1.10)

In making profiles, it is important to recognize that all the data cannot be taken for all the units simultaneously. This means that different crude charge rates, etc., will be involved. To account for this, a "normalization factor" as discussed in the following Procedure 5.1.1, is derived for each unit and applied to the calculated energy values.

5.1.1 Normalizing Energy Values To Typical Operations

An energy profile of a single unit represents a snapshot picture of the energy usage for one point in time and at one charge rate. This period of time is different for each unit even if all the data are taken in sequence. In order to combine the unit profiles into an overall refinery profile on a single refinery oil charge basis, they must be based on the same overall oil charge. Since the charge rates to each unit and the total refinery oil charge may fluctuate from the time the data are taken on one unit to the times data are taken on the other units, a "normalization" procedure is used to bring all the units to a common basis.

For very accurate profile results, each calculated energy value of the individual equipment or streams should be adjusted to the average feed to that equipment; since the energy consumption per barrel of feed to the equipment will vary slightly due to equipment efficiency varying with the feed rate. Also, the total energy consumption of some equipment, such as air cooler fans, utility pumps, and lights, may stay constant and not vary incrementally with the equipment feed or unit charge. A tremendous amount of additional work would be required to take into account the varying equipment efficiencies and other factors. Instead, the assumption is made that all the profile energy values are proportional to the combined unit charge; and therefore, a single factor, dependent only on the unit charge, is calculated and applied appropriately to adjust the energy values to a "normalized" condition. For small charge variations of 5 to 10 percent, only a minor error is incurred; but large variations in charge may require additional data and calculations at the different rates.

A normalization factor for each unit is calculated as outlined in the following steps. This factor is multiplied times the energy values from observed data before developing the Energy Balance Table, Profile Diagram, or Potential Heat Recovery tables and graphs. Since the flow rates to every unit are required, this procedure cannot be followed until after all the data for each unit has been taken.

Step 1: Determine the typical crude charge to the refinery during the data taking period as based on normal operations. Shutdowns and other abnormal operations should be excluded. Pipeline meters, crude shipping reports, crude tank gauges, etc., may be used to determine the total crude charge. Divide the total charge for the period by the number of hours in the period to determine the typical unit charge (or product). A refinery-wide weight balance will verify these values. Some adjustments may be required such as allowance for makeup or rundown from or to storage.

Note: If adequate routine data is not available, then the data for all the charge rates should be taken every time with each unit.

Step 2: Divide the typical charge rate to the unit by the observed charge rate determined above to give the normalization factor for the unit energy values. The relationship is,

$$\text{Normalization factor} = \frac{\text{Typical Unit Combined Charge}}{\text{Observed Unit Combined Charge}} \qquad (5.1\text{-}1)$$

Step 3: Multiply the normalization factor times the energy values to obtain the "normalized" energy use based on typical flows for the data taking period as shown by:

$$\text{Normalized Energy} = \text{Observed Energy} \times \text{Normalization Factor} \qquad (5.1\text{-}2)$$

5.1.2 Steam Weight Balance Table

The Steam Weight Balance Table should be developed while calculating the steam system energy values and is described in Step 3 of Procedure 4.5. An example of this table is shown as Table 5-1.

5.1.3 Steam Energy Balance Table

The Steam Energy Balance Table should be developed along with the Steam Weight Balance Table above and is described in Step 4 of Procedure 4.5. An example of this table is shown as Table 5-2. When space permits, the Weight and Energy tables may be combined to form one simplified table.

5.1.4 Heat Input and Heat Rejection Summary Table

Table 5-3 is an example of a Heat Input and Heat Rejection Summary for a crude unit and will serve as a guide for the procedures that follow.

5.1.4.1 Utilities Heat Input and Direct Rejection Losses

As shown in Table 5-3, the first section of the Heat Input and Heat Rejection Summary Table is labeled, "Utilities Heat Input and Direct Heat Rejection Losses". This section summarizes the energy inputs supplied by fuel, power, and steam and the amounts of energy from these sources that are directly rejected. Under each utility category the points of consumption are listed and the energy input and direct rejection given for each point. The type of direct rejection loss is identified and the rejection temperature, if applicable, are also listed. The procedures for developing each utility category are as follows:

TABLE 5-1

CRUDE UNIT STEAM SYSTEM WEIGHT BALANCE

M LB/HR CONSUMED (PRODUCED)

		DATA CLASS	STEAM			BFW	CONDENSATE
			600 lb	250 lb	50 lb		
A Steam Turbines							
LN-8B	Atm. twr. btm. pump turbine			down			
LN-12B	Vac. twr. recycle pump turbine			down			
LN-20B	BFW circulation pump turbine	C		0.6	(0.5)		0.1
	SUBTOTALS: Input			0.6			
	Output				(0.5)		0.1
B Process							
V-3	Atm. twr. stripping steam	A			20.7^3		20.7
V-5A	AGO twr. stripping steam	A			6.2^3		6.2
V-5B	HFO twr. stripping steam	A			12.0^3		12.0
V-5C	LFO twr. stripping steam	A			4.7		4.7
V-6	Vac. twr. ejectors	A		24.1			24.1
T-3	Chemical tank heating	B		1.0			(1.0)
X-22	Vac. seal tank heater	-			0.0		
	SUBTOTALS: Input			25.1	43.6		
	Output						67.7/(1.0)
C Heat Recovery							
H-1	Preheating BFW	A				[63.3]^2	
H-1	Superheating 50 lb. steam	A			[38.9]^2		
H-2	600 lb. steam generation	A	(64.0)			65.3	1.3
	SUBTOTALS: Input					65.3	
	Output		(64.0)				1.3
D Miscellaneous							
H-1 & 2	Heater surface cooling (temporary)	C		50.0	5.0		55.0
	Header condensation from cooling	C	0.2	0.2	0.2		(0.6)
	Leaks and misc. losses	C	3.0	3.0	3.0		9.0
	SUBTOTALS: Input		3.2	53.2	8.2	0.0	
	Output						64.0/(0.6)
	TOTALS: Input		3.2	78.9	51.8	65.3	
	Output		(64.0)		(0.5)		133.1/(1.6)
	Net consumed/(Produced)		(60.8)	78.9	51.3	65.3	131.5

NOTES:

1. Data Class; a) Measured
   b) Based on design or past operation data
   c) Engineering estimated
2. Quantities are for reference only. No material consumption or production
3. Superheated steam

TABLE 5-2

CRUDE UNIT STEAM SYSTEM ENERGY BALANCE(1)

MM BTU/HR(2)

ITEM NO.	DESCRIPTION	DATA(3) CLASS	GROSS INPUT	TOTAL EXPORT	REJECTED	TRANSFERRED TO PROCESS	PROCESS HEAT RECOVERED
A Steam Turbines							
LN-8B	Atm. twr. btm. pump turbine		down				
LN-12B	Vac. twr. recycle pump turbine		down				
LN-20B	BFW circulation pump turbine	C	0.8	0.4	0.4		
	SUBTOTALS: Input		0.8				
	Output			0.4	0.4		
B Process							
V-3	Atm. twr. stripping steam	A	28.5			28.5	
V-5A	AGO twr. stripping steam	A	8.5			8.5	
V-5B	HFO twr. stripping steam	A	16.5			16.5	
V-5C	LFO twr. stripping steam	A	5.5			5.5	
V-6	Vac. twr. ejectors	A	30.0			30.0	
T-3	Chemical tank heating	B	1.2	0.2		1.0	
X-22	Vac. seal tank heater	-	0.0			1.0	
	SUBTOTALS: Input		90.2				
	Output			0.2		90.0	
C Heat Recovery							
H-1	Preheating BFW	A		11.5			11.5
H-1	Superheating 50 lb. steam	A		7.7			7.7
H-2	600 lb. steam generation	A	23.3	84.8	0.6		62.1
	SUBTOTALS: Input		23.3				81.3
	Output			104.0	0.6		
D Miscellaneous							
H-1 & 2	Heater surface cooling (temporary)	C	68.1		68.1		
	Header condensation from cooling	C	0.8	0.1	0.7		
	Leaks and misc. losses	C	11.3		11.3		
	SUBTOTALS: Input		80.2				
	Output			0.1	80.1		
	TOTALS: Input		194.5				81.3
	Output			104.7	81.1	90.0	

ENERGY VALUES FOR THE PROFILE BALANCE AND HEAT REJECTION SUMMARY

As an Input: Steam and BFW = 0.8(turbines) + 90.2(process) + 81.3(Heat Recovery) + 68.1(Surface Cooling) + 12.1(misc.)
= 194.5 (Input)

As Outputs: 1) Steam Losses = 0.4(turbines) + 0.6(Generation) + 68.1(Surface Cooling) + 12.0(Misc.) = 81.1(Rejected)
2) Steam Generated= 81.3 (Heat Recovered)
3) Steam and Condensate (From Input) = 104.7 (Total Export) - 81.3 (Generated) = 23.4

NET ENERGY VALUES

Net Steam Energy Consumed by Unit = 194.5 (Gross Input) - 23.4 (Steam and Cond. exported from Input) = 171.1

Net Steam Energy Supplied to Unit = 194.5 (Gross Input) - 104.7 (Total Export) = 89.8

---

1. Energy Balance: Input + Recovered = Export + Rejected + Transferred
2. Steam Enthalpy Base Adjusted. Enthalpy of water at 60°F = 0
3. Data Class: A) Measured; B) Based on design or past operation; C) Estimated

TABLE 5-3 (1 of 4)

CRUDE UNIT
HEAT INPUT AND HEAT REJECTION SUMMARY

UTILITIES HEAT INPUT AND DIRECT HEAT REJECTION LOSSES

UTILITY	POINT OF CONSUMPTION	DATA(1) CLASS	ENERGY INPUT MM BTU/HR	DIRECT(2) REJECTION MM BTU/HR	TYPE OF LOSS	REJECTION TEMPERATURE LEVEL, °F
FUEL GAS	H-1 Crude Charge Heater	A	782.4	176.8	Stack	545
	H-2 Vacuum Heater	A	263.6	78.5	Stack	754
	SUBTOTAL		1046.0	255.3		
POWER	Pump Motors	A	13.9	0.7	Motor Losses	NA
	Fan Motors	A	1.4	1.4	To Atmos.	NA
	Miscellaneous	B	0.3	0.3	To Atmos.	NA
	SUBTOTAL		15.6	2.4		
STEAM	Turbine LW 20B	C	0.8	0.4	Turbine Losses	NA
	Process	A	90.2			NA
	Generation	A	23.3	0.6	Blow Down	459
	Surface Cooling H-1 & H-2 (3)	C	68.1	68.1	Open to Atmos.	NA
	Leaks & Misc.	C	12.1	12.0	Open to Atmos.	NA
	SUBTOTAL		195.3	81.1		
	TOTAL		1256.9	338.8		

TABLE 5-3 (2 of 4)
CRUDE UNIT
HEAT INPUT AND HEAT REJECTION SUMMARY (Cont'd)

HEAT REJECTED FROM PROCESS TO ENVIRONMENT

TO COOLING WATER

WATER COOLED HEAT EXCHANGERS

ITEM NO.	DESCRIPTION	DATA CLASS(1)	QUANTITY MM BTU/HR	TEMPERATURE, °F IN	TEMPERATURE, °F OUT
X-11	Crude Twr. OH Trim Condenser	A	76.6	215	139
X-13	LFO Product Cooler	A	Not in Use		
X-14	No. 2 Heating Oil Cooler	A	6.4	128	107
X-15	LVGO PA Cooler	A	62.8	292	139
X-18	1st Stage Intercondenser	B	6.5	238	108
X-19	2nd Stage Intercondenser	B	6.0	186	118
X-20	3rd Stage Intercondenser	B	4.6	328	178
	SUBTOTAL		162.9		

TO THE ATMOSPHERE

AIR COOLED HEAT EXCHANGERS

ITEM NO.	DESCRIPTION	DATA CLASS(1)	QUANTITY MM BTU/HR	TEMPERATURE, °F IN	TEMPERATURE, °F OUT
X-7	HFO Product Cooler	A	7.1	168	139
X-8	HFO Pumparound Cooler	A	16.5	328	295
X-9	HVGO Pumparound Cooler	A	34.5	430	406
X-10	Crude Twr. Ovhd Condenser	A	119.7	300	215
X-12	LFO Product Cooler	A	8.4	430	124
X-16	Desalter Water Effluent Cooler	A	10.6	242	167
	SUBTOTAL		196.8		

TABLE 5-3 (3 of 4)
CRUDE UNIT
HEAT INPUT AND HEAT REJECTION SUMMARY (Cont'd)

TO THE ATMOSPHERE (Cont'd)

RADIATION LOSSES

ITEM NO.	DESCRIPTION	DATA CLASS (1)	QUANTITY MM BTU/HR
H-1	Crude Charge Heater	A	6.3
H-2	Vacuum Heater	A	2.1
	Vessels	A	3.0
	Exchangers	A	0.3
	Process Piping	A	3.4
	Steam System	A	0.7
	Pumps	C	1.0
	SUBTOTAL		16.8

PRODUCT AND WASTE STREAMS

ITEM NO.	DESCRIPTION	DATA CLASS (1)	QUANTITY MM BTU/HR	TEMPERATURE, °F IN	TEMPERATURE, °F OUT
From X-14	No 2 HO Product	A	13.7	107	Ambient
From X-16	Desalter Water	A	15.0	167	Ambient
From V-7	Vac Seal Tank Water	A	1.3	114	Ambient
From V-10AX	Spent Caustic	A	0.4	123	Ambient
	SUBTOTAL		30.4		
	TOTAL FROM PROCESS		406.9		
	TOTAL HEAT REJECTION		745.7		

TABLE 5-3 (4 of 4)
CRUDE UNIT
HEAT INPUT AND HEAT REJECTION SUMMARY (Cont'd)

HEAT EXCHANGED BETWEEN PROCESS STREAMS (RECYCLED HEAT)

				TEMPERATURE, °F			
				HOT SIDE		COLD SIDE	
EXCHANGER	STREAMS EXCHANGING HEAT	DATA CLASS(1)	QUANTITY MM BTU/HR	IN	OUT	IN	OUT
X-1	Top Pumparound/Crude	A	93.8	375	266	107	234
X-2	HFO Product/Crude	A	111.3	550	168	107	285
X-3	HFO Pumparound/Crude	A	51.0	426	328	246	328
X-4	AGO/Crude	A	12.3	630	468	332	444
X-5	Vac. Twr. Btms./Crude	A	40.5	649	354	330	386
X-6	HVGO Pumparound/Crude	A	71.2	532	482	333	456
X-21	HVGO Pumparound/Crude	A	73.3	482	430	248	336
X-100	Desalter Water In/Out	A	1.6	253	242	128	139
	TOTAL		455.0				

Notes:

1. Data Class: A) Measured
   B) Based on design or past operation data
   C) Engineering estimate
2. Does not include radiation and convection losses
3. Temporary loss.

Fuel

The main use of fuels in a refinery is to provide the fuel source for process heaters and boilers. Other uses can occur. Natural gas, for example, is used to fuel flare pilots, as a purge gas, and as tank blanket gas. The "Fuel" utility input to a unit or to the total refinery could be composed of the combustion energy of any or all of the following fuel types which are listed as subheadings as appropriate under "Utilities".

- Natural Gas - Natural gas entering the plant by pipeline.
- Refinery Gas - Light product gases from the various units, such as hydrogen and methane, that are combined and added to the refinery fuel gas system.
- Fuel Gas - A combination of natural gas and refinery gas.
- Coke and CO Gas - The petroleum coke that is burned off the catalyst in the FCC unit, including partial combustion to CO. Also includes the heat of combustion energy from burning the CO in the CO boiler.
- Fuel Oil - Any residual oils or other oils used as fuels.

For each item listed in the following steps, enter the data on the Heat Input and Heat Rejection Summary Table as shown in Table 5-3.

Step 1: Enter the fuel energy input (HHV) and stack heat loss for each process heater or boiler that was calculated from Procedure 4.4.

Step 2: Enter the fuel energy input (HHV) for any fuel used for miscellaneous uses, such as purge gas that was calculated from Procedure 4.4.

Step 3: Subtotal the total fuel energy inputs and their direct rejection losses.

Note: The fuel inputs may be grouped according to types of fuel, such as Natural Gas, Fuel Gas, Coke and CO Gas, Fuel Oil, etc.

Power

Step 1: Enter the breakdown of electric power energy input to the unit and direct rejection losses for the following use categories; pump motors, fan motors, and miscellaneous that was calculated from Procedure 4.6.

Step 2: Subtotal the electric power inputs and direct rejection losses.

Steam

Step 1: From the Steam Energy Balance Table, referenced above in Procedure 5.1.3 (Table 5-2), enter the energy input and direct rejection losses for each major category of steam user , such as turbines, process uses, generation, and miscellaneous on the Heat Input and Heat Rejection Summary Table.

Step 2: Subtotal the steam energy inputs and direct rejection losses.

Step 3: Total the energy inputs and direct rejection losses from fuel, power, and steam.

5.1.4.2 Heat Rejected From Process to Environment

The next section of the Heat Input and Heat Rejection Summary Table is labeled, "Heat Rejected from Process to Environment". This section summarizes the heat rejected to cooling water by water cooled heat exchangers and the heat rejected directly to the atmosphere by air cooled heat exchangers, through radiation losses from equipment and piping, and from product and waste streams. Each water and air exchanger is listed by item number (usually the equipment number), description, the quantity of heat rejected, and temperature of the steam entering and leaving the exchanger (See Table 5-3). Radiation losses are listed by individual item number and description or by categories such as vessels, process piping, etc., and followed by the quantity of heat rejected. Product and waste streams are listed by item number (the equipment number from which the stream leaves the unit), description of the stream, the quantity of heat rejected, and the temperature at which it leaves the unit. The procedures for developing each such section are as follows. Enter the data from each step on the Heat Input and Heat Rejection Summary Table as shown in Table 5-3.

To Cooling Water

Water Cooled Heat Exchangers

Step 1: Enter the quantity of heat rejected in each water cooled heat exchanger which was calculated as the exchanger duty with Procedure 4.3.

Step 2: Subtotal the total heat rejected by water cooled heat exchangers.

To the Atmosphere

Air Cooled Heat Exchangers

Step 1: Enter the quantity of heat calculated as being rejected in each air cooled heat exchanger which was calculated as the exchanger duty with Procedure 4.3.

Step 2: Subtotal the total heat rejected by air cooled heat exchangers.

Radiation Losses

Step 1: Enter the quantity of heat rejected through radiation losses from each category of equipment which was estimated with Procedure 4.7.

Step 2: Subtotal the total radiation losses.

Product and Waste Streams

Step 1: Enter the quantity of heat rejected by each product and waste stream which was calculated as the stream enthalpy with Procedure 4.2. A product is a stream leaving the unit that never returns to a process unit but becomes part of the refinery's products shipped. Product and waste stream enthalpies are accrued as losses against the unit in which the streams are produced rather than a plant export, since the energy is lost anyway.

A waste stream is one going to the sewer or to the atmosphere, for example, wash water. Waste stream losses are included here because they are small by themselves and are similar to product losses.

Step 2: Subtotal the total heat rejected in product and waste streams.

Step 3: Total the heat rejected from the process to the environment.

Step 4: Add the total from Step 3 to the total direct rejection to give the Total Heat Rejection.

5.1.4.3 Energy Exchanged Between Process Streams (Recycled Energy)

The last section of the Heat Input and Heat Rejection Summary Table is labeled, "Energy Heat Exchanged Between Process Streams (Recycled Energy Heat)". This section summarizes the energy being recycled within a unit by exchanging energy (heat) between process streams by using crude/product exchangers, reactor feed/effluent exchangers, power recovery turbines, etc. Each exchanger or power recovery turbine is listed on the table by item number (equipment number), description of the streams exchanging energy, and followed by the quantity of energy being exchanged. For exchangers, the temperatures of the hot side fluid entering and leaving and the cold side fluid entering and leaving are also listed. Recycled energy is considered as both a gross energy input to the process and a gross energy output from the process. The procedure for developing this section is as follows. Enter the data from each step on the Heat Input and Heat Rejection Summary Table as shown in Table 5-3.

Step 1: Enter the quantity of energy which was calculated as being exchanged between process streams by each of the following categories. The type of energy value calculated and the procedure used are listed also.

Energy Exchange System	Type Value	Procedure
Reactor Feed/effluent exchanger	Duty	4.3
Fractionation tower feed/bottoms exchanger	Duty	4.3
Feed/product exchanger	Duty	4.3
Power recovery turbine	(Recycled energy)	4.8.2

Step 2: Total the heat being exchanged between process streams.

5.1.5 Import and Export Energy Summary Table

The Import and Export Energy Summary Table summarizes the energy being imported to a unit or the refinery by streams entering the unit and the energy being exported to other units by streams leaving the unit. The energy quantities were calculated as the stream enthalpies (referenced to 60°F) with procedures from Section 4. The classification of the type streams that are included in this table and the calculation procedures used are as follows:

Classification	Calculation Procedure
Petroleum liquids	4.2.2
Petroleum gases CO gas (between units) Combustion air	4.2.1 or 4.4.2 (Step 1)
Process water Chemicals	4.4.2 (Step 1, Eq. 4.4-3) with appropriate data

Note: The following streams are accounted for elsewhere or omitted entirely because they do not apply and are not included in the Import and Export Energy Summary Table:

Steam, Boiler Feed Water, Condensate (Procedure 5.1.2 and 5.1.3)
Product and Waste Streams (Procedure 5.1.4.2)
Cooling Water (Considered as a heat sink and not counted as part of the unit's system)

Table 5-4 is an example of an Import and Export Energy Summary Table for a crude unit. The procedures for developing the table are as follows.

Step 1: Under Import Streams, list each entering stream by stream identification, enthalpy, temperature entering unit, and where applicable the temperature after the preheat exchangers and the final temperature. The final temperature is the temperature to which the stream is finally raised by a process heater or steam heat exchanger. These temperatures may be compared with the temperature of export or waste streams to give an indication of the potential for adding more heat to the stream by heat exchange before a utility energy source must be used to further increase the temperature.

TABLE 5-4

CRUDE UNIT
IMPORT AND EXPORT ENERGY SUMMARY

IMPORT STREAMS TO UNIT	ENTHALPY, MM BTU/HR	TEMPERATURE, °F ENTERING UNIT	 AFTER PREHEAT	 FINAL
Crude Charge	43.2	98	423	665-680
Water to Desalters	9.5	128	135	250
Process Slop	No Flow			
Fuel Gas to Flash Direr	No Flow			
Water To Treater	No Flow			
Caustic to Treater	0.1	80	--	NA
THD-1792 Heavy Polymer	0.1	616	--	NA
Combustion Air to H-1 & H-2	13.4	80	--	2000+
Fuel to H-1 & H-2	7.5	102	--	2000+
TOTAL	73.8			

EXPORT STREAMS TO OTHER UNITS	ENTHALPY, MM BTU/HR	TEMPERATURE, °F LEAVING UNIT
Gas to SGU 7991	2.7	139
Naphtha to SGU 7991	19.1	139
HFO PA to SGU 7991	86.8	579
LFO to GU 292	63.1	430
AGO to FCC 1291	27.3	468
LVGO to FCC 1291	36.1	318
HVGO to FCC 1291	150.2	532
Vac. Twr. Btms. to DCU 891	29.7	354
Water to 293	1.5	139
Water to 1291	1.9	139
TOTAL	418.4	
NET EXPORT	344.6	

Step 2: Total the amount of energy imported. The import energy is used as an input in the Energy Balance Table (Procedure 5.1.6).

Step 3: Under Export Streams, list each leaving stream by stream identification, enthalpy, and temperature leaving.

Step 4: Total the amount of energy exported. The export energy is used as an output in the Energy Balance Table. The difference between Import and Export is shown as Net Import (or Net Export).

5.1.6 Energy Balance Table

Once the first four tables have been completed, the data can then be organized to give the energy balance for the unit in the Energy Balance Table. An example of an Energy Balance Table for a crude unit is given in Table 5-5. In the Energy Balance Table the gross energy inputs are broken down into two categories; inputs from utilities and inputs from other sources. Utilities inputs are comprised of the fuels, steam, and electric power used to operate the process. The utility input total is similar to the conventional unit input except that steam is on a gross basis rather than a net basis. Inputs from other sources are added to this and include the energy imported in feed streams, exothermic heat of reaction, the total internal heat exchanged, and any potential heat of any oil charge lost.

The gross energy outputs are also broken down into two categories, recovered energy and losses (also called net consumption). Recovered energy applies only to individual units and is comprised of the total internal heat exchange, process streams exported to other units, steam exported to other units, and the total steam generated within the unit. Losses include the energy lost from heater and boiler stacks, air cooled exchangers, water cooled exchangers, the steam system, the electrical system, radiation, products and wastes streams, endothermic heat of reaction, and the potential heat in the total oils and gases lost.

The Energy Balance Table is developed by columns as shown below. Some of the columns are repetitious and may be omitted to fit the user's needs. The steps describing each input and output item are outlined at the end of this procedure.

Column 1: List the calculated energy quantity (MM Btu/hr) as based on observed data for each input and output as described in the steps listed below.

Note: If the calculations are being made on a unit by unit basis, Column 1 gives the snapshot profile of the unit. The remainder of the table gives the normalized profile and cannot be completed until the data for all units have been taken and normalized according to Procedure 5.1.1.

Column 2: List the normalized energy quantity (MM Btu/hr) for each item listed above as developed in Section 5.1.1.

TABLE 5-5

CRUDE UNIT
ENERGY BALANCE

DESCRIPTION	OBSERVED[2] QUANTITY (MM BTU/HR)	NORMALIZED[1] QUANTITY (MM BTU/HR)	M BTU/BBL[2] OF UNIT CRUDE CHARGE	M BTU/BBL[2] OF REFINERY OIL CHARGE	PERCENT
GROSS ENERGY INPUT TO PROCESS					
From Utilities:					
Fuel Gas HHV	1046.0	1044.0	126.2	116.7	58.6
Total Steam and BFW Used(4)	194.5	194.1	23.5	21.7	10.9
Electric Power (3413 Btu/Kwh)	15.6	15.6	1.9	1.7	0.9
Subtotal: Utilities	1256.1	1253.7	151.5	140.2	70.4
From Other Sources:					
Feed Streams Import	73.8	73.7	8.9	8.2	4.1
Internal Recycle (Heat Exch.)	455.0	454.1	54.9	50.8	25.5
Subtotal: Other	528.8	527.7	53.8	59.0	29.6
TOTAL INPUT	1784.9	1781.4	215.3	199.2	100.0
GROSS ENERGY OUTPUT FROM PROCESS					
Recovered Energy:					
Internal Recycle (Heat Exch.)	455.0	454.1	54.9	50.8	25.5
Streams to Other Units	418.4	417.6	50.5	46.7	23.4
Steam and Condensate	23.9	23.9	2.9	2.7	1.3
Steam Generated	81.3	81.1	9.8	9.1	4.6
Subtotal: Recovered	978.6	976.7	118.1	109.2	54.8
Losses (Net Consumption):					
Heater Stacks	255.3	254.8	30.8	28.5	14.3
Air Coolers	196.8	196.4	23.7	22.0	11.0
Water Coolers	162.9	162.6	19.7	18.2	9.1
Steam Leaks[3,4]	80.4	80.2	9.7	9.0	4.5
Electrical System[3]	2.4	2.4	0.3	0.3	0.1
Radiation[3]	16.8	16.8	2.0	1.9	0.9
Product and Waste Streams[3]	30.4	30.3	3.7	3.4	1.7
Subtotal: Losses	745.0	743.6	89.9	83.1	41.7
Imbalance (Unaccounted for)	61.3	61.2	7.4	6.8	3.4
TOTAL OUTPUT	1784.9	1781.4	215.3	199.2	100.0

---

(1) Based on average unit rate of 198551 BPD corresponding with average refinery oil charge of 214636 BPD for period September 26, 1977 to October 7, 1977.

(2) Based on observed data of 9/26/77 at 198936 BPD of crude charge.

(3) Losses noted are accumulated as miscellaneous on the profile figure.

(4) Includes 68 MM Btu/hr of temporary losses.

Column 3: Divide the calculated energy quantities listed in Column 1 by the observed combined oil charge rate to the unit (or product) and list the value (M Btu/bbl). On some units, such as an alkylation unit, the conventional method of expressing per barrel relationships in terms of the main product rate (such as alkylate) may be followed. On other units, such as offsites and utilities, the charge rate may be too ambiguous to have any meaning; and the column may be omitted.

Column 4: Divide the normalized energy quantities listed in Column 2 by the typical oil charge to the refinery that was calculated in Step 1 of Section 5.1.1. List the energy value result (M Btu/bbl) for each item listed above.

Column 5: For each energy value listed in Column 2, calculate and list it as a percentage of the total input to the unit.

The procedures for entering the data for each item in the table are as follows. Headings and subheadings are included as shown. Refer to Table 5-5 for an example.

Gross Energy Input to Process

From Utilities

Step 1: Enter separately the total inputs from fuel, steam and power as taken from the Heat Input and Heat Rejection Summary Table (developed in Section 5.1.4).

Step 2: Subtotal the energy input from utilities.

For Other Sources

Step 1: Enter the import energy total for feed streams import from the Import and Export Energy Summary Table (developed in Section 5.1.5).

Step 2: Enter the total for Internal Recycle energy from the Heat Exchanged Between Process Streams from the Heat Input and Heat Rejection Summary Table (developed in Section 5.1.4.3).

Step 3: If there is an exothermic heat of reaction, enter the total here as calculated using calculation Procedure 4.8.1.

Step 4: Enter the amount of potential energy in any Oil Charge Loss which was estimated in Section 4.8.3. Usually, this will be limited to the Offsites unit as discussed in calculation Procedure 4.8.3.

Step 5: Subtotal the energy input from other sources.

Step 6: On the table, total the gross energy input to the process.

Gross Energy Output From Process

Recovered Energy

Step 1: Enter the same total for Internal Recycle energy as was listed as an input above.

Step 2: Enter the total energy value for the export streams to other units from the Import and Export Energy Summary Table (developed in Section 5.1.5).

Step 3: Enter the total for the remaining energy in the steam, boiler feedwater, and condensate that was recovered from steam, boiler feedwater, and condensate input to the unit and used. This value is obtained from the Steam Energy Balance Table (developed in Section 5.1.3).

Note: This energy value is only a part of the total steam export. The remainder is accounted for below in Step 4.

Step 4: Enter the total energy recovered from the process or absorbed from the boilers to preheat boiler feedwater, generate steam, and superheat steam. This energy value, labeled Steam Generated, is also obtained from the Steam Energy Balance Table (developed in Section 5.1.3).

Step 5: Subtotal the recovered energy.

Losses (Net Consumption)

Step 1: Enter the totals for energy losses from Furnace Stacks, Air Coolers, Steam Leaks, Electrical System, Radiation, and Product and Waste Streams as taken from the Heat Input and Heat Rejection Summary Table (developed in Section 5.1.4 above).

Step 2: Enter the total for the potential energy in the Oils and Gases lost, if any. This is the total of the value entered in Step 4 of inputs from other sources above and the portion of the fuel input in Step 1 under Utilities input above that was not burned in a Furnace but was flared after use. The latter fuel loss energy value is obtained from the direct rejection losses (which were not counted as stack losses in Step 1 above) under fuels in the Heat Input and Rejection Summary Table (developed in Section 5.1.4 above).

Step 3: Total and enter the energy value of all the losses entered above. The total losses may be considered the measured net energy consumption; but due to possible omitted values or errors, the actual consumption may be more or less as discussed in the following Step 4.

Step 4: Set the total output equal to the total input. Usually all inputs can be defined and measured more accurately than outputs; therefore, any difference is considered an output unless the facts indicate otherwise. Subtract the sum of the Losses and Recovered Energy from the total output and enter as a separate output which is called the Imbalance. The total output may be entered also to complete the balance.

Note: If the Imbalance is positive (negative) this indicates one or more of the following, respectively; (1) Less (more) input then measured, (2) more (less) export energy in steam or process streams, (3) additional (fewer) losses, (4) a difference caused by compositional change effects on enthalpy calculation in heats of reaction. If one can determine which of the above items is creating the imbalance, that item should be corrected. Otherwise, it is more conservative to consider the imbalance as a loss. Then, the unit energy consumption is defined as the Total Input less the Recovered Energy.

5.1.7 Energy Profile Diagram

The Energy Profile Diagram is a graphical presentation of the Energy Balance Table data to give a pictorial comparison among the inputs and outputs. An example of an Energy Profile Diagram for a crude unit is shown in Figure 5-1. Following is a procedure for developing the diagram as a bar chart. (Other formats such as "pie" charts or Sankey diagrams can also be developed).

Step 1: Draw a box at an arbitrary convenient height for the total input. Each unit diagram is made independent of the other units so the actual height of the input box is not a function of the input energy value.

Step 2: Draw the boxes for the Total Recovered Energy and Total Losses as shown in Figure 5-1. Scale the height of the boxes to the total input box according to their relative energy value.

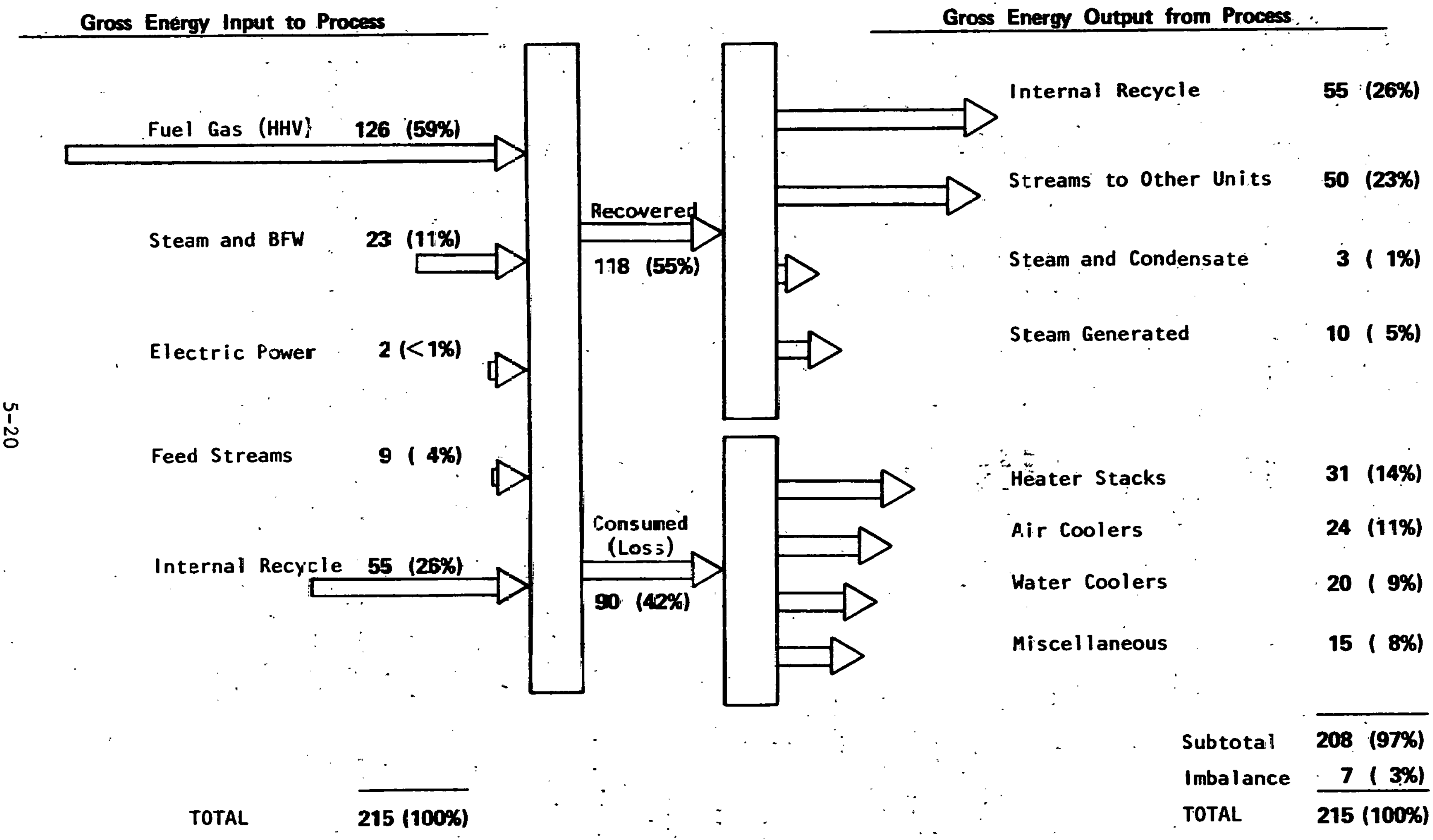
Step 3: Determine thelargest energy value in Column 3 in the Energy Balance Table out of the separate inputs or outputs. Determine the maximum arrow length that is convenient to display. Divide the maximum arrow length by the largest energy value to determine the scale factor. This scale factor will be unique to each unit.

Example: Crude unit profile, Figure 5.1.

$$\text{Scale factor} = \frac{3.0 \text{ inches}}{126.2 \text{ Btu/bbl}} \quad \begin{matrix}\text{(arbitrary maximum length)} \\ \text{(largest value)}\end{matrix}$$

$$= 0.024 \text{ inches/Btu/bbl}$$

Step 4: Draw arrows representing each Gross Energy Input to the input box as shown in Figure 5.1. The arrow length is determined by multiplying its energy value from Column 4 of the Energy Balance Table (M Btu/bbl of unit charge) by the scale factor from Step 3.



Based on observed data of 9/26/77 at 198936 BPD of crude charge rate.

Step 5: Likewise, draw arrows representing each Gross Energy output from their respective recovered or loss box. Some of the minor losses may be combined into a miscellaneous category, such as steam, electrical, radiation, and product and wastes.

Note: The Imbalance energy value is not represented with an arrow, since the area of the imbalance is not known.

Step 6: Enter the appropriate data desired from the Energy Balance Table, such as M Btu/bbl of unit oil charge and percent.

5.1.8 Potential Heat Recovery

The potential energy savings tables and graphs discussed in this section are developed from strictly a theoretical standpoint as an initial screening aid. Any schemes for attempting to recover the potentially available energy must be analyzed from the viewpoint of engineering and economic feasibility. Recovery schemes and analyses are beyond the scope of this Energy Profiling Technique which is limited to only pointing out potential areas for saving energy. Target values used in these procedures are for illustrative purposes only and should not be used as design values.

5.1.8.1 Potential Energy Savings from Furnaces

The potential energy savings from furnaces is the difference in fuel combustion energy required to supply the same total absorbed duty for the base, observed case and for the case if the percent excess air and/or stack temperature could be reduced to some lower levels. These energy saving values are calculated in Section 4.9.4 and normalized to averaged conditions following Procedure 5.1.1.

Step 1: Normalize all the fuel savings values that were calculated in Section 4.4.4 following Procedure 5.1.1.

Step 2: In a table as shown in Table 5-6, enter the fuel savings for each furnace in the unit that would result from reducing the excess air to the target level while maintaining the same stack temperature and total. Other data may be entered also, such as the furnace number and service, percent excess air (or stack oxygen), and stack temperature.

Step 3: In the same table as another column, enter the total fuel savings for each furnace in the unit that would result if the stack temperature were reduced to the target level by stack heat recovery and the excess air reduced to the same level as in Step 2, while maintaining the same total absorption as the base case.

Step 4: As the first point, plot the total value obtained in Step 2 for all the furnaces versus the highest stack temperature observed on a graph as illustrated in Figure 5-2.

TABLE 5-6

CRUDE UNIT
POTENTIAL HEAT RECOVERY

FROM HEATER STACKS

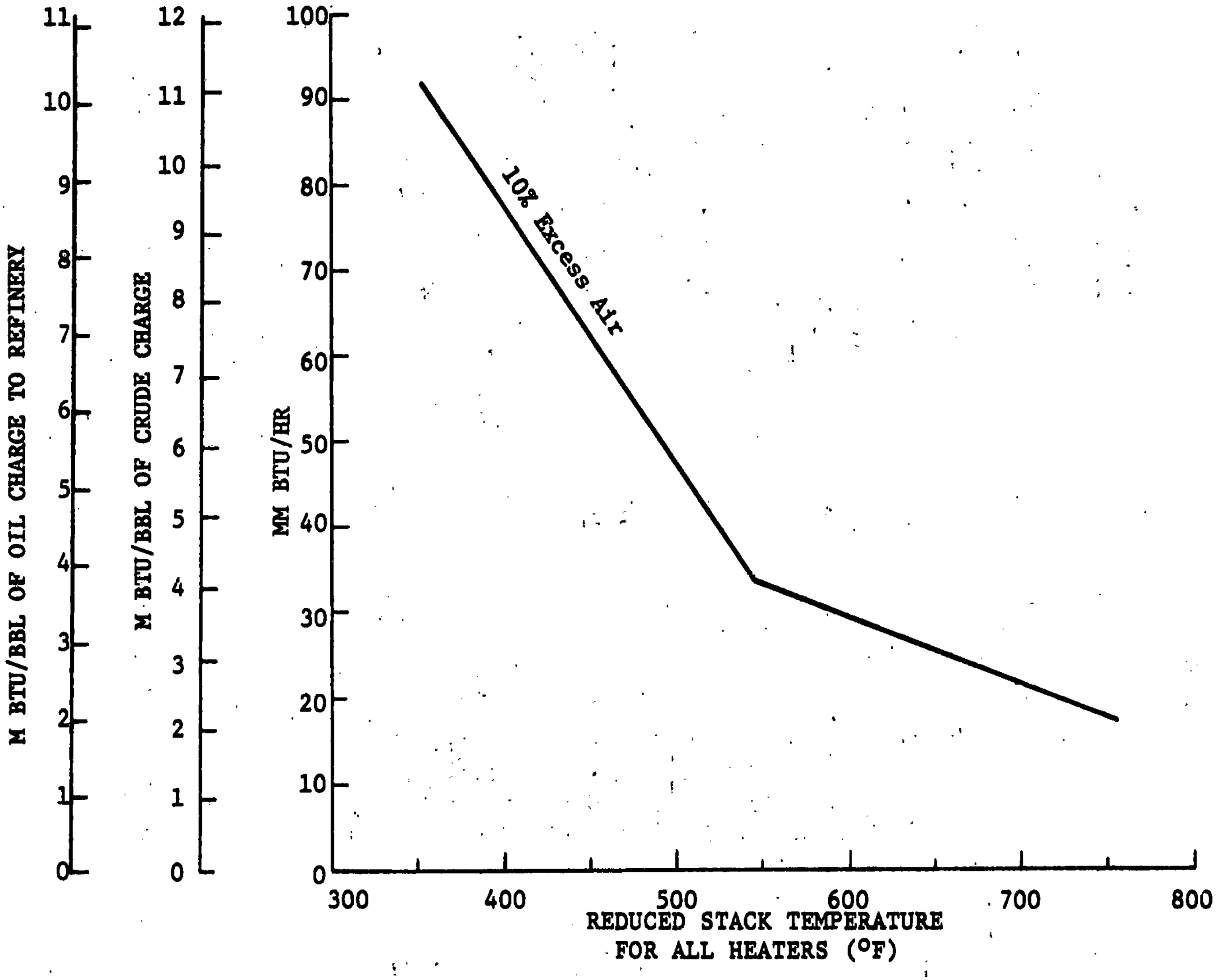
	OBSERVED DATA			POTENTIAL FUEL SAVINGS AT CONSTANT DUTY, MM BTU/HR	
FIRED HEATER	STACK TEMP °F	% EXCESS AIR	STACK LOSS MM BTU/HR	REDUCING EXCESS AIR TO 10%	REDUCING EXCESS AIR TO 10% AND STACK TEMP. TO 350°F
H-1	545	16.8	188.6	7.0	51.2
H-2	754	30.4	86.8	10.5	40.8
TOTAL			275.4	17.5	92.0

FROM AIR AND WATER COOLED HEAT EXCHANGERS

		TEMPERATURE, °F		HEAT REJECTED ABOVE TEMPERATURE LEVELS (°F), MM BTU/HR					
PROCESS STREAM	EXCHANGER	IN	OUT	200	250	300	350	400	450
HFO PA	X-8(A)	328	295	16.3	16.3	13.9	0	0	0
HVGO PA	X-9(A)	430	406	34.4	34.4	34.4	34.4	34.4	0
CRUDE TWR-OVHD.	X-10(A) &X-11(W)	300	139	150.5	46.9	0	0	0	0
LFO PROD.	X-12(A)	430	124	6.6	5.2	3.9	2.4	0.9	0
LVGO PA	X-15(W)	292	139	38.9	18.2	0	0	0	0
DES. WATER	X-16(A)	242	167	5.9	0	0	0	0	0
	TOTAL			252.6	120.9	52.2	36.8	35.3	0

FIGURE 5-2

CRUDE UNIT HEATER STACKS
TOTAL POTENTIAL ENERGY SAVINGS FOR
REDUCING EXCESS AIR AND STACK TEMPERATURES



Based on data of 9/26/77 averaged to 198551 BPD crude charge.

Step 5: Plot the total value for all the furnaces obtained in Step 3 at the target stack temperature. If there is only one furnace, this point and the initial point from Step 4 may be connected with a straight line, since the change in the flue gas specific heat is nearly linear.

Step 6: If there is more than one furnace, the graphs are combined as illustrated by Figure 5-2 and as follows: starting with the furnace with the highest stack temperature, add the incremental amount of fuel savings between Step 2 and Step 3 to the total initial value plotted in Step 4 and plot at the target stack temperature as a temporary, working value. Draw a straight line between the points from the initial point toward the temporary lower temperature value, but stop at the point where the line intercepts the next highest stack temperature. This point becomes an inflection point in the total graph, and the graph slope changes.

Step 7: Add the incremental amount of fuel savings between Step 2 and Step 3 for the furnace with the next highest stack temperature to the temporary point on the target stack temperature line from Step 6 and plot at the target stack temperature as the next temporary working value. Again, connect the two points with a straight line from the inflection point to the intercept of the next highest stack temperature.

Step 8: Repeat Step 7 until all furnaces have been plotted and the curve has intercected the total value determined in Step 3.

Step 9: The entire procedure above may be repeated for other levels of excess air to obtain a family of curves if desired.

One important comment must be made about this procedure for estimating potential fuel savings in fired heaters. This procedure is based on the assumption of maintaining a constant duty absorbed by the process stream passing through the heater. One method by which the stack temperature can be reduced while maintaining the same overall duty is to recover the heat from the stack gases and add it to the combustion air by some method of preheating the combustion air.

Another method of reducing the stack temperature would be to add an additional heat recovery section where the heat recovered is used to generate steam or heat another process stream. This method would not reduce the amount of fuel being used in the heater but would reduce the fuel being used somewhere else in the refinery such as in the steam boilers (if the heat recovery section is generating steam). Potential fuel savings for this method would be about the same.

5.1.8.2 Potential Energy Recovery from Air and Water Cooled Heat Exchangers

The procedure used to develop the amount of heat available for potential recovery from air and water cooled heat exchangers above various temperature levels is as follows:

Step 1: Determine the temperature levels of interest for recovering heat. Start at a temperature lower than the temperature thought to be actual practical for recovering heat and increase in equal increments of approximately 50°F. In the example, 200°F was used as the lowest temperature.

Step 2: Calculate the enthalpy of a stream entering an air or water cooled heat exchanger at the inlet temperature and at the various lower temperature levels, using calculation Procedure 4.2. For condensers, see Step 10 of "Preparing Computer Program Input" in the example Procedure 4.2.1.2.

Step 3: Subtract the enthalpy at each of the various temperature levels from the inlet temperature enthalpy. The result gives the heat rejected above each temperature level.

Step 4: Enter the data on the Potential Heat Recovery Table as shown in Table 5-6 and sum the heat rejected at each of the various temperature levels for all air and water cooled heat exchangers in the unit. The inlet temperatures to the large coolers will create inflection points on the final graph. The graph accuracy will be increased if the enthalpies of all the other coolers are also calculated (may be linear interpolated) at these inflection points as well as the other levels.

Step 5: Plot the totals against the various temperature levels as shown in Figure 5-3.

Example: The following data were calculated for an air cooled heat exchanger for a stream entering at 425°F and leaving at 95°F.

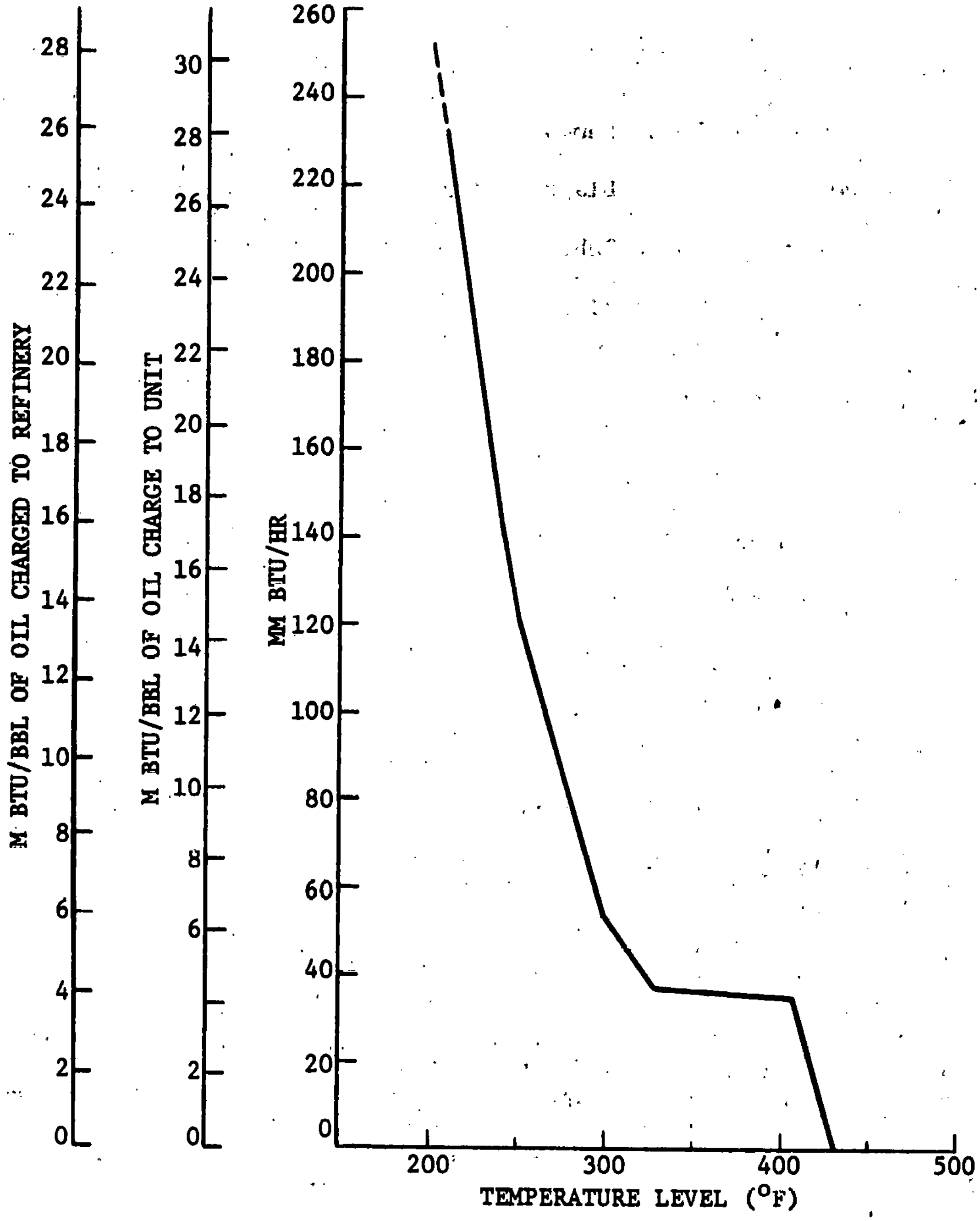
Temperature Level, °F	200	250	300	350	400	425
Enthalpy, MM Btu/hr	3.5	6.3	9.1	11.8	14.6	16.0
Heat Rejected Above Temperature	12.5	9.5	6.9	4.2	1.4	

Data calculated for air and water cooled heat exchangers for a crude unit are given in Table 5-6 and graphed on Figure 5-3.

FIGURE 5-3

CRUDE UNIT AIR AND WATER COOLERS

TOTAL ENERGY AVAILABLE FOR POTENTIAL RECOVERY ABOVE VARIOUS TEMPERATURE LEVELS



Based on data of 9/26/77 averaged to 198551 BPD of unit oil charge.

5.2 THE TOTAL REFINERY PROFILE

After the profiles for all the individual units have been completed, data from them are combined into another series of tables and figures to form the overall refinery profile. Examples of these are given in this section as appropriate. The overall refinery profile consists of the following:

(1) Utility summaries for the overall refinery

- Steam Weight Balance
- Steam Energy Balance
- Steam Energy Balance on a Net Basis
- Electric Power Summary

(2) Energy Balances and Diagrams for the Overall Refinery

- Energy Balance Table
- Energy Profile Diagram
- Energy Use by Units Table
- Energy Use by Units Profile Diagram

(3) Potential Heat Recovery for the Overall Refinery

- Potential Energy Savings from Furnace Table
- Potential Energy Savings from Furnace Graph
- Potential Energy Savings from Air and Water Cooled Exchangers Table
- Potential Energy Savings from Air and Water Cooled Exchangers Graph

5.2.1 Utility Summaries for the Overall Refinery

The various utilities may be summarized for the overall refinery such as fuel, steam, electric power, air, and cooling water. Procedures are given for the most important one, steam, and for power, since it is required to do the individual units.

5.2.1.1 Steam Weight Balance

An overall Steam Weight Balance is made by listing and summing the total flow quantities at each level of steam, condensate, etc. from each of the individual unit profiles that are consumed or produced. The quantities should be adjusted to normalized data when available. An example of an overall Steam Weight Balance is shown in Table 5-7. The difference between the consumed and produced for each level is shown as an imbalance. A larger imbalance can be expected in the steam system than from the process since so many quantities will not be based on metered flows. A separate survey of the plant's steam producers and major consumers may be necessary if the imbalance is large.

TABLE 5-7

AN OVERALL REFINERY STEAM SYSTEM WEIGHT BALANCE(1)
M LB/HR

	STEAM								CONDENSATE CONSUMED (PRODUCED)				
	600 LB		250 LB		50 LB		BFW			HIGH	LOW		MAKEUP
UNIT	CONSUMED	PRODUCED	CONSUMED	PRODUCED	CONSUMED	PRODUCED	CONSUMED	PRODUCED	LOSS(2)	PRESSURE	PRESSURE	COLD	CONSUMED
AVU-191	3.2	64.0	78.9	0	51.8	0.5	65.3		133.1		(1.6)		
NU-291	45.0		0.2		44.6				0.6				
GU-292	44.0		0.4	46.4			2.8		0.8				
GU-293	57.6					57.6							
AU-491			53.5		118.9				5.0	(53.5)	(113.9)		
SRU-591					69.3	8.2			0.4		(69.3)		
DCU-891	16.8	18.7	10.7			13.5	18.7		13.8		(.2)		
FCCU-1291	124.5		64.0	51.1	92.5	8.0	53.8		115.3	(34)		(125.3)	
CRU-1391	97.6	108.0	1.5				114		8.9			(95.7)	
AEU-1791			177.4		2.4				1.6	(176.6)	(1.6)		
THDU-1792	26.3	48.0	57.7			26.3	54		1.7	(57.7)			
SGU-7991	31.5					30.5			1.0				
UTILITIES	411.3	769.1	53.6	425.0	129.2	141.4	805.3	1138.1	58.2	321.8	240.0	220.7	342.8
OFFSITES			56.2						3.5		(49.2)		
TOTALS:													
Output from steam system	857.8		554.1		508.7		1113.9		343.9	321.8	240.0	220.7	
Input to steam system		1007.8		522.5		286.0		1138.1		(321.8)	(235.8)	(221.0)	342.8
Imbalance	150.0			41.6		222.7	24.2			5.0			

---

1. The overall weight balance is sum of individual unit weight balances as made on respective unit survey dates during period of 9/26/77 - 10/6/77.

2. Condensate loss is steam consumed that is not ultimately returned to boilers as condensate. eg., stripping steam, leaks.

3. Weight Balance: Produced by units (Steam, BFW, Condensate) + Makeup = Consumed by units (Steam, BFW) + Condensate Loss

5.2.1.2 Steam Energy Balance

An overall Steam Energy Balance is made by listing and summing the normalized total energy values of input, rejected, etc., from each of the individual unit profiles. An example of an overall refinery Steam Energy Balance is shown in Table 5-8. The total inputs (gross input, waste heat recovered, absorbed from boilers) must equal total outputs (total export, rejected, transferred to process) or an error has been made in the accounting.

Even with this balance, however, there will most likely be some unaccounted for steam. By definition, the total energy exported has to be input to some unit elsewhere. Usually, more steam will be produced than can be accounted for consumed. Since this steam is actually consumed by some units (which are unknown), the energy value is accounted for as follows: Subtract the sum of the gross inputs from the sum of total exports and add to any overall energy tabulation by unit as a miscellaneous item (corrected to the appropriate units).

5.2.1.3 Steam Energy Balance on a Net Basis

Since the steam system energy values are shown in the unit profiles on a gross basis, an additional table showing some net consumption values may be useful. An example of this table is shown as Table 5-9. The procedure for developing the table is to list and sum the energy values for each unit from the overall Steam Energy Balance Table as follows:

Step 1: Sum the transferred to process total and the direct rejected total and list for the net consumed.

Step 2: Sum the waste heat recovered total and the absorbed from boiler total and list for the total produced by the unit.

Step 3: Subtract the total produced by the unit from the net consumed by unit and list to give the net supplied to (or by) the unit.

Step 4: Total each of the energy values above for all the units. The energy value under net supplied should be the same imbalance value as determined above in Section 5.2.1.2 (unless the refinery imports or exports steam).

5.2.1.4 Electrical Power Summary

The Electric Power Summary is best made from a plant-wide survey made one day when the plant units are at normal operation as discussed in Section 4.6. The power consumption for each unit is listed and corrected to other appropriate units as desired. An example of this table is shown as Table 5-10.

TABLE 5-8

AN OVERALL REFINERY STEAM SYSTEM ENERGY BALANCE(1)

MM BTU/HR(2)

UNITS	GROSS INPUT	TOTAL EXPORT	REJECTED	WASTE HEAT RECOVERY	ABSORBED FROM BOILER	TRANSFERRED TO PROCESS
AVU-191	194.1	105.0	80.2(3)	81.1		90.0
NU-291	58.1	50.9	1.1			6.1
GU-292	60.2	57.0	1.0			2.2
GU-293	75.5	66.9	0.8			7.8
AU-491	200.0	43.8	8.0			148.2
SRU-591	82.6	26.3	0.9	9.6		65.0
DCU-891	41.0	44.4	5.6	22.0		13.0
FCCU-1291	367.8	103.6	22.1	50.3		292.4
CRU-1391	149.2	147.0	8.4	125.6		119.4
AEU-1791	206.4	60.8	2.0		—	143.6
THDU-1792	114.5	113.6	2.3	63.6		62.2
SGU-7991	42.4	36.2	2.4			3.8
UTILITIES	813.4	1641.7	20.1		900.9	52.5
OFFSITES	71.4	9.4	4.7			57.3
TOTALS:						
Input to Units	2476.6			352.2	900.9	
Output from Units		2506.5	159.6			1063.5

UNACCOUNTED FOR ENERGY FOR OVERALL CONSUMPTION

Unaccounted Steam = 2506.5 MM Btu/Hr (Total Export) - 2476.6 MM Btu/Hr (Gross Input)

= 29.9 MM Btu/Hr

= 3.3 M Btu/BBL of oil charge to refinery.

---

1. The overall heat balance is the sum of the individual unit balance as made on the respective unit survey data during the period of 9/26/77 - 10/6/77 after being "normalized" to average flow conditions.

   Energy Balance: Gross input to units + waste heat recovery from unit + heat absorbed from boilers = Total Export from Unit + heat rejected + Energy transferred to process

2. Steam Enthalpy base adjusted. Enthalpy of water = 0 at 60°F.

3. Includes 68.1 MM Btu/Hr temporary loss.

TABLE 5-9

AN OVERALL REFINERY STEAM SYSTEM
ENERGY BALANCE(1) ON A NET BASIS
MM BTU/HR(2)

	NET CONSUMED(3) BY UNIT	TOTAL PRODUCED BY UNIT	NET SUPPLIED TO (BY) UNIT
AVU-191	170.2 (4)	81.1	89.1
NU-291	7.2		7.2
GU-292	3.2		3.2
GU-293	8.6		8.6
AU-491	156.2		156.2
SRU-591	65.9	9.6	56.3
DCU-891	18.6	22.0	(3.3)
FCCU-1291	314.5	50.3	264.2
CRU-1391	127.8	125.6	2.2
AEU-1791	145.6		145.6
THDU-1792	64.5	63.6	0.9
SGU-7991	6.2		6.2
UTILITIES	72.6	900.9	(828.3)
OFFSITES	62.0		62.0
TOTAL	1223.1	1253.1	(29.9)

Unaccounted for consumption = 29.9

---

1. Based on sum of individual unit balances after normalizing for period 9/26/77 - 10/6/77.
   Energy Balance: Net supplied to unit = Net consumed - Produced

2. Enthalpy of water = 0 at 60°F

3. Net Consumed = direct rejection + transferred to process.

4. Includes 68 MM Btu/Hr temporary loss.

TABLE 5-10

AN OVERALL REFINERY ELECTRICAL POWER SUMMARY(1)
CONSUMPTION BY UNITS

UNIT	POWER QUANTITY KWH/DAY	ENERGY(2) EQUIVALENT MM BTU/HR	PERCENT OF POWER TOTAL
AVU-191	107646	15.3	13.7
NU-291	25818	3.7	3.3
GU-292	19218	2.7	2.5
GU-293	19218	2.7	2.5
AU-491	66003	9.4	8.4
SRU-591	16131	2.3	2.1
DCU-891	69918	9.9	8.9
FCCU-1291	162182	23.1	20.7
CRU-1391	20726	2.9	2.6
AEU-1791	30228	4.3	3.9
THDU-1792	13818	2.0	1.8
SGU-7991	18064	2.6	2.3
UTILITIES	141697	20.2	10.1
OFFSITES	73496	10.5	9.4
TOTAL	784163	111.5	100.0

---

1. Based on 24 hour survey of 10/6/77 - 10/7/77. Individual unit quantities are prorated from the substation and motor control centers measured values based on the unit's percent of the total rated load connected.

2. Converted at 3413 Btu/Kwh.

5.2.2 Energy Balances and Diagrams for the Overall Refinery

The energy profiles for the overall refinery are made on a net basis and do not consider the inter-unit and intra-unit exchange of energy.

5.2.2.1 Energy Balance

An Energy Balance Table is made for the overall refinery by listing each input and output in terms of the following: (1) MM Btu/hr, (2) M Btu/bbl of crude charge, (3) M Btu/bbl of refinery oil charge (optional), and (4) percent of total. An example of this table is shown as Table 5-11. The energy values for each item in each unit's Energy Balance Table are summed and listed except as noted below:

Exception 1: Only the steam that is imported to the plant (if any) is entered as an input from steam.

Exception 2: Only feed streams crossing the plant boundary (crude charge, combustion air, etc.) are entered as an input from import streams. These are taken from the individual unit's Import and Export Energy Table as appropriate.

Exception 3: All recovered energy items are omitted unless the refinery exports steam, hot products, or power to another location where the energy is used.

Following the convention used for the individual units, the difference between the total net energy input and the total losses is entered as an imbalance under outputs. The energy value total is the overall energy consumption for the refinery.

5.2.2.2 Energy Profile Diagram

A bar type diagram is constructed by drawing arrows representing each input and output from the Energy Balance Table above in Section 5.2.2.1. This diagram is similar to the one for the individual units except that no recovered energy block is shown. An example of this diagram is shown as Figure 5-4. The energy values, in terms of M Btu/bbl of oil charged and percent, are indicated for each arrow and the totals.

5.2.2.3 Energy Use by Units

Since the individual unit profiles are not scaled to each other in respect to relative energy use, a table and diagram are made to give this relative comparison.

TABLE 5-11

AN OVERALL REFINERY ENERGY BALANCE[1]

	QUANTITY MM BTU/HR	M BTU/BBL OF CRUDE OIL CHARGE	M BTU/BBL OF REFINERY OIL CHARGE	PER CENT
ENERGY INPUT TO PLANT				
From Utilities:				
Natural Gas (HHV)	916	110.7	102.4	18.3
Refinery Gas (HHV)	2411	291.5	269.6	48.1
Coke and CO Gas (HHV)	1050	126.9	117.4	21.0
Electric Power (3413 Btu/Kwh)	111	13.4	12.4	2.2
Subtotal: Utilities	4488	542.5	501.8	89.6
From Other Sources:				
Feed Streams Import	110	13.3	12.3	2.2
Exothermic Reaction	121	14.6	13.5	2.4
Oil Charge Lost[2]	288	34.8	32.2	5.8
Subtotal: Other	519	62.7	58.0	10.4
TOTAL INPUT	5007	605.2	559.8	100.0
ENERGY OUTPUT AS LOSSES				
Heater and Boiler Stacks	935	113.0	104.6	18.7
Air Cooled Exchangers	1554	187.8	173.7	31.0
Water Cooled Exchangers	1221	147.6	136.5	24.4
Steam System	160	19.3	17.8	3.2
Electrical System	40	4.8	4.5	0.8
Radiation	219	26.5	20.6	4.4
Products and Wastes	85	10.3	9.6	1.7
Endothermic Reaction	339	41.0	37.9	6.8
Total Oils and Gases Lost	321	38.8	35.9	6.4
TOTAL LOSSES	4875	589.2	545.1	97.4
Imbalance	132	16.0	14.7	2.6
TOTAL	5007	605.2	559.8	100.0

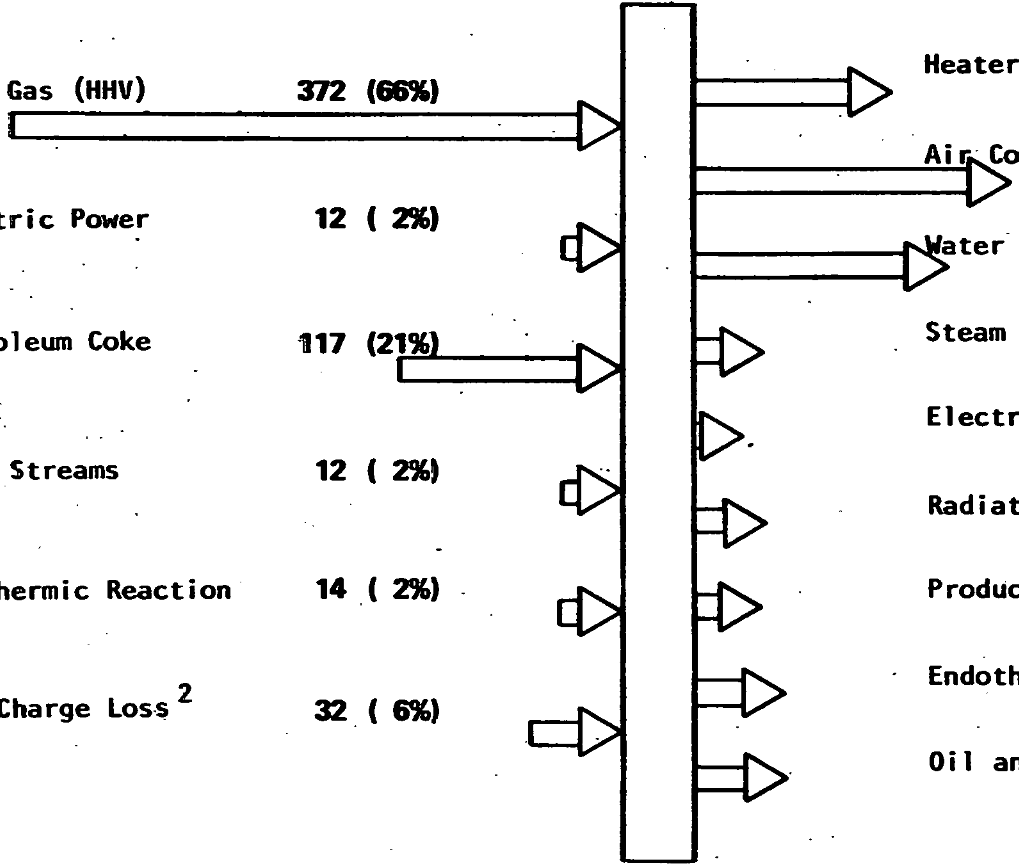
---

(1) Based on the sum of the individual unit balances, including the Petrochemical Units, which were "normalized" to a total oil charge (crude and Iso-butane and toluene) of 214636 BPD for period September 26, 1977 to October 7, 1977.

(2) Energy value of combustible portion of oil charge consumed by evaporation, flaring, etc., that is not included in with the fuel.

FIGURE 5–4 – AN OVERALL REFINERY ENERGY PROFILE

(M Btu/bbl of Oil Charge to Refinery and Per Cent)[1]



Energy Input to Plant	
Fuel Gas (HHV)	372 (66%)
Electric Power	12 (2%)
Petroleum Coke	117 (21%)
Feed Streams	12 (2%)
Exothermic Reaction	14 (2%)
Oil Charge Loss[2]	32 (6%)
TOTAL	560 (100%)

Energy Output as Losses	
Heater and Boiler Stacks	105 (19%)
Air Coolers	174 (31%)
Water Coolers	137 (24%)
Steam System	18 (3%)
Electrical System	5 (1%)
Radiation and Convection	21 (4%)
Products and Wastes	10 (2%)
Endothermic Reactions	38 (7%)
Oil and Gas Losses	36 (6%)
Subtotal	545 (97%)
Imbalance	15 (3%)
TOTAL	560 (100%)

---

1. Based on period 9/26/77 - 10/6/77 at 214636 BPD oil charge (crude, IC_4 and toluene) to refinery.
2. Energy value of combustible portion of stock loss.

Table

An overall energy use by units table is made by listing the following energy values in terms of M Btu/bbl of oil charged to the refinery: (1) measured gross input, (2) measured net input, (3) measured losses, and as a percent of the total (4) net input percent. An example of this table is shown as Table 5-12. The gross input and losses are taken directly from the individual unit Energy Balance Table. The net input is the gross input minus the losses and by convention is considered the energy consumption for the unit. The total of the net inputs and the total losses from this table must equal the total input arrived at in Section 5.2.2.1. The imbalance is identified and accounted for as discussed in the following steps.

Step 1: List the energy values for each unit and sum for a subtotal.

Step 2: To each column, add the energy value calculated as unaccounted for steam in Section 5.2.1.2.

Step 3: Add the "Feed Streams Import" energy value for all the units (taken from the unit's Energy Balance Table, Section 5.1.6) and subtract the plant "Feed Streams Import" value (taken from the overall balance table, Section 5.2.2.1). This gives the accounted for inter-unit import which must equal the inter-unit export.

Step 4: Add the "Streams to Other Units" energy value for all the units (taken from the unit's Energy Balance Table, Section 5.1.6). This is the inter-unit export.

Step 5: Subtract the accounted for import from Step 3 from the export in Step 4 to give the energy loss between units that has not been accounted for. It is reasonable to assume that this is a radiation type loss. This difference is added to each column in the Energy Use by Units Table as "Interunit Radiation Loss".

Step 6: For the losses column, there may be additional loss not accounted for which the remaining energy value is needed to bring the total to the total input.

Diagram by Units

The overall Energy Distribution by Units Energy Profile Diagram is drawn as a bar type chart similar to previous diagrams with arrows, with lengths scaled to the relative energy values, representing the following: (1) on the input side, each input as shown on the diagram described in Section 5.2.2.2, and (2) on the output side, the net energy input for each unit from the Energy Use by Units Table above. An example of the diagram is shown as Figure 5-5.

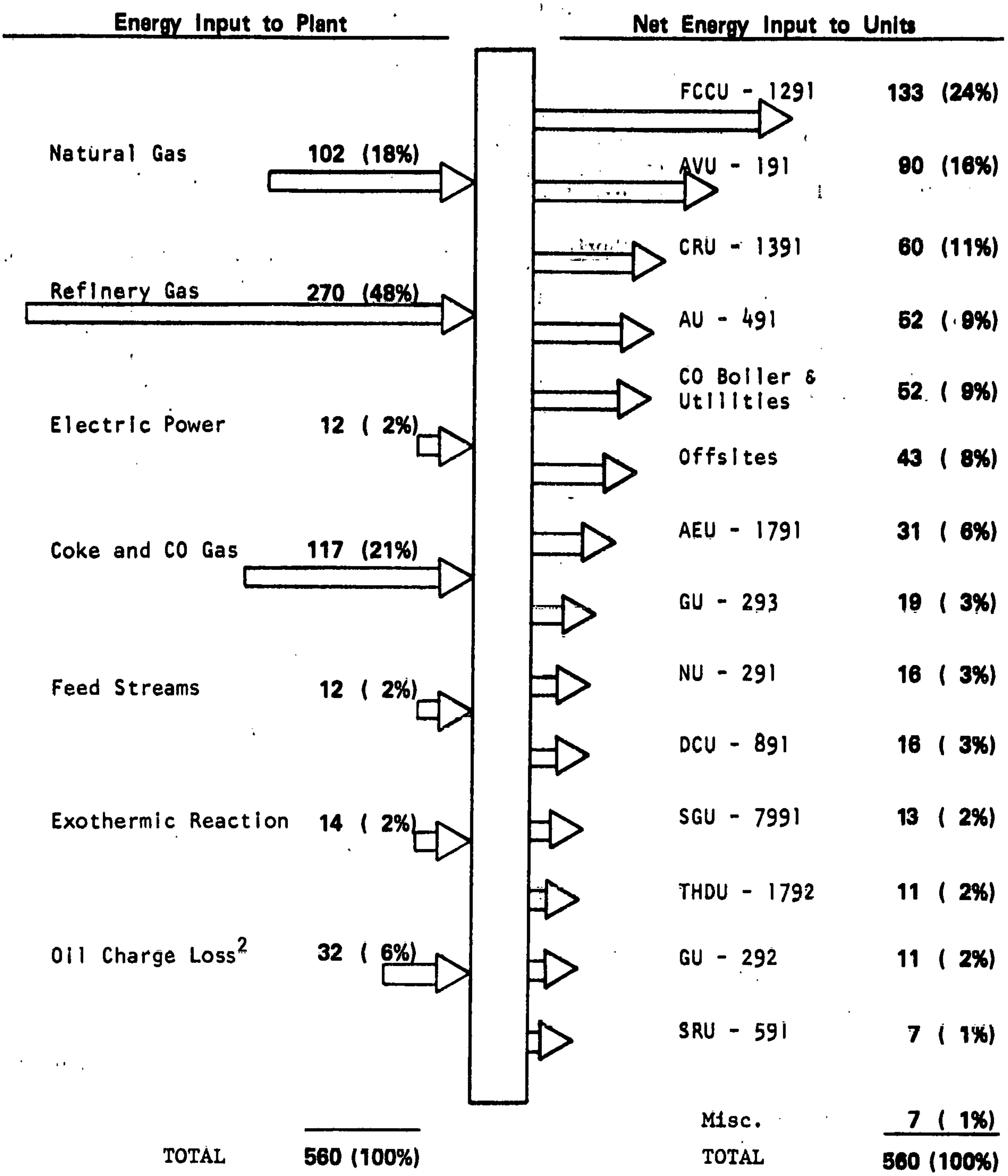
TABLE 5-12

AN OVERALL REFINERY NET ENERGY USE BY UNITS

UNIT	M BTU/BBL OF OIL CHARGE TO REFINERY			NET INPUT PERCENT OF TOTAL
	MEASURED GROSS INPUT	MEASURED NET INPUT	MEASURED LOSSES	
Atmospheric and Vacuum Unit 191	199.2	90.0	83.1	16.1
Naphfining Unit 291	47.3	15.7	14.4	2.8
Gulfining Unit 292	26.5	10.7	11.0	1.9
Gulfining Unit 293	39.3	19.0	19.3	3.4
Alkylation Unit 491	61.1	51.9	50.3	9.3
Sulfur Recovery Unit 591	17.7	7.3	7.6	1.3
Delayed Coking Unit 891	26.3	15.6	15.3	2.8
Fluid Catalytic Cracking Unit 1291	224.9	133.4	129.2	23.8
Catalytic Reforming Unit 1391	115.4	59.6	59.6	10.6
Aromatics Extraction Unit 1791	42.5	31.3	34.1	5.6
Thermal Hydro-Dealkylation Unit 1792	30.4	10.9	11.5	1.9
Saturate Gas Unit 7991	27.0	13.0	12.4	2.3
CO Boilers and Utilities	238.7	51.5	50.6	9.2
Offsite Facilities	43.8	42.8	42.6	7.6
Subtotal	1140.1	552.7	541.2	98.7
Interunit Radiation Loss	3.9	3.9	3.9	0.7
Unaccounted Steam	3.3	3.3	3.3	0.6
Unaccounted Losses	--	--	11.5	--
TOTAL	1147.3	559.9	559.9	100.0

FIGURE 5–5 – AN OVERALL REFINERY ENERGY PROFILE
ENERGY DISTRIBUTION BY UNITS

(M Btu/bbl of Oil Charge to Refinery and Per Cent)[1]



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1. Based on period 9/26/77 - 10/6/77 at 214636 BPD oil charge (Crude, IC_4 and toluene).
2. Energy value of combustible portion of stock loss.

5.2.3 Potential Heat Recovery for Overall Refinery

If the additional series and graphs covering potential heat recovery, as described in Section 5.1.8, were developed for each unit, they are combined to form an overall table or graph for the entire refinery. The two areas of heater stacks and air and water coolers are discussed in this section. Target values used in this section are for illustrative purposes only and should not be used as design values.

5.2.3.1 Potential Energy Savings from Furnaces

The same procedure is used for the overall graph as used for the individual units in Section 5.1.8.1. All the furnaces are combined and treated as a unit. Examples of the overall tables and graph are shown as Table 5-13 and Figure 5-6.

5.2.3.1 Potential Energy Savings from Air and Water Cooled Heat Exchangers

The overall graph is made by summing the individual unit totals for heat rejected above certain temperature levels by air and water coolers and plotting these totals against the temperature level following the same procedure discussed in Section 5.1.8.2. An example of this overall table and graph are shown as Table 5-14 and Figure 5-7.

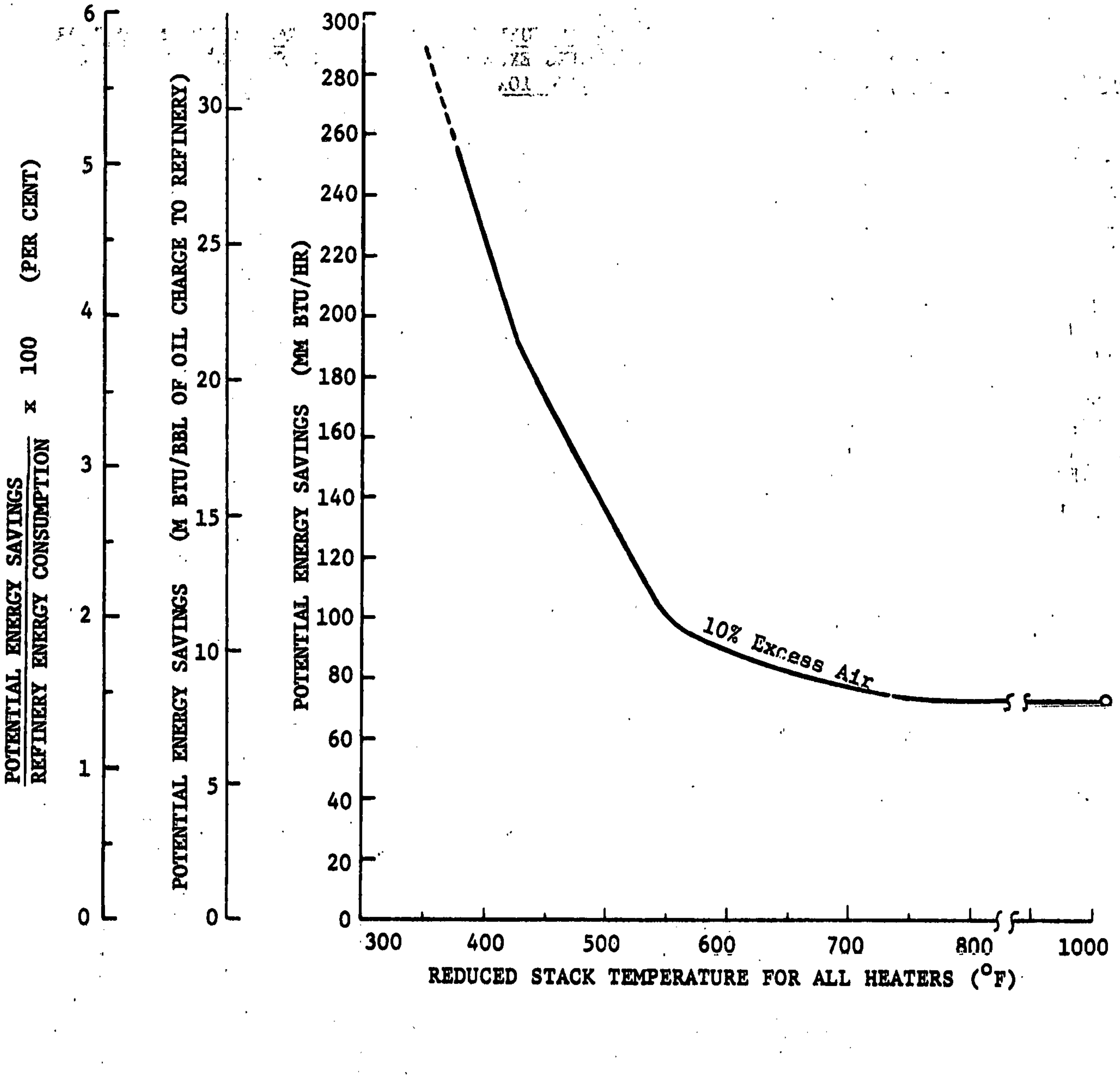
TABLE 5-13

AN OVERALL REFINERY TOTAL REFINERY STACK HEAT LOSS AND POTENTIAL FUEL SAVINGS

		POTENTIAL FUEL SAVINGS AT CONSTANT DUTY, MM BTU/HR	
UNIT	TOTAL STACK LOSS, MM BTU/HR	REDUCING EXCESS AIR TO 10%	REDUCING EXCESS AIR TO 10% AND STACK TEMP. TO 350°F
AVU-191	254.8	17.5	91.8
NU-291	29.1	1.4	8.0
GU-292	9.4	2.0	4.0
GU-293	18.0	0.7	7.7
AU-491	52.9	3.5	12.3
SRU-591	5.8	NA	NA
DCU-891	25.5	0.4	4.3
FCC-1291	20.2	10.9	15.6
CRU-1391	110.2	25.8	94.1
AEU-1791	15.2	2.7	6.4
THDU-1792	18.3	1.7	4.5
SGU-7991	2.8	0.7	1.6
UTILITIES	370.9	3.7	35.9
OFFSITES	2.5	0.1	1.1
TOTAL	935.4	71.1	287.3

FIGURE 5-6

AN OVERALL REFINERY HEATER AND BOILER STACKS TOTAL POTENTIAL ENERGY SAVINGS FOR REDUCING EXCESS AIR AND STACK TEMPERATURE



Based on data of 9/26/77 - 10/6/77 at 214636 BPD oil charge.

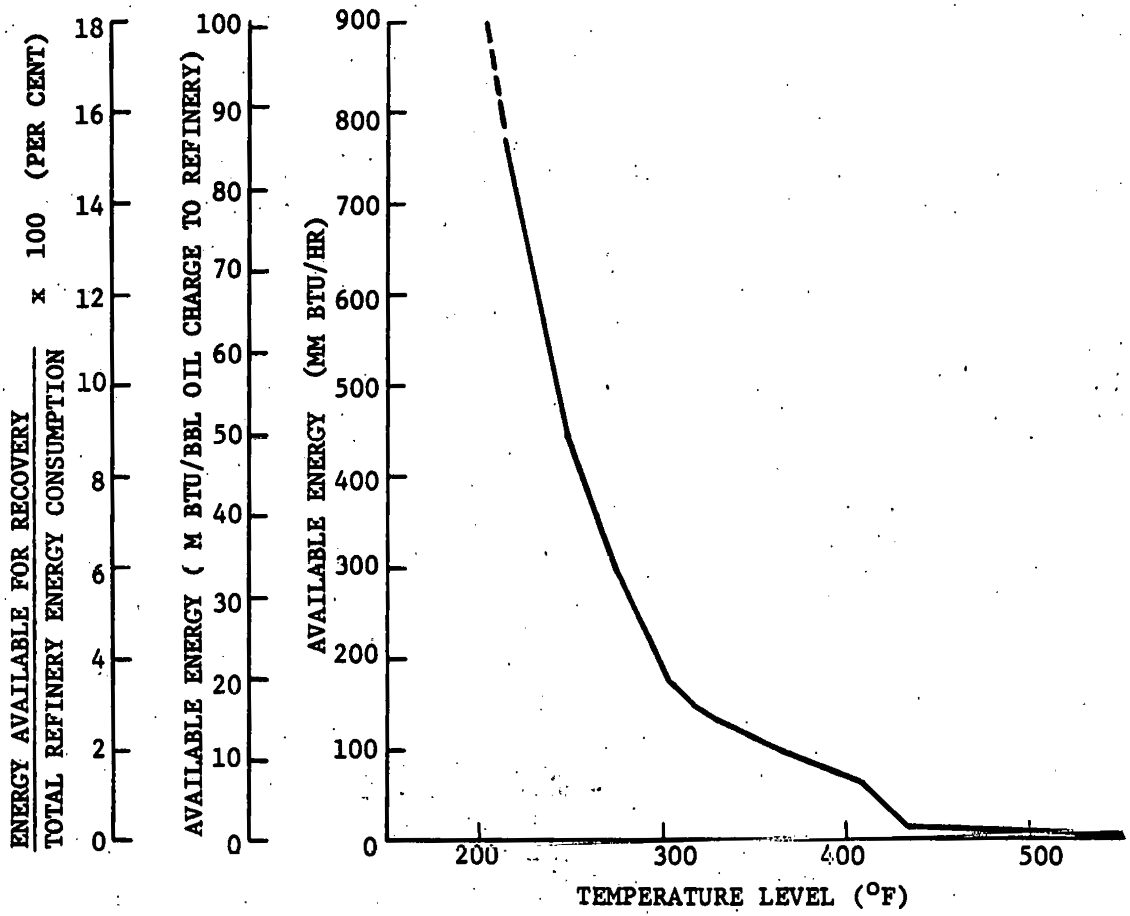
TABLE 5-14

AN OVERALL REFINERY
HEAT AVAILABLE FOR POTENTIAL RECOVERY FROM AIR AND WATER COOLED PROCESS STREAMS AS A FUNCTION OF TEMPERATURE LEVEL

UNIT	TOTAL HEAT REJECTED ABOVE TEMPERATURE LEVELS (°F) BY AIR AND WATER COOLED HEAT EXCHANGERS, MM BTU/HR							
	200	250	300	320	406	432	550	650
AVU-191	252	121	52	41	35	0	0	0
NU-291	23	8	0	0	0	0	0	0
GU-292	50	36	28	24	8	3	0	0
GU-293	97	74	65	62	23	12	5	5
AU-491	28	13	2	1	0	0	0	0
SRU-591	14	0	0	0	0	0	0	0
DCU-891	18	9	1	0	0	0	0	0
FCC-1291	243	89	20	12	1	0	0	0
CRU-1391	78	47	13	0	0	0	0	0
AEU-1791	58	0	0	0	0	0	0	0
THDU-1792	59	29	0	0	0	0	0	0
SGU-7991	14	3	2	2	1	<1	0	0
UTILITIES	0	0	0	0	0	0	0	0
OFFSITES	0	0	0	0	0	0	0	0
TOTAL	934	429	183	141	68	15	5	0
% OF TOTAL HEAT REJECTED IN AIR & WATER COOLERS	33.7	15.4	6.6	5.1	2.4	0.5	0.2	0.0
% OF TOTAL CONSUMPTION	18.7	8.6	3.7	2.8	1.4	0.3	0.1	0.0

FIGURE 5-7

AN OVERALL REFINERY AIR AND WATER COOLERS
TOTAL ENERGY AVAILABLE FOR POTENTIAL RECOVERY
ABOVE VARIOUS TEMPERATURE LEVELS



Based on data of 9/26/77 - 10/6/77 averaged to 214636 BPD oil charge to refinery.

SECTION 6

DISCUSSION

The purpose of developing a refinery energy profile is to determine where energy enters a refinery, is used, and ultimately discarded, with the primary objective of identifying areas of potential energy savings. Using this technique, a unit by unit picture of the energy usage in a petroleum refinery is developed. The technique requires a substantial number of manhours, but is a rigorous method that will produce accurate results. It points out areas of potential energy savings by identifying and quantifying individual losses within the refinery.

A user should also keep in mind that an energy profile for a refinery is essentially a "snapshot" for one point in time and is a function of many factors which are subject to frequent changes. The properties of the crude being processed, the types of products, and quality specifications can all affect energy usage. The length of time a unit has been in operation since its last scheduled shutdown for routine cleaning and repairing can also affect energy consumption for each unit.

6.1 Unique Approaches

The approach taken in developing a refinery energy profile contains concepts that may differ from normal refinery energy balance calculations. An example is including internal recycle heat as part of the heat requirements of each unit. The heat exchanged between process streams is a part of the heat requirement of a unit and needs to be considered in evaluating the energy usage of a unit. Another example is the calculation of all steam values on a gross basis instead of on a net basis. This gives a clearer picture of steam utilization. The technique also contains procedures for estimating the potential savings from loss areas such as heater stacks and air and water cooled heat exchangers. One concept employed in calculations that should also be pointed out is the adjustment of all enthalpy calculations to a base of 60°F and 0 psig. A common basis is necessary so that import or export energy values can be calculated for streams crossing system boundaries. For refinery calculations this was the most convenient basis to use even though steam table data and some other common data had to be converted to the new base.

The energy input to individual units and to the entire refinery include sources that are not normally considered. Most calculations of refinery energy consumption are based on the utilities consumption. However, in order to have a complete energy profile, the energy input from all other sources must also be considered. The other sources are the import energy in feed streams (which includes combustion air to furnaces), exothermic heats of reaction, and the combustion energy value of any stock losses (which are entered as oil charge loss). Since any oil charge loss is a potential energy source that is lost and cannot be used by anyone, they represent an energy consumption by the refinery.

6.2 Modifying the Technique

The technique is written to produce an accurate energy profile for an entire refinery but does contain alternate procedures that can be used to simplify the preparation of a profile at some sacrifice in accuracy. Depending on the use being made of the technique, some steps that can be taken to simplify the procedure are:

1. Limit profiling to particular units or even individual pieces of equipment.
2. Combine air and water cooled heat exchangers that are in series and calculate only the combined duty.
3. Eliminate small or low inlct temperature air or water cooled heat exchangers or simply prorate from design data.
4. Delete calculation of internal recycle.
5. Calculate steam values on a net basis.

This list is not intended to be complete but to illustrate the types of modifications the individual user can make in applying the technique to his particular situation.

REFERENCES

1. American Petroleum Institute, Technical Data Book - Petroleum Refining, 1976.
2. Simulation Sciences Inc. SSI/100 Process Simulator Manual.
3. American Society of Mechanical Engineers, 1967 ASME Steam Tables, 1967.
4. Kennan and Keys, Thermodynamic Properties of Steam, Wiley, 1936.
5. Malloy, J. F., Thermal Insulation, Van Nostrand, 1969.
6. Thermal Insulation Manufacturers Association.

APPENDIX A

COMPUTER PROGRAM INPUT AND OUTPUT EXAMPLES

TABLE A-1

INPUT FOR OIL FLOW METER

ITEM	INPUT DATA
Location	AVU 191 Crude Unit
Index Number	191 - FR - 150
Service	Crude to H-1 Cells 1 & 2
Fluid	Oil
Device	Standard Orifice
Taps	Flange
Flange Type	300RF
Meter Type	Force Balance
Pipe I.D., In.	13.124
Orifice I.D., In.	9.332
Range, In. H_2O	100
Temp., °F	423
Gravity Code	API Gravity
Gravity	34.6
VIS 1, SUV	49.1
VIS 1 Temp., °F	77
VIS 2, SUV	42.5
VIS 2 Temp., °F	100
Job Code	Calculate Meter Factor

FIGURE A-1

TYPICAL COMPUTER OUTPUT FOR OIL FLOW METER ORIFICE CALCULATION

```
                              METER FLOW CALCULATION

   CODE        LOCATION              INDEX      SERVICE

001 030 0    CRUDE UNIT            191-FR-150  CRUDE TO H-1 CELLS 1+2

REMARKS:

          HARDWARE                                               OPERATING CONDITIONS

ELEMENT         CONCENTRIC ORIFICE                       TEMP DEG F               423.
FLUID           OIL                                      PRESSURE PSIG
PIPE I.D.       13.124                                   GRAVITY API               34.6
BORE             9.332                                   SPECIFIC GRAV 60        0.8519
RANGE IN.H2O    100.0                                    VISCOSITY 1 SSU           49.1 AT   77. F
TAPS            FLG.                                     VISCOSITY 2 SSU           42.5 AT  100. F
METER TYPE      F.B.                                     VISCOSITY CODE
SEALS           NONE                                     MOISTURE PCT
SEAL GRAVITY                                             DIVISIONS               10.00
FLANGE TYPE     300R


                                   CALCULATED VALUES

                    BETA RATIO       0.7111        GB  (OIL)          0.8519
                    CP               1.0069        GF  (OIL)          0.7030
                    RE (BORE)         2723185.     CG  (GAS)
                    Z (SEALS)                      CTF (GAS)
                    Y (GAS OR STM)                 CPV (GAS)
                    M (STM)                        W (STM OR MISC)
                    E (WATER)                      VIS. CENTIPOISE    0.3599
                    K                0.6946

         QUANTITIES MARKED WITH * WERE SPECIFIED TO BE REPLACED CALCULATED VALUES


                         FLOW FACTOR     485.32   BPH/DIV
```

TABLE A-2

INPUT FOR GAS FLOW METER

ITEM	INPUT DATA
Location	AVU 191 Crude Unit
Index Number	191 - FI - 154
Service	Fuel Gas to H-1
Fluid	Gas
Device	Standard Orifice
Taps	Flange
Flange Type	300RF
Meter Type	Bellows
Pipe I.D., in.	10.020
Orifice I.D. In.	7.014
Range, in. H_2O	100
Temp., °F	105
Pressure, Psig	55
Gravity Code	Sp Gr
Gravity	0.6067
Job Code	Calculate Meter Factor

```
                    FLOW FACTOR    10083.20  LB/H/DIV
                     BTU FACTOR      1.1767
```

FIGURE A-2

TYPICAL COMPUTER OUTPUT FOR GAS FLOW METER ORIFICE CALCULATION

```
                              METER FLOW CALCULATION

   CODE        LOCATION            INDEX       SERVICE

 D01 019 4   CRUDE UNIT          191-FI-154  FUEL GAS TO H-1

 REMARKS:

         HARDWARE                                           OPERATING CONDITIONS

 ELEMENT        CONCENTRIC ORIFICE                  TEMP DEG F              105.
 FLUID          GAS                                 PRESSURE PSIG            55.0
 PIPE I.D.      10.020                              GRAVITY API
 BORE            7.014                              SPECIFIC GRAV 60        0.6067
 RANGE IN.H2O   100.0                               VISCOSITY 1 SSU                  AT       F
 TAPS           FLG.                                VISCOSITY 2 SSU                  AT       F
 METER TYPE     F.B.                                VISCOSITY CODE
 SEALS          NONE                                MOISTURE PCT
 SEAL GRAVITY                                       DIVISIONS               10.00
 FLANGE TYPE    300R


                               CALCULATED VALUES

            BETA RATIO       0.7000       GB  (OIL)
            CP               1.0008       GF  (OIL)
            RE (BORE)         6022273.    CG  (GAS)          1.2838
            Z (SEALS)                     CTF (GAS)          0.9594
            Y (GAS OR STM)   0.9803       CPV (GAS)          1.0036
            M (STM)                       W (STM OR MISC)
            E (WATER)                     VIS. CENTIPOISE    0.0080
            K                0.6887

     QUANTITIES MARKED WITH * WERE SPECIFIED TO BE REPLACED CALCULATED VALUES



                    FLOW FACTOR  116236.38  SCFH/DIV
```

TABLE A-3

INPUT FOR STEAM FLOW METER

ITEM	INPUT DATA
Location	AVU 191 Crude Unit
Index Number	191 - FR - 191
Service	600 lb. Steam from H-2
Fluid	Steam
Device	Standard Orifice
Taps	Flange
Meter Type	Force Balance
Flange Type	300RF
Pipe I.D., In.	7.981
Orifice I.D., In.	5.449
Range, In H_2O	200
Temp., °F	706
Pressure, Psig	600
Job Code	Calculate Meter Factor
Steam BTU Factor*	1.1767

* Ratio of enthalpy at flowing conditions (706°F and 600 Psig) to enthalpy at 212°F and 14.696 Psig.

FIGURE A-3

TYPICAL COMPUTER OUTPUT FOR STEAM FLOW METER ORIFICE CALCULATION

```
                                          METER FLOW CALCULATION

   CODE        LOCATION              INDEX      SERVICE                                     PRINTED

 001 050 0   CRUDE UNIT            191-FR-191  600 LB STEAM FROM H-2 STACK

 REMARKS:

            HARDWARE                                                  OPERATING CONDITIONS

 ELEMENT        CONCENTRIC ORIFICE                          TEMP DEG F               706.
 FLUID          STM                                         PRESSURE PSIG            600.0
 PIPE I.D.       7.981                                      GRAVITY API
 BORE            5.449                                      SPECIFIC GRAV 60
 RANGE IN.H2O   200.0                                       VISCOSITY 1 SSU                   AT        F
 TAPS           FLG.                                        VISCOSITY 2 SSU                   AT        F
 METER TYPE     F.B.                                        VISCOSITY CODE
 SEALS          NONE                                        MOISTURE PCT
 SEAL GRAVITY                                               DIVISIONS               10.00
 FLANGE TYPE    300R

                                          CALCULATED VALUES

                  BETA RATIO        0.6827        GB  (OIL)
                  CP                1.0122        GF  (OIL)
                  RE (BORE)          4383512.     CG  (GAS)
                  Z (SEALS)                       CTF (GAS)
                  Y (GAS OR STM)    0.9956        CPV (GAS)
                  M (STM)           1.0000        W (STM OR MISC)    0.9500
                  E (WATER)                       VIS. CENTIPOISE    0.0267
                  K                 0.6808

         QUANTITIES MARKED WITH * WERE SPECIFIED TO BE REPLACED CALCULATED VALUES
```

FIGURE A-4

SSI-100 INPUT DATA CARDS FOR OVERHEAD CONDENSER EXAMPLE

```
TITL PROJ=DOE.PROB=EXAMPLE
DIME LIQVOL=BBL.PRES=PSIG
DESC
DESC DOE REFINERY ENERGY PROFILE SAMPLE CALCULATION:
DESC ENTHALPY CALCULATIONS FOR GAS.LIQUID.AND MIXED PHASE STREAMS
DESC FOR DETERMINING OH COND DUTY AND OH PROD EXPORT VALUES
DESC USING         STAB OH
COMP
ID 1,1/2/3/4/5/6/26/7/8/10/50
NONS 12,S 0-4   , ,72.16, 80/13,S 4-10 , .64.91,142/14,S10-30 . .58.12.209/*
     15,S30-50 , ,53.28.263/16,S50-90 , .49.21,313/17,S90-100, .46.56.348
STREAM
PROP STRM=1,BASIS=G,PHASE=V,TEMP=97,PRES=15,RATE=0.0452 *
     COMP=1,45.7/0.8/16.9/8.5/0.3/3.9/1.3/1.5/2.3/13.3/5.5
PROP STRM=2,BASIS=V,PHASE=L,TEMP=97,PRES=15,RATE=207 *
     COMP=12,4/6/20/20/40/10
PROP STRM=3,BASIS=V,PHASE=L,TEMP=97,PRES=15,RATE=37 *
     COMP=12,4/6/20/20/40/10
NAME 1,OH GAS/2,REFLUX/3,OH LIQ PROD/4,TOTAL LIQ/5,TOTAL OH
UNIT
FLASH UNO=1,NAME=LIQ MIX
      ADIAB TEST=97,PRES=15
      FEED 2,3
      PROD L=4
FLASH UNO=2,NAME=OH MIX
      ISO TEMP=97,PRES=15
      FEED=1,4
      PROD M=5
HCURVE UNO=3,NAME=STAB OH
SPEC STRM=1,OPT=2,POINT=1,TEMP=97,97  ,PRES=15,15
SPEC STRM=1,OPT=1,POINT=1,TEMP=60,60  ,PRES=0.01,0.01
SPEC STRM=3,OPT=1,POINT=1,TEMP=60,60  ,PRES=0.01,0.01
SPEC STRM=3,OPT=1,POINT=1,TEMP=97,97,PRES=15,15
SPEC STRM=5,OPT=2,POINT=1,TEMP=319,319,PRES=25,25
SPEC STRM=5,OPT=0,POINT=1,TEMP=135,135,PRES=20,20
SPEC STRM=5,OPT=0,POINT=1,TEMP=97,97,PRES=15,15
SPEC STRM=5,OPT=0,POINT=12,TEMP=320,200,PRES=25,20
END
```

Table A-4
TYPICAL INPUT FOR FURNACE CALCULATIONS

1.	Test Unit	AVU-191 H-1 crude heater	
2.	Test No.	1	
3.	Time	8:00 AM - 4:00 PM	
4.	Date	September 26, 1977	
5.	Air Temp.	80°F	
6.	Air Humidity	0.017 lb water/lb dry air	
7.	Wind Speed	10.0 MPH	
8.	Type of Fuel	Refinery Fuel Gas	
9.	No. of Gas Components	12	
	Component		
(a)	Hydrogen	30.0	Vol. %
(b)	Methane	38.3	"
(c)	Ethane	18.6	"
(d)	Propane	4.8	"
(e)	Propene	3.8	"
(f)	Iso-Butane	0.3	"
(g)	Normal Butane	0.2	"
(h)	Betenes	0.2	"
(i)	Iso-Pentane	0.1	"
(j)	Normal Pentane	0.0	"
(k)	Carbon Dioxide	0.0	"
(l)	Nitrogen	3.7	"
(m)			
(n)			
(o)			
10.	Gas Charge Rate	796 MSCFH	
11.	Gas Temp.	102°F	
12.	Oil Charge	None	lb/hr
13.	Oil Temp.	---	
14.	Temp. at Stack	545°F	
15.	Temp at Top of Rad. Sect.	1454°F	
16.	Oil HHV	---	
17.	Oil Heat Cap (Cp)	---	
18.	Oil Ult. Anal. wt%		
(a)	H	---	
(b)	C	---	
(c)	S	---	
(d)	N	---	
(e)	O	---	
19.	Atomizing Steam $\#H_2O/\#Oil$	---	
20.	Stack Gas Analysis		
(a)	$\%O_2$	3.3	
(b)	PPM CO	0.0	
(c)	PPM NOX	---	
(d)	PPM SO_2	0.0	
21.	Top of Rad. Sect. Gas Analysis		
(a)	$\%O_2$	2.1	
(b)	PPM CO	0.0	
(c)	PPM NOX	---	
(d)	PPM SO_2	0.0	
22.	Process Oil Rate BBL/Hr	---	

FIGURE A-5
TYPICAL COMPUTER OUTPUT FOR FURNACE CALCULATION

```
 AVU-191 H-1 CRUDE HEATER   TEST 1 OF 9/26/77   RUN 1
                       COMBUSTION CALCULATIONS

               PCT   LB/LB  BTU/LB LBAIR/ LBH20/ LBC02/ LBS02/ LB N2/
 COMPOUND      VOL    FUEL    FUEL LBFUEL LBFUEL LBFUEL LBFUEL LBFUEL
 H2          30.00 0.0345   2101.  1.173  0.308  0.000  0.000  0.000
 CH4         38.30 0.3498   8354.  5.988  0.786  0.960  0.000  0.000
 C2H6        18.60 0.3184   7107.  5.089  0.573  0.932  0.000  0.000
 C3H8         4.80 0.1205   2610.  1.876  0.197  0.361  0.000  0.000
 C3H6         3.80 0.0911   1916.  1.337  0.117  0.286  0.000  0.000
 IC4H10       0.30 0.0100    211.  0.153  0.016  0.031  0.000  0.000
 C4H10        0.20 0.0067    141.  0.102  0.011  0.021  0.000  0.000
 C4H8         0.20 0.0064    134.  0.094  0.009  0.021  0.000  0.000
 IC5H12       0.10 0.0042     87.  0.063  0.007  0.013  0.000  0.000
 C5H12        0.0  0.0000      1.  0.000  0.000  0.000  0.000  0.000
 N2           3.70 0.0590      1.  0.000  0.000  0.000  0.000  0.059
            ------ ------  ------ ------  -----  -----  -----  -----
 TOTALS     100.00 1.0000  22657. 15.872  2.019  2.620  0.0    0.059

 HEATING VALUE(HHV)    22657. BTU/LB FUEL
 HEATING VALUE (HHV)    1050. BTU/CF FUEL
 DENSITY              0.04636 LB/CF
 SP.GRAV. (AIR=1.0)    0.6090
 THEOR. AIR REQ'D      15.872 LB/LB FUEL
 TOTAL NITROGEN        12.233 LB/LB FUEL
 TOTAL WATER            2.019 LB/LB FUEL


STACK TEMP  545.F  FUEL RATE  36901.LB/HR  HUMIDITY  0.017 LB/LB DRY AIR
RAD   TEMP 1454.F  FUEL TEMP    102.F      AIR TEMP   80.F

STACK ANALYSIS
 TOTAL HEAT INPUT (HHV)       850375424. BTU/HR  100.00 PCT
 DRY GAS LOSS                  78296480. BTU/HR    9.21 PCT
 MOISTURE LOSS                110638416. BTU/HR   13.01 PCT
 TOTAL STACK LOSS             188934896. BTU/HR   22.22 PCT
 PCT EXCESS AIR                                   16.81 PCT
 OXYGEN IN FLUE GAS (DRY BASIS)                    3.30 PCT
 OXYGEN IN FLUE GAS (WET BASIS)                    2.70 PCT
```

APPENDIX B

PROGRAMMABLE CALCULATOR PROGRAM INPUT LISTINGS

FIGURE B-1 (Sheet 1 of 3)

LIQUID HYDROCARBON ENTHALPY PROGRAM FOR HP-97

Step	Key	Code	Remarks
001	*LBLA	21 11	
002	GSB1	23 01	Sp Gr
003	RCL1	36 01	
004	RCL3	36 03	
005	+	-55	
006	RCL5	36 05	
007	+	-55	
008	RCL7	36 07	VABP
009	+	-55	
010	RCL9	36 09	
011	+	-55	
012	5	05	
013	÷	-24	
014	STO3	35 03	
015	RCL9	36 09	
016	RCL1	36 01	
017	-	-45	
018	8	08	Slope
019	0	00	
020	÷	-24	
021	STO1	35 01	
022	RCL3	36 03	
023	3	03	
024	.	-62	
025	2	02	
026	4	04	
027	RCL1	36 01	
028	x	-35	
029	-	-45	
030	RCL6	35 06	MeABP
031	RCL3	36 03	
032	x	-35	
033	RCL1	36 01	
034	x	-35	
035	+	-55	
036	RCL2	36 02	
037	RCL3	36 03	
038	x	-35	
039	RCL1	36 01	
040	X^2	53	
041	x	-35	
042	+	-55	
043	RCL8	36 08	
044	RCL3	36 03	
045	x	-35	
046	RCL1	36 01	
047	3	03	
048	Y^x	31	
049	x	-35	
050	+	-55	
051	RCL4	36 04	
052	RCL3	36 03	
053	X^2	53	
054	x	-35	MeABP
055	RCL1	36 01	
056	x	-35	
057	+	-55	
058	RCL0	36 00	
059	RCL1	36 01	
060	X^2	53	
061	x	-35	
062	+	-55	
063	RCLE	36 15	
064	+	-55	
065	3	03	
066	1/X	52	
067	Y^x	31	
068	RCLA	36 11	K
069	÷	-24	
070	STOB	35 12	
071	PRTX	-14	
072	RTN	24	
073	*LBL1	21 01	
074	SFC	16-11	
075	PRTX	-14	
076	STOA	35 11	
077	2	02	
078	X>Y?	16-34	
079	RTN	24	
080	RCLA	36 11	
081	1	01	
082	3	03	Sp Gr
083	1	01	
084	.	-62	
085	5	05	
086	+	-55	
087	1	01	
088	4	04	
089	1	01	
090	.	-62	
091	5	05	
092	X⇄Y	-41	
093	÷	-24	
094	STOA	35 11	
095	RTN	24	
096	*LBLB	21 12	
097	STOB	35 12	Stor K
098	R↓	-31	&
099	GSB1	23 01	
100	RCLB	36 12	Calc Sp Gr

FIGURE B-1 (Sheet 2 of 3)

LIQUID HYDROCARBON ENTHALPY PROGRAM FOR HP-97

Step	Key	Code	Remarks
101	PRTX	-14	
102	RTN	24	
103	*LBLC	21 13	Change Flow & Temp.
104	STOC	35 13	
105	R↓	-31	
106	GSBD	23 14	H
107	RTN	24	
108	*LBLD	21 14	Calc. H New T
109	STOD	35 14	
110	RCLI	36 46	Keeps previous H
111	STO9	35 09	
112	P⇄S	16-51	
113	RCL2	36 02	
114	RCLA	36 11	
115	x	-35	
116	RCL1	36 01	
117	+	-55	
118	RCLB	36 12	A_1
119	x	-35	
120	RCL0	36 00	
121	+	-55	
122	RCL3	36 03	
123	RCL4	36 04	
124	RCLB	36 12	
125	x	-35	
126	+	-55	
127	RCLA	36 11	
128	÷	-24	
129	+	-55	
130	P⇄S	16-51	
131	STO1	35 01	
132	P⇄S	16-51	
133	RCL7	36 07	
134	RCLA	36 11	
135	÷	-24	
136	RCL6	36 06	A_2
137	+	-55	
138	GSB2	23 02	
139	EEX	-23	
140	6	06	
141	CHS	-22	
142	x	-35	
143	RCL9	36 09	
144	RCLA	36 11	
145	÷	-24	A_3
146	RCL8	36 08	
147	+	-55	
148	GSB2	23 02	
149	EEX	-23	
150	9	09	
151	CHS	-22	
152	x	-35	
153	CHS	-22	
154	P⇄S	16-51	A_3
155	STO5	35 05	
156	R↓	-31	
157	STO3	35 03	
158	RCLD	36 14	
159	SPC	16-11	
160	PRTX	-14	
161	RCLE	36 15	
162	+	-55	
163	STOD	35 14	
164	RCLE	36 15	
165	6	06	
166	0	00	
167	+	-55	
168	STO7	35 07	
169	-	-45	
170	RCL1	36 01	
171	x	-35	
172	RCLD	36 14	
173	X^2	53	
174	RCL7	36 07	h(Btu/lb)
175	X^2	53	
176	-	-45	
177	RCL3	36 03	
178	x	-35	
179	+	-55	
180	RCLD	36 14	
181	3	03	
182	Y^x	31	
183	RCL7	36 07	
184	3	03	
185	Y^x	31	
186	-	-45	
187	RCL5	36 05	
188	x	-35	H(MM Btu/hr)
189	+	-55	
190	RCLC	36 13	
191	PRTX	-14	
192	x	-35	
193	RCLA	36 11	
194	x	-35	
195	3	03	
196	4	04	
197	9	09	
198	.	-62	
199	7	07	
200	9	09	

FIGURE B-1 (Sheet 3 of 3)

LIQUID HYDROCARBON ENTHALPY PROGRAM FOR HP-97

```
Step   Key     Code
 201    x       -35
 202   EEX      -23
 203    6        06      H
 204    ÷       -24      MM Btu/hr
 205   STOI    35 46
 206   PRTX     -14
 207   RTN       24    ____________
 208   *LBL2   21 02
 209   RCL5    36 05
 210   RCLB    36 12     part of
 211    x       -35      GSBD
 212    1        01
 213    +       -55
 214    x       -35
 215   RTN       24    ____________
 216   *LBLE   21 15      H =
 217   RCL9    36 09     Hh-Hn-1
 218    -       -45
 219   SPC     16-11
 220   PRTX     -14
 221   RTN       24
```

Data Card

Primary Registers

```
-1.525900+00   0
 0.000000+00   1
 1.438000-03   2
 0.000000+00   3
-5.616000-07   4
 0.000000+00   5
 1.128000-03   6
 0.000000+00   7
 7.591000-05   8
 0.000000+00   9
 0.000000+00   A
 0.000000+00   B
 0.000000+00   C
 0.000000+00   D
 4.596700+02   E
 0.000000+00   I
```

Secondary Registers

```
-1.171260+00   0
 2.372200-02   1
 2.490700-02   2
 1.149820+00   3
-4.653500-02   4
 8.246300-01   5
 5.608600+01   6
-1.381700+01   7
 9.675700+00   8
-2.365300+00   9
```

FIGURE B-2 (Sheet 1 of 3)

FURNACE CALCULTION PROGRAM FOR HP-97

CARD 1 - INPUT

```
001  *LBLA      21 11
002    F3?   16 23 03
003   GTO6      22 06
004   GTOA      22 11
005  *LBL6      21 06
006    SPC      16-11
007    F1?   16 23 01
008   PRTX        -14
009      1         01
010      0         00
011      0         00
012      ÷        -24
013   STOA      35 11
014   RCLD      36 14
015      +        -55
016   STOD      35 14
017      9         09
018   STOI      35 46
019  *LBL3      21 03
020    MRG      16-62
021    PSE      16 51
022    F3?   16 23 03
023   GTO4      22 04
024   GTO3      22 03
025  *LBL4      21 04
026   GSBa   23 16 11
027   DSZI   16 25 46
028   GTO4      22 04
029   RCL0      36 00
030    F1?   16 23 01
031   PRTX        -14
032   RCLD      36 14
033    RTN         24
034  *LBLa   21 16 11
035   RCLi      36 45
036   RCLA      36 11
037      ×        -35
038    P⇄S      16-51
039   ST+i   35-55 45
040    P⇄S      16-51
041    RTN         24
042  *LBLB      21 12
043   STO1      35 01
044    SPC      16-11
045    F1?   16 23 01
046   PRTX        -14
047     R↓        -31
048   STO2      35 02
049    F1?   16 23 01
050   PRTX        -14
```

```
051     R↓        -31
052   STO3      35 03
053    F1?   16 23 01
054   PRTX        -14
055    P⇄S      16-51
056    RTN         24
057  *LBLC      21 13
058   STOB      35 12
059    SPC      16-11
060   PRTX        -14
061     R↓        -31
062   PRTX        -14
063    EEX        -23
064      3         03
065      ×        -35
066   STOC      35 13
067   RCL6      36 06
068      ×        -35
069    EEX        -23
070      6         06
071      ÷        -24
072   PRTX        -14
073    P⇄S      16-51
074   STO4      35 04
075    P⇄S      16-51
076      0         00
077   STO0      35 00
078    SPC      16-11
079   RCLC      36 13
080   RCL9      36 09
081    P⇄S      16-51
082   RCL3      36 03
083    P⇄S      16-51
084   GSBb   23 16 12
085   RCL8      36 08
086   RCLC      36 13
087      ×        -35
088    EEX        -23
089      6         06
090      ÷        -24
091    F1?   16 23 01
092   PRTX        -14
093   ST+0   35-55 00
094      +        -55
095    P⇄S      16-51
096   STO0      35 00
097    P⇄S      16-51
098   RCL4      36 04
099   RCL3      36 03
100      +        -55
```

FIGURE B-2 (Sheet 2 of 3)

FURNACE CALCULATION PROGRAM FOR HP-97

CARD 1 - INPUT

```
101   RCL1      36 01
102    +          -55
103   RCLB      36 12
104    x          -35
105    1           01
106    0           00
107    0           00
108   ENT↑        -21
109    4           04
110    .          -62
111    7           07
112    7           07
113    3           03
114   RCLB      36 12
115    x          -35
116    -          -45
117    ÷          -24
118   STOE      35 15
119   RCL5      36 05
120    ÷          -24
121    1           01
122    0           00
123    0           00
124    x          -35
125   PSE       16 51
126   RCLE      36 15
127   RCL5      36 05
128    +          -55
129   RCLC      36 13
130    x          -35
131    4           04
132    .          -62
133    7           07
134    7           07
135    3           03
136    x          -35
137   STOI      35 46
138    .          -62
139    0           00
140    1           01
141    9           05
142    4           04
143   P⇄S       16-51
144   RCL2      36 02
145   P⇄S       16-51
146   GSBb   23 16 12
147   RCLI      36 46
148    1           01
149    3           03
150    .          -62
151    1           01
152    ÷          -24
153   P⇄S       16-51
154   RCL1      36 01
155    x          -35
156   STO9      35 09
157    .          -62
158    4           04
159    7           07
160   RCL2      36 02
161   P⇄S       16-51
162   GSBb   23 16 12
163    1           01
164    0           00
165    5           05
166    9           09
167    .          -62
168    1           01
169   P⇄S       16-51
170   RCL9      36 09
171   P⇄S       16-51
172    x          -35
173   EEX         -23
174    6           06
175    ÷          -24
176   F1?    16 23 01
177   PRTX        -14
178   ST+0   35-55 00
179   RCL0      36 00
180   PRTX        -14
181   P⇄S       16-51
182   RCL4      36 04
183    +          -55
184   STOD      35 14
185   P⇄S       16-51
186   SPC       16-11
187   PRTX        -14
188   RTN          24
189   *LBLb  21 16 12
190    6           06
191    0           00
192    -          -45
193    x          -35
194    x          -35
195   EEX         -23
196    6           06
197    ÷          -24
198   F1?    16 23 01
199   PRTX        -14
200   ST+0   35-55 00
```

FIGURE B-2 (Sheet 3 of 3)

FURNACE CALCULATION PROGRAM FOR HP-97

CARD 1 - INPUT

```
201     RTN          24
202   *LBLD       21 14
203       9          09
204    STOI       35 46
205   *LBL5       21 05
206    RCLi       36 45
207    PRTX         -14
208    DSZI    16 25 46
209    GTO5       22 05
210     RTN          24
211   *LBLE       21 15
212    CLRG       16-53
213     P⇄S       16-51
214    CLRG       16-53
215    X=0?       16-43
216    GTO7       22 07
217     SF1    16 21 01
218       0          00
219     RTN          24
220   *LBL7       21 07
221     CF1    16 22 01
222       1          01
223     RTN          24
```

FIGURE B-3 (Sheet 1 of 3)

FURNACE CALCULATION PROGRAM FOR HP-97

CARD 2 - STACK LOSS

```
001  *LBLA     21 11
002   P⇄S      16-51
003  ENT↑        -21
004     1         01
005     0         00
006     0         00
007     ÷        -24
008  STO6       35 0
009    R↓        -31
010  STOA      35 11
011  PRTX        -14
012  RCL0      36 00
013   CHS        -22
014   P⇄S      16-51
015  RCL0      36 00
016     +        -55
017  RCLE      36 15
018  RCL5      36 05
019     ÷        -24
020     1         01
021     +        -55
022     ÷        -24
023  STOI      35 46
024  RCL5      36 05
025     ÷        -24
026  STO0      35 00
027   P⇄S      16-51
028  RCLI      36 46
029  RCL4      36 04
030     ÷        -24
031  RCL0      36 00
032  RCL4      36 04
033     ÷        -24
034     +        -55
035     1         01
036     +        -55
037   P⇄S      16-51
038  STO0      35 00
039  GSB1      23 01
040   P⇄S      16-51
041  RCL9      36 09
042  RCLD      36 14
043  STO7      35 07
044     x        -35
045  STO8      35 08
046   P⇄S      16-51
047   RTN         24
048  *LBLB     21 12
049   SPC      16-11
050  STOB      35 12
```

```
051  PRTX        -14
052    R↓        -31
053  STOA      35 11
054  PRTX        -14
055  RCL4      36 04
056  RCL3      36 03
057     +        -55
058  RCL1      36 01
059     +        -55
060  RCLB      36 12
061     x        -35
062     1         01
063     0         00
064     0         00
065  ENT↑        -21
066     4         04
067     .        -62
068     7         07
069     7         07
070     3         03
071  RCLB      36 12
072     x        -35
073     -        -45
074     ÷        -24
075  RCLC      36 13
076     ÷        -24
077  STOE      35 15
078  GSB1      23 01
079  GSB2      23 02
080   RTN         24
081  *LBL1     21 01
082   P⇄S      16-51
083     0         00
084  STO5      35 05
085   P⇄S      16-51
086  RCLE      36 15
087     4         04
088     9         09
089     .        -62
090     4         04
091     1         01
092  GSBa   23 16 11
093  RCLE      36 15
094     3         03
095     .        -62
096     7         07
097     7         07
098     3         03
099     x        -35
100  RCL4      36 04
```

FIGURE B-3 (Sheet 2 of 3)

FURNACE CALCULATION PROGRAM FOR HP-97

CARD 2 - STACK LOSS

```
101      +         -55
102      5          05
103      2          02
104      .         -62
105      1          01
106    GSBa   23 16 11
107    RCL3      36 03
108      3          03
109      6          06
110      .         -62
111      6          06
112      9          09
113    GSBa   23 16 11
114    RCL1      36 01
115      1          01
116      1          01
117      .         -62
118      5          05
119      3          03
120    GSBa   23 16 11
121    RCL2      36 02
122    RCLC      36 13
123      x         -35
124      .         -62
125      0          00
126      4          04
127      7          07
128      5          05
129      x         -35
130    P⇄S       16-51
131    RCL9      36 09
132    P⇄S       16-51
133      +         -55
134    STOI      35 46
135    RCLC      36 13
136      ÷         -24
137      2          02
138      .         -62
139      1          01
140      3          03
141    GSBa   23 16 11
142      1          01
143      0          00
144      5          05
145      9          09
146      .         -62
147      1          01
148    RCLI      36 46
149      x         -35
150     EEX        -23
```

```
151      6          06
152      ÷         -24
153     F1?   16 23 01
154    PRTX        -14
155     P⇄S      16-51
156    ST+5   35-55 05
157    RCL5      36 05
158    PRTX        -14
159    RCLD      36 14
160    RCL5      36 05
161      -         -45
162    RCLD      36 14
163      ÷         -24
164    RCL6      36 06
165      -         -45
166     SPC      16-11
167    PRTX        -14
168    STO9      35 09
169     P⇄S      16-51
170     RTN         24
171   *LBL2      21 02
172     P⇄S      16-51
173    RCL8      36 08
174     X⇄Y        -41
175      ÷         -24
176    STOI      35 46
177    RCLE      36 15
178    RCL0      36 00
179      x         -35
180      -         -45
181     P⇄S      16-51
182    RCL0      36 00
183      ÷         -24
184    PRTX        -14
185     CHS        -22
186     P⇄S      16-51
187    RCL4      36 04
188      +         -55
189    RCLI      36 46
190    PRTX        -14
191     X⇄Y        -41
192    PRTX        -14
193     P⇄S      16-51
194     RTN         24
195   *LBLa   21 16 11
196      ÷         -24
197    RCLC      36 13
198      x         -35
199    RCLA      36 11
200      6          06
```

FIGURE B-3 (Sheet 3 of 3)

FURNACE CALCULATION PROGRAM FOR HP-97

CARD 2 - STACK LOSS

```
201       0         00
202       -        -45
203       x        -35
204     EEX        -23
205       6         06
206       ÷        -24
207     F1?   16 23 01
208    PRTX        -14
209     P⇄S      16-51
210    ST+5   35-55 05
211     P⇄S      16-51
212     RTN         24
213   *LBLE      21 15
214    X=0?      16-43
215    GTO3      22 03
216     SF1   16 21 01
217       0         00
218     RTN         24
219   *LBL3      21 03
220     CF1   16 22 01
221       1         01
222     RTN         24
```

TABLE B-1

COMPONENT DATA CARDS FOR HP-97 FURNACE PROGRAM
PRIMARY REGISTER VALUES

	Comp. No.	Mole Comp./Mole Fuel				Mole req'd/ Mole fuel	HHV Btu/lb	Mol. Wt. lb/mole	Latent Heat Btu/SCF	C_p (Vol) Btu/SCF-°F
		SO_2	H_2O	CO_2	N_2					
Register No.	0	1	2	3	4	5	6	7	8	9
COMPONENT										
H_2	1	0	1	0	1.886	0.5	324.2	2.016	0.0	.012
CO	2	0	0	1	1.886	0.5	322.6	28.011	0.0	.0185
Methane	3	0	2	1	7.546	2.0	1009.7	16.043	0.0	.0228
Ethane	4	0	3	2	13.206	3.5	1768.9	30.070	6.46	.0336
Propane	5	0	4	3	18.865	5.0	2517.4	44.097	18.38	.0482
Propene	6	0	3	3	16.978	4.5	2333.7	42.081	17.55	.0418
Iso-butane	7	0	5	4	24.524	6.5	3252.8	58.124	22.79	.0638
N-butane	8	0	5	4	24.524	6.5	3262.3	58.124	26.64	.0649
Iso-Pentane	9	0	6	5	30.184	8.0	4000.4	72.151	28.29	.0783
N-Pentane	10	0	6	5	30.184	8.0	4009.3	72.151	30.10	.0795
I-Butene	11	0	4	4	22.638	6.0	3080.9	56.108	23.89	.0587
Hexane	12	0	7	6	35.844	9.5	4756.0	86.178	35.27	.0932
N_2	13	0	0	0	0.0	0.0	0.0	28.013	0.0	.0192
CO_2	14	0	0	1	0.0	0.0	0.0	44.010	0.0	.0273
O_2	15	0	0	0	-3.773	-1.0	0.0	32.000	0.0	.0202
H_2S	16	1			5.660	1.5	637.6	34.080	21.2	.0228
H_2O	17	0	1	0	0.0	0.0	0.0	18.015	50.32	.0228

FIGURE B-4 (Sheet 1 of 2)

RADIATION LOSS PROGRAM FOR HP-97

```
001  *LBLA      21 11
002    SPC      16-11
003    F1?   16 23 01
004   PRTX        -14
005   STOB      35 12
006     R↓        -31
007    F1?   16 23 01
008   PRTX        -14
009      8         08
010      8         08
011      ×        -35
012      6         06
013      8         08
014      .        -62
015      9         09
016      +        -55
017      6         06
018      8         08
019      .        -62
020      9         09
021      ÷        -24
022     √X         54
023   STOD      35 14
024    RTN         24
025  *LBL6      21 06
026    SPC      16-11
027    F1?   16 23 01
028   PRTX        -14
029   STOC      35 13
030     R↓        -31
031    F1?   16 23 01
032   PRTX        -14
033   STO1      35 01
034     R↓        -31
035    F1?   16 23 01
036   PRTX        -14
037   STO0      35 00
038     R↓        -31
039   PRTX        -14
040   STOA      35 11
041    RTN         24
042  *LBLB      21 12
043   GSB6      23 06
044   GSB3      23 03
045   STOI      35 46
046   GSB1      23 01
047   RCLI      36 46
048      ×        -35
049    EEX        -23
050      6         06
051      ÷        -24
052   PRTX        -14
053   ST+9   35-55 09
054    RTN         24
055  *LBLC      21 13
056   GSB6      23 06
057   GSB3      23 03
058   GSB2      23 02
059      ×        -35
060    EEX        -23
061      6         06
062      ÷        -24
063   PRTX        -14
064   ST+9   35-55 09
065    RTN         24
066  *LBLD      21 14
067   RCL9      36 09
068    SPC      16-11
069   PRTX        -14
070    RTN         24
071  *LBLE      21 15
072    X=0?     16-43
073   GTO5      22 05
074    SF1   16 21 01
075      0         00
076   STO9      35 09
077    RTN         24
078  *LBL5      21 05
079    CF1   16 22 01
080      1         01
081    RTN         24
082  *LBL1      21 01
083   RCL0      36 00
084     Pi      16-24
085      ×        -35
086   RCL1      36 01
087      ×        -35
088   RCL0      36 00
089     X²         53
090     Pi      16-24
091      ×        -35
092      2         02
093      ÷        -24
094      +        -55
095   STOE      35 15
096    RTN         24
097  *LBL2      21 02
098   RCL1      36 01
099   RCL0      36 00
100      ×        -35
101   STOE      35 15
102    RTN         24
```

FIGURE B-4 (Sheet 2 of 2)

RADIATION LOSS PROGRAM FOR HP-97

```
103  *LBL3     21 03
104   RCLA     36 11
105   RCLB     36 12
106      -       -45
107      1        01
108      .       -62
109      2        02
110      5        05
111     Yˣ        31
112      .       -62
113      2        02
114      9        09
115      6        06
116      x       -35
117   RCLD     36 14
118      x       -35
119    F1?  16 23 01
120   PRTX       -14
121   STOI     35 46
122   RCLA     36 11
123   GSB4     23 04
124   RCLB     36 12
125   GSB4     23 04
126      -       -45
127   RCLC     36 13
128      x       -35
129      .       -62
130      1        01
131      7        07
132      4        04
133    EEX       -23
134      8        08
135    CHS       -22
136      x       -35
137    F1?  16 23 01
138   PRTX       -14
139   RCLI     36 46
140      +       -55
141   PRTX       -14
142    RTN        24
143  *LBL4     21 04
144      4        04
145      5        05
146      9        09
147      .       -62
148      6        06
149      7        07
150      +       -55
151      4        04
152     Yˣ        31
153    RTN        24
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