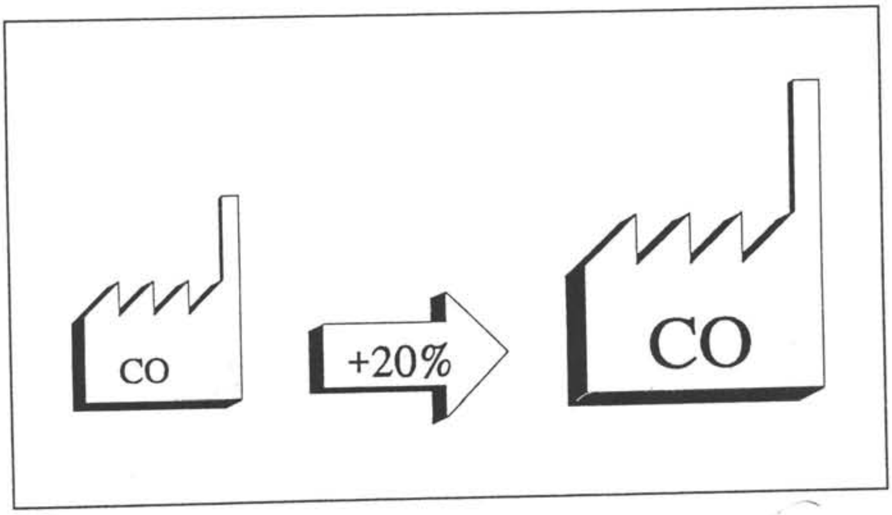
3034
3035
3036
3037

confidential

Capacity increase of a CO-plant

Study of the capacity increase of an existing CO-plant

G-groep, february 1993



TU Delft
Technische Universiteit Delft

Faculteit der Werktuigbouwkunde en Maritieme Techniek
Laboratorium Apparatenbouw voor de Procesindustrie

CAPACITY INCREASE OF A CO-PLANT

CONTENTS

Summary

5 Simulation

8 Nitrogen removal

9 Plant cost calculations

10 Alternative methods for CO-production

12 Experiences with ASPEN Plus

Appendices

PREFACE

This report is the result of the G-group study at the Delft University of Technology in spring 1993. The G-group study, which lasted 12 weeks, is carried out by students mechanical- and chemical engineering and is done before graduating.

We would like to thank everybody who has helped us with the completion of this report, in particular our supervisors ing. A. de Bruin, prof. dr. ir. J. de Graauw, prof. ir. J. Grievink, ir. V. Mattheij, drs. F.A. Meijer and dr. Ž. Olujić.

Their coaching, criticism and ideas have been of great value for the completion of this report.

G-group :

Asheesh Doerdjan	WB
René van Eerten	WB
Marc van Gestel	WB
Ed Hanenberg	WB
Alexander Hilkhuijsen	WB
Jasper Kwakkelstein	WB
Arnold Tol	WB
Maarten Verhaar	WB
Ivo Ketelaars	ST
Patrick den Ridder	ST
Sjila Santegoeds	ST
Jeroen Stoffels	ST
John Zevenbergen	ST

SUMMARY

This report is the result of a study of the G-Groep of february 1993. In Bergen op Zoom GE Plastics (GEP) has two plants for producing CO. This CO is an intermediate in the production of different plastics.

The purpose of this study is to accomplish a capacity increase of 20 % of the actual CO production in CO plant II. The different options to upscale the plant were handled in a pre-study. The main subjects for investigation are:

* removing N_2 from the natural gas feed
* changing the reformer, eventually adding a pre-reformer
* changing the feed composition
* investigate gas separation processes after the reformer
* producing a simulation by using, on request of GEP, the ASPEN PLUS program
* look for alternative CO production systems

In order to have an economically feasible method, the total group of thirteen students was divided in four groups and one ASPEN PLUS expert. After a few weeks some groups finished most of their work and some students went to other groups. The occupation of the groups was as follows:

1) investigate the reformer to get 20 % more CO output and give data to simulate with ASPEN.
2) investigate the gas separation processes after the reformer with the new streams of group one and give data to ASPEN in order to simulate the gas separation units.
3) investigate a possible way to remove the N_2 from the natural gas feed and analyse the advantages of this removal on the production capacity.
4) investigate the other ways to produce and separate CO with a totally new plant based on different technology.

The conclusion of group 1 is that an increase of the reformer capacity is possible by using an extra feedstream consisting of CO_2, eventually in combination with a pre-reformer. With this extra CO_2 an increase of CO production of approximately 20 % is possible. If the feed is for 80 % free of N_2 the increase in CO production or heatduty is neglectible.

Group 2 has calculated that a greater gasflow coming out of the reformer, in the case of only adding extra CO_2 to the reformer feed, can be treated in the stripping section of the MEA-system with addition of several heatexchangers, and that the regeneration of the MEA solution has a limit of 17 % capacity increase when operating at 90 % flooding. This 17 % capacity increase is sufficient for a total plant scale up of 20%, because the CO_2 concentration is lower in the new plant. When using a pre-reformer the equipment in the MEA section does not need to be changed. The columns in the coldbox all have sufficient overcapacity for 20% capacity increase in both cases. Pumps and compressors also handle the capacity increase in both cases.

Group 3 has simulated a plant which has a N_2 removal of 80 % out of the natural gas stream needed for 20 % more CO production. The N_2-removal is done by cryogenic

separation. The costs of such a plant are not only so high that a commercial use is not recommendable, but also the use of N_2 free natural gas as feedgas has no use for higher CO production, according the conclusion of group 1.

Group 4 has made a study for a total new plant with the same CO production as the scaled up existing plant and this new plant consists of a CO_2 reformer with a CO Vacuum Swing Adsorption (VSA) system for the CO recovery. The new plant makes no use of the unit for N_2 free natural gas feed, because of cost calculations. The CO in this plant is produced for $ 0.60/kg. Also the costs for a COSORB (CO-complex adsorption system) and a H_2 fuel cell system, for electricity generation out of the H_2-rich stream of the H_2-PSA, are calculated.
Coal gasification would only be economical producing more then 6.5 ton/hr, which is far more then 1.22 ton/hr and therefore not an option.

Working with ASPEN gave a lot of difficulties but most of them were problems with our computernetwork. The program itself has been very usefull to calculate the new streams and all physical properties of the stream.

The upscaled plant will have a CO price of ± $0.88 which is less expensive than the current CO price.

The costs for one ton CO with the total new process designed by group 4 is $ 0.60. So the conclusion is when a total new plant will be made a good alternative will be the process of group 4.

Some further attention can be given to cost calculations, which are only an indication of the new CO production costs.

1. INTRODUCTION

In Bergen op Zoom General Electric Plastics produces carbon monoxide in CO-plant I and CO-plant II. The carbon monoxide is produced by steam reforming of natural gas over a nickel based catalyst. After reforming the process gas contains many components: CO, CO_2, CH_4, H_2, H_2O and N_2, so the next step in the production of carbon monoxide is purification of the process gas. The purification steps are carbon dioxide removal, drying and cryogenic separation of methane, carbon monoxide and hydrogen.

The goal of this G-group is to investigate the possibility to increase the capacity of CO plant II by twenty percent, using Aspen for the simulations. Hence the capacity has to be increased from 1,26 tons per hour to 1.51 tons pure CO per hour.

A short description of the current proces is given in chapter two. In chapter three the reformer, which is the main bottle neck for capacity increase, is investigated. The way the plant is modelled in Aspen is described in chapter four. After the modelling, we have used Aspen to investigate the different influences on the production capacity, hence chapter five deals with the simulation and calculation of the streams in the CO-plant. In chapter six the removal and recovery of CO_2 with MEA is discussed. After the CO_2 separation the process gas is purificated to CO and N_2 by means of cryogenic separation; this is described in chapter seven. Because natural gas is used as feed in the current process, we have to deal with N_2 in the process gas. So in chapter eight advantages and methods for N_2 removal are studied. In chapter nine the total costs are estimated. Alternatives for the production of CO are discussed in chapter ten. Recommandations and conclusions for the capacity increase of CO-plant II are given in chapter eleven. Finally the experiences with ASPEN are described in chapter twelve.

2. THE CURRENT PROCESS

In this chapter CO plant II will briefly be discussed, in order to understand the production process of CO. The information of the plant was released by General Electric Plastics [2.1]. If we summerize the information we get a block scheme with design main stream-numbers, which can be found in appendix 2. With the aid of this block scheme the process is described. Appendix 2 is completed with the KTI process flow diagrams of CO plant II.

2.1 Feed of the plant

The feed which is used for the production of CO is Dutch natural gas. The properties of this gas can be found in a book published by the Nederlandse Gasunie [2.2]. The composition of this gas is given in table 2.1.

table 2.1: Average composition of natural gas

Component	Formula	% (mol)	% (mass)
methane	CH_4	81.29	69.97
ethane	C_2H_6	2.87	4.63
propane	C_3H_8	0.38	0.90
butane	C_4H_{10}	0.15	0.47
pentane	C_5H_8	0.04	0.16
hexane	C_6H_{14}	0.05	0.23
nitrogen	N_2	14.32	21.52
oxygen	O_2	0.01	0.02
carbon dioxide	CO_2	0.89	2.10
		100	100

2.2 Desulphurisation of the natural gas

Since sulphur poisons the reformer catalyst, it is necessary to remove the sulphur from the natural gas. If no recycled hydrogen is added to the natural gas feedstream then the gas stream goes to a carbon bed desulphurizer.

At normal production conditions however recycled hydrogen is used. Then the gas stream follows another desulphurisation route; the feed is transported through a cobalt-molybdenum catalyst bed (COMOX). In this bed the sulphur compounds are converted in H_2S. In a zinc oxide reactor H_2S is adsorbed.

2.3 Reforming of natural gas

The feedstream to the reformer exists of four separate streams:

- Desulphurized natural gas with or without recycled hydrogen.
- Recycled CO_2 from the CO_2 removal section.
- Recycled tail gas from the CO recovery section.
- Process steam.

The feedstream enters at a temperature of 487 °C and is sent into tubes which are packed with a catalyst. The chemical reactions which occur in the reformer can be described by two main reactions:

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \qquad \text{endothermic} \qquad (2.1)$$

$$CO_2 + H_2 \rightleftharpoons CO + H_2O \qquad \text{endothermic} \qquad (2.2)$$

The overall reaction is endothermic and favoured at high temperature. The energy needed for the reactions is provided by side wall mounted burners. The heat is transferred by radiation and convection to the process gas in the catalyst tubes. The flue gasses are used for pre-heating of the feed and steam production. The burners are started up with natural gas and when H_2-rich gas from the CO recovery unit is availible natural gas is replaced by the H_2-rich gas.

At the reformer outlet (temperature 860 °C) the methane equilibrium is approached to 20 °C lower, so the equilibrium constant of 840 °C is taken. The CO equilibrium is approached to 0 °C , so the equilibrium constant of 860 °C is taken. Hence with known outlet pressure, temperature and feed composition it is possible to calculate the reformer outlet composition.

In the reformer the steam to carbon ratio should stay above a certain minimum value because of the carbon deposition tendencies. This is the reason why an excess of steam is added. The reformer outlet temperature is decreased in two cooling steps to a temperature of 40 °C. The condensated steam is almost completely separated from the process gas.

2.4 Process gas purification

In the MEA section the CO_2 is removed from the process gas. The process gas is counter currently transported through an absorbtion column with a monoethanolamine (MEA) stream at a temperature of 40 °C. The CO_2 reacts with MEA according to the next reaction:

$$HO\text{-}CH_2\text{-}CH_2\text{-}NH_2 + H_2O + CO_2 \rightleftharpoons HO\text{-}CH_2\text{-}CH_2\text{-}NH_3 + HCO_3 \quad (2.3)$$

The CO_2 rich MEA solution is transported to the MEA stripper. The CO_2 can be released from the solution at low pressure and a temperature of 120 °C. The CO_2 stream flows to the compressor where it is compressed and recycled to the reformer.

The process gas is compressed in a compressor and transported to the process gas drying unit where the temperature is reduced to 35 °C. The formed condensate is separated by a gas liquid separator. In the last step of the drying unit the process gas is transported to a set of mole sieve beds where the last bit of H_2O is removed. The process gas leaving the drying unit contains H_2O and CO_2 at a level of 0.1 ppm volume. This ratio is necessary to avoid clogging problems in the cold box.

The process gas coming from the drying unit contains H_2, CO, N_2 and CH_4. To separate this gas, cryogenic separation is used (Linde Coldbox). This separation method is based on the difference in boiling points. The process gas is cooled to -200 °C by heat exchangers. For this process, the required refrigeration can be obtained by H_2 expansion and a CO recycle loop. A disadvantage of the cryogenic process is that the nitrogen present in the process gas can not be completely seperated from the carbon monoxide, because of the close physical properties (boiling point and molecular weight). At the end the process gas contains CO and N_2 in a 9:1 ratio.

Literature

[2.1] Design and operating manual carbon monoxide plant II, General Electric Plastic, KTI.

[2.2] Geerssen, T.M., Physical properties of natural gases. Groningen, 1988.

3.THE REFORMER

3.1.Theory

3.1.1.The reformer

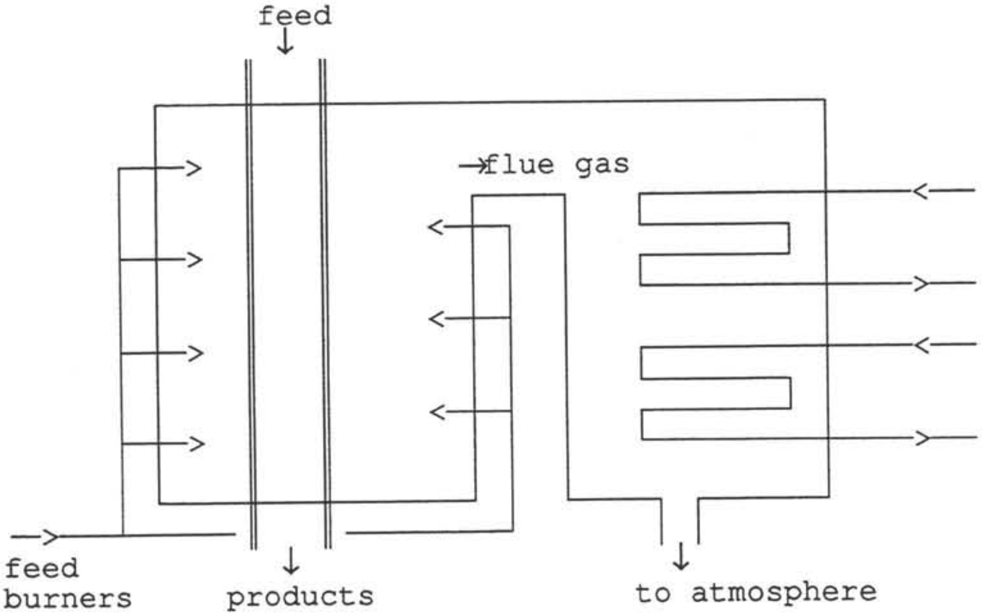


Figure 3.1. A schematic representation of the reformer.

The reformer consists of 20 tubes, which are filled with a catalyst. The tubes are suspended in a furnace which are heated with side wall mounted burners. The hot flue gas leaving the furnace is used to heat other streams.

When the CO plant is started up the burners are fed with methane. When the plant is in operation enough hydrogen is produced to feed the burners. Methane and hydrogen are fed to the burners with an excess of oxygen. The reactions taking place are:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad \Delta H = -802.6 \text{ kJ/mol} \qquad (3.1)$$

$$H_2 + 0.5O_2 \rightarrow H_2O \qquad \Delta H = -241.8 \text{ kJ/mol} \qquad (3.2)$$

Table 3.1 lists 11 reactions [3.1] which in theory may occur between CH_4, CO_2, CO, H_2, H_2O and carbon. Whether the reactions occur depends on the composition of the gas by a given pressure and temperature. Reactions 3.3 to 3.7 are mutually depended. Therefor only 2 of these reactions are needed to calculate the conversion of methane and carbon dioxide. In literature usually reactions 3.3 and 3.4 are used to calculate the conversion, because these reactions give the best understanding in what happens in the reformer. Reactions 3.8 to 3.13 are carbon deposition reactions which are unfavourable in the reformer.

Table 3.1. Possible reactions in methane steam reforming.

number	reactions	ΔH_{298} KJ/mol
3.3	$CH_4 + H_2O \rightleftharpoons CO + 3H_2$	+ 206.1
3.4	$CO + H_2O \rightleftharpoons CO_2 + H_2$	- 41.15
3.5	$CH_4 + 2H_2O \rightleftharpoons CO_2 + 4H_2$	+ 165.0
3.6	$CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2$	+ 247.3
3.7	$CH_4 + 3CO_2 \rightleftharpoons 4CO + 2H_2O$	+ 330.0
3.8	$CH_4 \rightleftharpoons C + 2H_2$	+ 74.82
3.9	$2CO \rightleftharpoons C + CO_2$	- 173.3
3.10	$CO + H_2 \rightleftharpoons C + H_2O$	- 131.3
3.11	$CO_2 + 2H_2 \rightleftharpoons C + 2H_2O$	- 90.13
3.12	$CH_4 + 2CO \rightleftharpoons 3C + 2H_2O$	- 187.6
3.13	$CH_4 + CO_2 \rightleftharpoons 2C + 2H_2O$	- 15.3

When natural gas is used as a feed higher alkanes are also present. The reactions of these alkanes are listed in Table 3.2. The most important reaction of Table 3.2 is the carbon deposition reaction (3.16); higher alkanes have a higher potential for carbon deposition than lower alkanes.

Table 3.2. Possible reactions in methane steam reforming when higher alkanes are present.

number	reactions	ΔH_{298} KJ/mol
3.14	$C_nH_{2n+2} + (n-1)H_2 \rightleftharpoons nCH_4$	-
3.15	$C_nH_{2n+2} + nH_2O \rightleftharpoons nCO + (2n+1)H_2$	+
3.16	$C_nH_{2n+2} \rightleftharpoons nC + (n+1)H_2$	+

Equilibrium constants

All reactions in Table 3.1 and 3.2 are equilibrium reactions. To predict the composition of the process gas at a given temperature and pressure, the equilibrium constants must be calculated. Therefor the equations have to be solved simultaneously. The equilibrium constants of the most important reactions, reactions 3.3 and 3.4, can be calculated with the following equations [3.2]:

for reaction 3.3

$$K_3=\exp[-\frac{27464}{T}+30.707] \tag{3.1}$$

and for reaction 3.4 below 773 K

$$K_4=\exp[\frac{4578}{T}-4.33] \tag{3.2}$$

and for reaction 3.4 above 773 K

$$K_4=\exp[\frac{4084}{T}-3.765] \tag{3.3}$$

with
T : the equilibrium temperature (K)
K_3: the equilibrium constant for reaction 3.3 (atm^2)
K_4: the equilibrium constant for reaction 3.4 (-).

With the K-values now calculated and the feed composition known, the composition can now be calculated with the following equations, assuming that no carbon deposits and that all higher alkanes are converted into methane.

$$K_3=\frac{P_{CO}*P_{H_2}^3}{P_{CH_4}*P_{H_2O}} \tag{3.4}$$

and

$$K_4=\frac{P_{H2}*P_{CO2}}{P_{CO}*P_{H2O}} \tag{3.5}$$

where P_i is the partial pressure of the components which can be calculated with the following equation.

$$P_i=\frac{n_i}{n_{tot}}*P \tag{3.6}$$

with
n_i : number of moles of component i
n_{tot}: total number of moles
P : pressure (Pa)

3.1.2.Carbon-free operation of the reformer

Carbon formation in a steam reformer will reduce the activity of the catalyst. As a result of the carbon deposition the rate of heat transfer decreases, resulting in higher temperatures of the reformer tubes. These higher temperatures will eventually lead to overheating. This overheating will increase the carbon formation, resulting in a self-accelerating situation and breakdown of the catalyst.
In the plant the steam to carbon ratio must be optimized. Steam favours the methane conversion, prevents carbon formation but too much steam is not economical.

Carbon formation can take place by the following reactions [3.3]:

Methane cracking	$CH_4 \rightleftharpoons C + 2H_2$	$\Delta H = 74.8$ kJ/mol	(3.8)
Boudouard coking	$2CO \rightleftharpoons C + CO_2$	$\Delta H = -173.3$ kJ/mol	(3.9)
CO reduction	$CO + H_2 \rightleftharpoons C + H_2O$	$\Delta H = -131.3$ kJ/mol	(3.10)
Higher hydrocarbons	$C_nH_m \rightleftharpoons nC + m/2\ H_2$		(3.17)

sub reaction (3.8). The methane cracking reaction is endothermic and exhibits a volumetric increase. Hence it is favoured by high temperatures and low pressures. Because methane is consumed and hydrogen is produced in the reformer, the methane cracking reaction will most likely take place near the reactor inlet, where methane is still present. Temperatures at the reformer outlet will thermodynamically favour cracking, but then there is so much hydrogen and so little methane, that there is no affinity for the coking reaction.
sub reaction (3.9) and (3.10). Both the Boudouard and CO reduction reactions are exothermic and result in a volumetric decrease. Hence these reactions are thermodynamically favoured by low temperatures and high pressures. Since there is no CO at the inlet of the reformer, both the Boudouard and the CO reduction reactions can not take place even though they are thermodynamically favoured. A region near the reformer inlet can however exist, where temperatures are low enough and concentrations of CO and H_2 high enough to enable these reactions to thermodynamically take place.
sub reaction (3.17). Higher hydrocarbons are prone to carbon formation. If not reformed in the upper part of the tubes, they will crack to carbon further down. Since the amount of higher hydrocarbons in natural gas is low and due to the saturated character of these hydrocarbons, we have not evaluated them separately. The hydrocarbons will crack due to the activity of the catalyst, so they will be considered to be CH_4. The critical steam to carbon ratio will be taken more conservative in the beginning of the reformer to cope with the carbon-forming potential of the higher hydrocarbons.

From the reactions 3.9 and 3.10 it can be seen that H_2O and CO_2 will remove the deposited carbon. To optimize the flow in the reformer it is necessary to consider the risk of carbon formation.
The risk of carbon formation is evaluated by means of " The principle of equilibrated gas ". [3.4]. This principle states: " Carbon formation is to be expected if the gas shows affinity for

carbon after the establishment of the methane reforming and the shift equilibria ". The principle is no law of nature, it's merely a rule of thumb which results in a steam to carbon ratio that is rather conservative. Since the principle is a rule of thumb, a total analysis of the reformer is necessary for complete safety. This analysis should contain kinetic factors of carbon formation and gasification, radial temperature profiles, catalyst activity etc.. Since such an analysis is very complex it will not be carried out in this report.

With known feed, K-values, temperatures and pressures in the reformer it is possible to calculate the equilibrated gas composition. With this calculated composition it is possible to calculate the potential for coke formation.

Potential for carbon formation:

$$-\Delta G_e = R * T * \ln(\frac{K_{3,i}}{Q_e}) \tag{3.7}$$

with
$K_{3,i}$: equilibrium constant for graphite formation for reaction i (i = 8 or 9)
Q_e : P_{H2}^2/P_{CH4} or P_{CO2}/P_{CO}^2 (K values of reactions 3.8 and 3.9 of the equilibrated gas)

no potential for carbon formation results in $\Delta G_e > 0 \rightarrow Q_e > K$
hence:

$P_H^2/P_{CH4} > K_{3,8}$
$P_{CO2}/P_{CO}^2 > K_{3,9}$

The CO reduction reaction does not have to be considered, because the shift reaction is at equilibrium inside the pellets and therefore its affinity for coking will be the same as the Boudouard reaction. $K_{3,8}$ and $K_{3,9}$ are given in figure 3.2 [3.5].

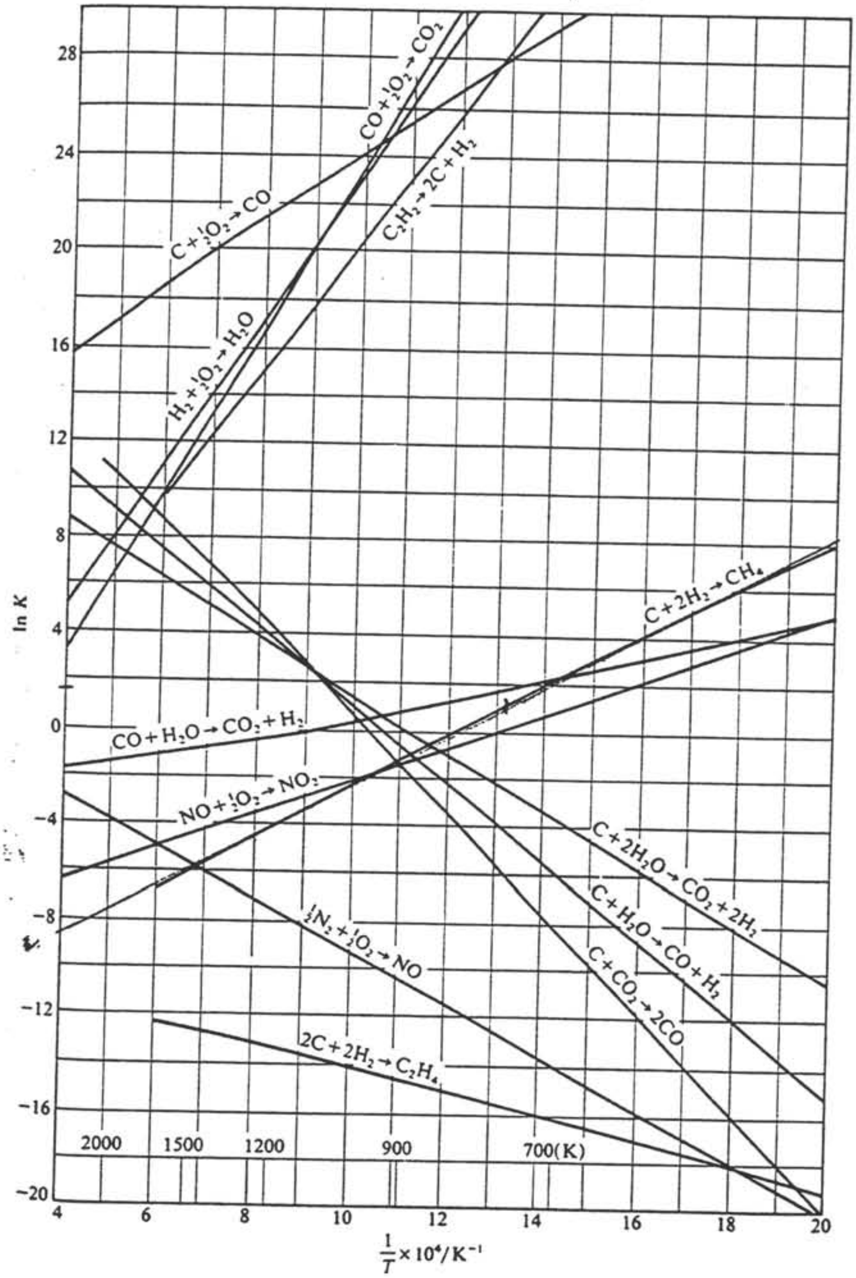


Figure 3.2. Equilibrium constants as a function of temperature for some common reactions.

3.1.4. Necessary energy input in the reformer tubes.

Introduction.

Heat transfer in the reformer is important. Therefor we want to know how much energy is approximately needed to heat the gas and to let the reactions take place. The extent of conversion of the two most important reactions can be calculated with the Mercury program, given in appendix 3.2. In this program the higher alkanes are assumed to be immediately converted into methane before participating in the proces. After the higher alkanes being converted, the total energy needed for the (real) conversions and heating can be calculated.

Hydrogen and air are burned to supply the energy, needed for the reactions in the reformer. The feed is preheated to 760.15 K. It then enters the reformer, where the higher alkanes are converted into CH_4, according to reaction (3.14). These reactions are endothermic. We have to devise a path, for purposes of calculation, to proceed from reactants (here the higher alkanes) at 760.15 K to product (here CH_4), also at 760.15 K. Since data are available for the standard heats of reaction at 298.15 K, the most convenient path is the one which includes the reactions at 298.15 K.

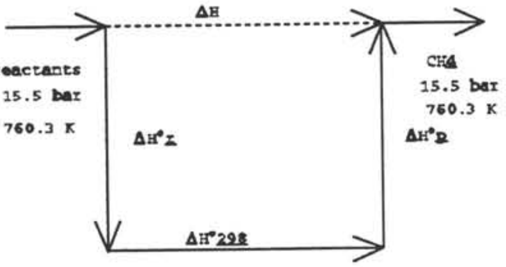


Figure 3.3. Path for calculation first reactions

The dashed line represents the actual path, with enthalpy change ΔH. Since this enthalpy change is independent of the path chosen, equation (3.8) is valid.

$$\Delta H=\Delta H^{\circ}{}_{R}+\Delta H^{\circ}{}_{298}+\Delta H^{\circ}{}_{P} \tag{3.8}$$

For the calculation of ΔH°_{298}, reaction (3.14) has to be considered. The calculation of ΔH°_{r} means that first of all we have to convert a real gas into an ideal gas, see equation 3.14. This enthalpy change is H^R. Secondly we have to "cool" the now ideal gas at 760.15 K to 298.15 K. For ΔH°_{p} it is the other way around, which means that after the reaction, the product CH_4 is "warmed" as an ideal gas, and then made a real gas at 15.5 bar and 760.15 K.

Approximate results of H^R for mixtures can often be obtained with critical parameters for the mixture and a simple linear mixing rule for the acentric factor. Since values for the actual critical properties T_c and p_c for mixtures are rarely known, the pseudoparameters T_{pc} and p_{pc} are used, determined again by a simple linear mixing rule. Thus by definition,

$$T_{pc}=\Sigma y_i * T_{ci} \tag{3.9}$$

$$p_{pc}=\Sigma y_i * p_{ci} \tag{3.10}$$

$$\omega=\Sigma y_i * \omega_i \tag{3.11}$$

The pseudoreduced temperature and pseudoreduced pressure, which replace T_r and p_r, are determined by

$$T_{pr}=\frac{T}{T_{pc}} \tag{3.12}$$

and

$$p_{pr}=\frac{p}{p_{pc}} \tag{3.13}$$

Thus, for a mixture at a given T_{pr} and p_{pr} we may determine a value of H^R using the following equation:

$$\frac{H^R}{R*T_{pc}}=p_{pr}*[B^0-T_{pr}*\frac{dB^0}{dT_{pr}}+\omega*(B^1-T_{pr}*\frac{dB^1}{dT_{pr}})] \tag{3.14}$$

$$B^0=0.083-\frac{0.422}{T_{pr}^{1.6}}$$

$$B^1=0.139-\frac{0.172}{T_{pr}^{4.2}}$$

$$\frac{dB^0}{dT_{pr}}=\frac{0.675}{T_{pr}^{2.6}}$$

$$\frac{dB^1}{dT_{pr}}=\frac{0.722}{T_{pr}^{5.2}}$$

After this the enthalpy change has to be calculated after "cooling" the stream from 760.15 K to 298.15 K via the ideal path. This can be done with equation (3.15):

$$\Delta H^{ig} = (\Sigma n_i * c_{p_{mh,i}}) * (T_2 - T_1) \tag{3.15}$$

Here n_i is the number of moles of each higher alkane that enters the reformer in one hour. This because the flows are given in moles per hour, and for the SI unit of enthalpy only mole-numbers are of interest here.

$$c_{p_{mh,i}} = R * (A_i + B_i * T_{am} + \frac{C_i}{3} * (4 * T_{am}^2 - T_1 * T_2) + \frac{D_i}{T_1 * T_2}) \tag{3.16}$$

with

$$T_{am} = \frac{T_1 + T_2}{2}$$

So now $\Delta H°_R$ is known:

$$\Delta H°_R = \Delta H^R + \Delta H^{ig}$$

In general a chemical reaction can be written as

$$|\nu_1| A_1 + |\nu_2| A_2 + \cdots \rightarrow |\nu_3| A_3 + |\nu_4| A_4 + \cdots$$

where $|\nu_i|$ are stoichiometric coefficients and A_i chemical formulas. The species on the left are reactants; those on the right are products. We adopt a sign convention for ν_i that makes it

positive (+) for products

negative (-) for reactants

The ν_i with their accompanying signs are called stoichiometric numbers. So in reaction (3.3)

$\nu_{CH4} = -1$ $\nu_{H2O} = -1$ $\nu_{CO2} = 1$ $\nu_{H2} = 3$

This sign convention allows the definition of a standard heat of reaction to be expressed mathematically by the equation:

$$\Delta H_{298}° = \Sigma \nu_i * H_{298}°{}_i \tag{3.17}$$

where $H°_i$ is the enthalpy of species i in its standard state and the summation is over all products and reactants. The standard-state enthalpy of a chemical compound is equal to its heat of formation plus the standard-state enthalpies of its constituent elements. If we arbitrarily set the standard-state enthalpies of all elements equal to zero as the basis of calculation, then the standard-state enthalpy of each compound is its heat of formation. In this event, $H°_{298,i} = \Delta H°_{fi}$ and (equation 3.18) becomes

$$\Delta H^\circ_{298}=\Sigma\nu_i*\Delta H^\circ_{fi} \tag{3.18}$$

where the summation is over all products and reactants. We here assume that the higher alkanes are all converted in CH_4 at a temperature of 760.15 K.

After this the enthalpy change for the product CH_4, can be calculated. When this is "heated" and "made" a real gas, the same formulas can be used as for the reactants. Only T_1 and T_2 are switched. Now also ΔH^P can be calculated.

$$\Delta H^\circ_p=\Delta H^P+\Delta H^{ig} \tag{3.19}$$

Because the flow of these higher alkanes is relatively small, it can be expected that the total heat needed so far is not very much, but for significant reasons we must look at this as well.

The CH_4 formed by these reactions can be added to the amount of CH_4 already available in the feed. At this point we are able to look at the main reactions occurring in the reformer and which are mainly of interest for the heat balance of the reformer. Figure 3.4 represents the way we modelled the problem, that is, how to calculate the required enthalpy change ΔH between entering gas and leaving gas.

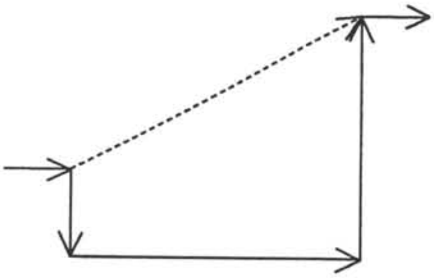


Figure 3.2. Path of main reactions

The calculations are about the same as those for the higher alkanes, that is why the formulas mentioned above can be used. This means that we also have to convert the real gas into an ideal gas, then "cool" to 298.15 K, let the reactions take place, and "warm" the products formed here to 1133.15 K. The calculations are performed with the program *mathcad*. This can be found in appendix 3.1.

3.1.4. The overall heat transfer coefficient.

The heat transfer in the reformer from the burner gas through the tubes to the process gas is limiting. In order to produce more carbon monoxide there are, in case of the reformer, three possible ways to do so. The first and most obvious option is a change in the reformer feed. The question then is: when will the heat transfer become limiting. The second option is to change the material the tubes are made of. The better the tube material conducts heat or the higher the service temperature of the tube, the more carbon monoxide can be produced. The third option is a combination of the two options mentioned above.

For the calculation of the transferred heat, equation (3.20) is used.

$$\phi_w = U * A * \Delta T_{ln} \tag{3.20}$$

with

Φ_w : Transferred heat (= heat or energy flow) (W)
U : Overall heat transfer coefficient (W/m^2/K)
A : Outside tube wall area for heat transfer (m^2)
$(\Delta T)_{ln}$: Logarithmic mean temperature difference (K)

The overall heat transfer coefficient expresses the combined effect of the whole series of resistances through which the transferred heat must flow. Generally there are three resistances. First of all the resistance for heat transfer from the outside fluid to the outside tube wall. Secondly the resistance for heat transfer through the tubes. Finally the third resistance will be from the inside tube wall to the inside fluid, see equation (3.21).

$$\frac{1}{U} = \frac{D_i}{D_u * h_u} + \frac{D_i}{2 * k_w} * \ln\frac{D_u}{D_i} + \frac{1}{h_i} \tag{3.21}$$

with

U : Overall heat transfer coefficient
D_u : External tube diameter
D_i : Internal tube diameter
h_i : Internal heat transfer coefficient
h_u : External heat transfer coefficient
k_w : Conductivity of tube material

In this particular case the outside tube wall temperature is known. This means that the outside resistance can be omitted.

In literature an empirical relation for the resulting equation for the calculation of the overall heat transfer coefficient was found, see equation (3.22) [3.6].

$$\frac{1}{U}=\frac{D_{ti}}{2*\lambda_{st}}*\ln\frac{D_{te}}{D_{ti}}+\frac{1}{a_w}+\frac{D_{ti}}{8*\lambda_{er}} \qquad (3.22)$$

with

$$a_w=\frac{8.694*\lambda^{\circ}_{er}}{D_{ti}^{\frac{4}{3}}}+\frac{0.512*\lambda_g*D_{ti}*Re_p*Pr^{\frac{1}{3}}}{d_p} \qquad (3.23)$$

$$\lambda_{er}=\lambda^{\circ}_{er}+\frac{0.111*\lambda_g*Re_p*Pr^{\frac{1}{3}}}{1+46*\frac{d_p^2}{D_{ti}^2}} \qquad (3.24)$$

As can be seen from equation (3.22), the overall heat transfer coefficient only deals with the resistances to heat transfer of the tube material, the process gas and the catalyst particles. This means that the "black box" considerably reduces. On the other hand, this implies that the outside tube wall temperature as well as the outside tube area have to be known. Indeed this is the case. Both parameters can be found or be calculated from the data given by KTI [3.7]. The logarithmic mean temperature difference, better known as the driving force for heat transfer, is given by equation (3.25).

$$\Delta T_{\ln}=\frac{(T1-t1)-(T2-t2)}{\ln\frac{T1-t1}{T2-t2}} \qquad (3.25)$$

3.1.5. Possible ways to increase the CO-plant capacity

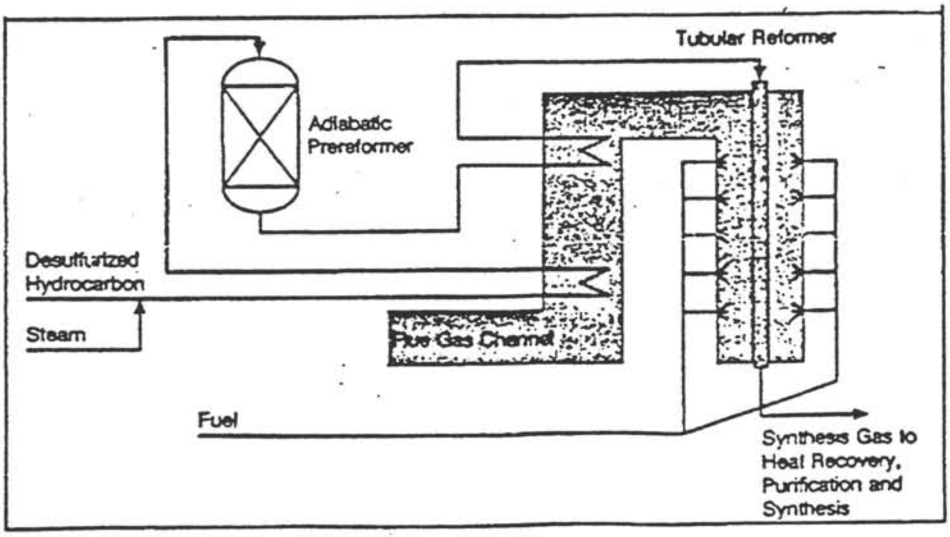
The heat transfer in the reformer tubes is the limiting factor. Therefore other feeds or other pieces of equipment must be used to increase the CO production.

3.1.5.1. Less N_2 in the feed

One possible way to increase the CO production is to reduce the amount of N_2 in the feed. Because N_2 is an inert gas, the energy needed to heat the nitrogen in the reformer tubes are pure wastes of energy. By removing the nitrogen this energy can be used for reaction energy, needed for the production of CO.

3.1.5.2. Using a pre-reformer

A possible way to increase the CO production is to put a pre-reformer ahead of the reformer. A pre-reformer is an adiabatic reactor [3.9], which converts all the higher hydrocarbons into a mixture of carbon oxides and hydrogen. The methane reforming and shift reactions are taking place to chemical equilibrium. A pre-reformer operates with a inlet temperature of 380-520 °C. Since the pre-reformer is an adiabatic reactor the temperature will decrease about 50 °C. After the pre-reformer the gas is heated again and sent to the reformer. A pre-reformer is packed with several types of catalysts. In top, where there is no risk of carbon formation, an alkali free catalyst is used (15%), then an intermediate alkali promoted catalyst (25%) and at the bottom again an alkali free catalyst is used (65%). A schematic arrangement of a pre-reformer in combination with a reformer is given in figure 3.5.



Case "C"
Installation of
adiabatic Pre-
Reformer with
heat of the
process gas both
before and after
the Pre-Rreformer

Figure 3.5. A schematic representation of a pre-reformer in a plant.

The advantages and disadvantages resulting from installation of a pre-reformer are summarized below:

- Low risk of carbon formation in the reformer even with higher hydrocarbons in the feed due to their conversion in the pre-reformer.
- All sulphur is removed from the feed in the pre-reformer.
- The steam to carbon ratio can be lowered in the reformer.
- The capacity of the plant can be increased, because there is an extra heat input after the pre-reformer.

Disadvantages of a pre-reformer:

- The pre-reformer will result in a larger pressure drop.
- The pre-reformer will increase the investment cost.

3.1.5.3. Adding CO_2 to the feed

A possible way to increase the CO production is to add CO_2 to the feed. While the reaction reaction enthalpy of the reaction of CO_2 into CO is 1/5th the reaction enthalpy of the reaction of CH_4 to CO (see Table 3.1), more CO can be produced with the same energy consumption in the reformer tubes. An other advantage is that CO_2 reacts with deposited coke to form CO (reaction 3.9), so the steam to carbon ratio can probably be lowered. The steam to carbon ratio can also be lowered because during the reaction of CO_2 to CO also water is formed (reaction 3.4). A disadvantage of this method is the price of CO_2 which is about twice that (per mole) of CH_4. Following the patent of Green [3.10] the H_2 to CO_2 ratio must be close to one.

3.2.Calculations and results

3.2.1.Design

Simulation with Aspen

The reformer was first simulated with the design concentrations and specifications (appendix 5). These data correspond to a production of 1220 kg/h CO. The results of this simulation can be found in appendix 5 and in Table 3.3.

Table 3.3. The heat duties of the heat exchangers, calculated with the design feed.

equipment	heat duty (10^5 W) design
H-2101	41.7807
H-2102	4.3005
H-2103	8.0790
H-2104	2.7157
H-2105A	4.4251
H-2105B	5.4867
H-2106	6.5278
H-2107	18.3583
V-2101	-0.4166
V-2103	4.3241

Heat transfer in the reformer tubes

The temperature gradient inside and outside (tube wall) the tubes can be considered to be linear. The composition half-way is considered to be the average composition in the tubes from inlet to outlet. The conductivity, specific heat and the viscosity of the process gas are based on this composition, the average temperature and the average pressure. The composition half-way the tubes was determined with the mercury (appendix 3.2) program, with the assumption that K_3 is -10 °C, see also Table 3.4 for the composition of the gas half-way the tubes.

Table 3.4. Composition of the process gas half-way the tubes.

Comp.	Φ_{mol} kmol/hr	Percentage (mol%)	Φ_m kg/hr	Percentage (weight%)
H_2	78.0	0.263	155.2	0.029
CO_2	41.9	0.142	1840.8	0.344
CO	15.8	0.053	444.2	0.083
H_2O	119.9	0.405	2156.6	0.403
N_2	8.8	0.030	246.1	0.046
CH_4	31.7	0.107	508.4	0.095
	296.1	1.000	5351.3	1.000

In order to determine the energy flow, three parameters are needed, as can be seen from equation (3.20).

A (Outside tube area)

Information given by KTI [3.7].

$$A = 75\ m^2$$

$(\Delta T)_{ln}$ (Logarithmic mean temperature difference)

Can be determined with equation (3.25) and Figure (3.6) [3.6].

$$(\Delta T)_{ln} = \frac{(720-487)-(925-860)}{\ln\frac{720-487}{925-860}} = 132K \qquad (3.25)$$

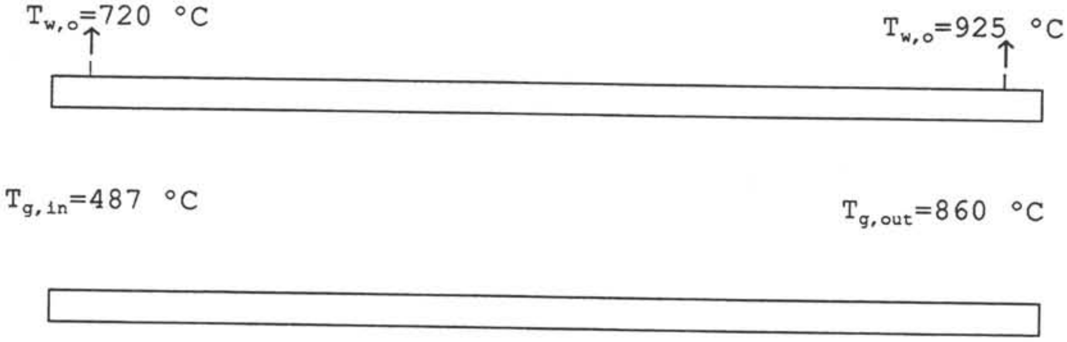


Figure 3.6. Temperature profile of the reformer tubes.

U (Overall heat transfer coefficient)

Can be determined with equation (3.21). See for the results of the calculation of the coefficient appendix 3.3.

U = 448 W/m^2/K

This results in the following energy flow.

$$\phi_w = U * A * (\Delta T)_{ln} = 448 * 75 * 132 = 4.44 MW$$

The overall heat transfer coefficient can also be calculated, or rather be verified, by using equation (3.20) with the data given by KTI [3.7].

$$\phi_w = U * A * (\Delta T)_{ln}$$

$$4.17 MW = U * 75 * 132$$

$\Longrightarrow$ U = 421 W/m^2/K

This means a difference of only 6 percent. Besides the accuracy of the equations used, the difference between the two overall heat transfer coefficients is most likely caused by depositions, mainly of carbon on the tube wall and the catalyst particles. The depositions have a lower thermal conductivity resulting in a lower energy flow. The calculated heat transfer coefficient can be corrected for the depositions with a so called foulingfactor.

Coke formation

With the iteration program given in appendix 3.2 the design (KTI) equilibrium constants are calculated and with figure 3.2 the thermodynamic equilibrium constants are determined, see Table 3.5. The calculated equilibrium constants are larger than the thermodynamic equilibrium constants, because with the equations used, no allowance is made for the higher alkanes and the higher temperatures near the tube wall.

Table 3.5. Thermodynamic and design (KTI) equilibrium constants for the coke deposition reactions.

T (°C)	P (bar)	Therm. $K_{3,8}$ (atm^2)	Therm. $K_{3,9}$ (-)	Design (KTI) $K_{3,8}$ (atm^2)	Design (KTI) $K_{3,9}$ (-)
487	15.00	0.30	365	0.498	618
500	14.88	0.41	221	0.637	390
550	14.41	0.86	40.4	1.53	75.3
600	13.94	1.92	9.97	3.37	17.8
650	13.47	4.06	4.06	7.17	5.35
700	13.00	6.36	1.00	15.1	1.95
750	12.53	13.5	0.30	32.9	0.874
800	12.06	24.5	0.135	77.3	0.484
850	11.59	34.8	0.052	198	0.336
860	11.50	40.4	0.045	240	0.318

Appendix 3.1. Reformer heat duty calculations.

Appendix 3.2. Prediction of the streams and calculation of the equilibrium constants.

Appendix 3.3. Calculation of the design (KTI) overall heat transfer coefficient.

Literature

3.1. J. Xu and G.F. Froment, A.I.Ch.E.Jl, 1989 **35** 88.

3.2. M.H. Hyman, Hydrogen Processing and Petroleum Refiner, 1968 **47** 131.

3.3. E.S. Wagner and G.F. Froment, Hydrogen Processing, July 1992, 69.

3.4. J.R. Rotrup-Nielsen, Science and Technology, Springer Verlag, 82 (1983), vol. 5.

3.5. J.M. Smith, H.C. van Ness, Introduction to Chemical Engineering Thermodynamics, 509 (1987).

3.6. J.C. De Deken, E.F. Devos and G.F. Froment, Steam reforming of natural gas, Chem. React. Eng., 1982 281.

3.7. Process data sheets for the reformer of CO plant II, KTI.

3.8. Design and operating manual.

3.9. L. Storgaard and H. Topϕe, Hydrogen Processing, 1992 137.

3.10. R.V. Green, U.S. US Patent 3,943,236 (1976).

4.2 CO_2 removal section

The CO_2 removal section involves the CO_2 removal including the water removal, the CO_2 compression and the desulphurisation (see appendix 2, flowsheet 200-FP-41/45). We will look at each of these different functions, including their operation units, separately.

The first step is to determine which units are indispensable with regard to the model. We therefore have to look at the main process streams. It is not necessary to sum up every unit in ASPEN+, because the operation units given by ASPEN can perform several functions in one block. One of these functions is the pressure of the process streams. It is usually provided by pumps or compressors. These types of equipment have been left out as much as possible in order to simplify the flowsheet.

The CO_2 removal section consists of several main operation units. Besides the two packed columns there are some auxiliary units like a reboiler, heat exchangers and knock out drums (K.O. drums). The water cooled heat exchangers (H2108, H2111, H2112) are modelled as HEATER blocks. For these blocks one can specify output temperature and pressure. The other heat exhangers (H2109A, H2109B) are modelled as one block. The block we used is the HEATX block. This block has two in- and outlet streams for the cold and hot streams. For the reboiler (type kettle reboiler) we had to use a separate block. This because ASPEN simulates a reboiler as a part of the column, where the heat stream is given. In order to get this heat stream we placed a HEATER block where the process stream entered the reboiler. Then we connected this heat stream to the reboiler.
The K.O. drums are ordinary vessels where the mixed phases are separated into a gas stream and a liquid stream. All these types of equipment are modelled by a FLASH2 block. This is a block where normally the input is flashed, by pressure drop or temperature difference. This becomes a K.O. drum when these variables are kept constant. A special approach is needed for the MEA vent tank (V2110). It does officially not contribute to the separation process but because it has some losses which are leaving the entire proces we had to simulate it as a separate block. For this block the SEP block was used in which the components that were leaving the process stream could be specified.
The two packed columns (V2105, V2106), which are the driving forces behind this section, are modelled as two RADFRAC blocks. These blocks use rigorous fractionation calculations and can also be used for absorbers and strippers. In case of the stripper it is necessary to specify a reboiler duty in order to let ASPEN know a reboiler is connected.
All the streams which are bypassing the main process, like the streams to and from the mixer (M2104) and the aeration/inhibitor injection tank (V2111), are left out because they are not taking part in the main process. This means that the equipment connected to these streams are not modelled either.

In the CO_2 compression section the CO_2 rich gas is compressed by several two stage reciproking compressors (K2103). These are presented in the model as two COMPR blocks. The only problem is that ASPEN is not equiped with this type of compressor. Therefore the most flexible one is used which is the polytropic cenrifugal compressor.
The interstage and final cooling, provided by two water cooled heat exhangers (H2113,

H2114), are, like in the CO_2 removal section, modelled as HEATER blocks. For the K.O. drums (V2113, V2114) the same blocks were used as the blocks applied in the CO_2 removal section, serving the same purpose. All other auxiliary equipment, like suction dampers and filters, were left out because of the earlier mentioned reason.

The desulphurisation of the process stream is achieved by a catalyst which is packed in a vessel (V2115). Because the stream has only traces of sulphur and the feed (in ASPEN) has no sulphur components what so ever, the unit is totally neglected even though it causes a small pressure drop.

For a total view of the modelled equipment and flows in this section see appendix 4.

4.3 Drying section

This section has two main functions, namely the compression of the process gas and the removal of the last traces of water and CO_2 (see appendix 2, flowsheet 200-FP-42). This is necessary for usage of the process gas in the cryogenic separation section. These functions, with their operation units, will be discussed also separately.

The compression of the process gas is achieved by a reciproking compressor (K2104). This is presented in the model as a COMPR block. Because of the earlier mentioned problem the polytropic cenrifugal compressor is chosen.
The final cooling, provided by a water cooled heat exhanger (H2115), is again modelled as a HEATER block. For the K.O. drums (V2116, V2117) the FLASH2 blocks where used. All other auxiliary equipment, like suction dampers and filters were again left out because of the reason mentioned above.

The actual drying of the process stream occurs in three columns filled with a zeolite mole sieve. Two of these columns are actually working while the third one is being regenerated by a H_2 rich stream. Even though the process is complicated because of the different residence times, valves and controlling sequences, this part of the process is modelled by just one block. Because of the simplicity of the drying process itself and the preference of the mole sieve a SEP block is chosen in which the several amounts of the compents in the different streams are specified.

For a total view of the modelled equipment and flows in this section see appendix 4.

4.4 Cryogenic separation section (coldbox)

The goal of this section is to separate the CO from the other components in the process stream. This is done by cryogenic separation which occurs in a special unit called the coldbox. It is then compressed and ready for further usage in other processes on the site (see appendix2, flowsheet 200-FP-43/44). Again the section is discussed in these two above mentioned parts.

The coldbox is probably the most complicated unit of the plant. Not only because of the fact that the separation ocurrs at extremly low temperatures but also because of the complexity of the equipment, the recycle streams and the heat transfer in this unit. It is therefore important how the different streams are modelled. The model is primarily based on the compositions of the different streams. The heat transfer between the streams and units are modelled in such way it only serves a controlling purpose. The coldbox consists of five operation units, namely one heat exchanger and four columns with reboilers and/or condensors. One of the columns is rather complicated. This because of the huge condensor part in the top.

The feed gas cooler (E21) is modelled as a MHEATX block. This block has several in- and outlets and therefore very suitable for this purpose. All other heat transfer units, like reboilers and condensors (E22, E23U/L, E24, E25, E27), are, for the same reason mentioned in paragraph 4.2, presented as HEATER blocks. These different blocks however are not connected to the corresponding reboilers or condensors because of the complexity of the heat balance.

The CO-wash column (T21) consists of two parts. The upper part where the vaporized liquid is condensed and washed and the lower part where the actual mass transfer takes place. Because of this obvious difference in duty the column is modelled in three separate parts. The lower part is modelled as a RADFRAC block and the upper part as two FLASH2 blocks (there are two different temperatures present). The way the mass flows in the upper part however is difficult to predict. Therefore a simple construction is made by returning the liquid flow of the second FLASH2 block to the first FLASH2 block.

The other columns (T22, T23, T24) are also entered as RADFRAC blocks with different reboiler and/or condensor specifications. The CO/CH_4 splitter (T22) has a reboiler and the feed flash column (T23) has a condensor. Therefore the condensor (T22) and the reboiler duties (T23) are specified. The reflux flash column (T24) has both.

Other equipment, like (controlling) valves, where modelled as HEATER blocks. Also the decision was made to leave out the expansion machines because they do not contribute to the separation process but only to the state in which the H_2 rich gas is leaving the CO-wash column (T21).

The CO rich product gas is compressed by several two stage reciproking compressors (K2105). These are modelled as two COMPR blocks. The interstage- and final cooling, also provided by two water cooled heat exhangers (H2118, H2119), are, like in the CO_2 compression section, modelled as HEATER blocks. All other auxiliary equipment like suction dampers and filters were again left out.

For a total view of the modelled equipment and flows in this section see appendix 4.

Literature

4.1 Design and operating manual carbon monoxide plant II, General Electric Plastic, KTI.

4.2 Aspen Plus User Guide, 1988, Aspen Technology, Inc.

5.SIMULATION AND CALCULATION OF THE STREAMS IN THE PLANT

In this chapter the simulation of the different options as described in chapter 3 will be discussed. First the design values are being simulated in order to get good settings for the different blocks, to simulate the different possibilities to increase the capacity. Furthermore the coke deposition and the heat transfer coefficient are investigated.

5.1 Design

For simulation of the process the design data of the KTI and Linde flowsheets were used (see appendix 2). The pressure, temperature and composition of the streams were pursued as much as possible. The different blocks are specified with a temperature (difference) and a pressure (drop) as much as possible. The blocks with other specifications are discussed separately.

In the reformer section the reformer tubes, simulated by a Gibbs reactor, contain one or more reactions that do not reach equilibrium, a restricted chemical equilibrium calculation must be performed and a set of linearly independent reactions involving all components present in the system must be supplied. In this case reaction 5.1 has its equilibrium at 840 °C as calculated in the Design and Operating Manual [5.1]. All other reactions reach equilibrium at the reactor temperature (design temperature 860 °C). In order to give a temperature approach for reaction 3.3 the following nine reactions were supplied to Aspen:

$CH_4 + H_2O \rightarrow CO + 3H_2$ $\quad T_{app.} = -20°C$ (5.1)

$CO + H_2O \rightarrow CO_2 + H_2$ (5.2)

$C_2H_6 + H_2 \rightarrow 2CH_4$ (5.3)

$C_3H_8 + 2H_2 \rightarrow 3CH_4$ (5.4)

$C_4H_{10} + 3H_2 \rightarrow 4CH_4$ (5.5)

$C_5H_{12} + 4H_2 \rightarrow 5CH_4$ (5.6)

$C_6H_{14} + 5H_2 \rightarrow 6CH_4$ (5.7)

$O_2 + 2CO \rightarrow 2CO_2$ $\quad T_{app.} = -860°C$ (5.8)

$N_2 + C_4H_{10} + 2H_2O \rightarrow 2MEA$ $\quad T_{app.} = 2000°C$ (5.9)

Although the last two reactions will not occur in the reformer these reactions are given, because the components O_2 and MEA appear further on in the process. To make sure that none of these reactions will take place a large temperature approach is given.

For the heat exchangers in the reformer section, were steam is generated, the vapor fraction is given in stead of the temperature. The flash2 block is simulated with a temperature and a vapor fraction in the outlet stream. For the splitters the mass fractions and a pressure drop are specified.

All attempts to split the steam stream failed, therefore it was necessary to disconnect these streams. The H_2 rich stream to the burners is also not connected to simplify the simulation process. This could be done, because the stream does not contribute to the actual process.

In the CO_2 removal section the separation block is specified with the component fractions, calculated from the design flowsheets, and a pressure drop of zero. For the absorber (V2105) the number of stages and the reboiler and condensor duty are specified (both zero). The number of stages required are defined by pursuing the design top stream composition. The stripper (V2106) is simulated with the number of stages, the condensor duty (zero) and an estimation of the reboiler duty. The final value of the reboiler duty is found by simulating the column with a spec on the mass flow of CO_2 leaving the top.

Between the two columns (MEA) is, in the original flowsheet, a loop in which the MEA circulates. Aspen, however, does not converge if this loop is closed. This because a little bit of MEA and water is transferred to other streams. This can be solved by entering a MEA buffer or by disconnecting the loop. The last option is chosen.
An other difficulty occurs when the heater duty (H2110), which provides the duty for the reboiler, is connected to the column (V2106). The duties differ so much from each other that the desired separation is not possible. Therefore the heat stream is disconnected and the duty of the heater serves only a controlling purpose.

In the drying section only the separator has diviant specifications. The separation block is specified with component fractions, calculated from the design flowsheets, and a pressure drop of zero.

For the cryogenic separation section a heat duty of zero and a pressure drop is given for all modelled valves. The recycle H_2 rich stream to the reformer is given by a mass flow of H_2 in the splitter B1. For the columns first the condensor and reboiler duties, which are zero are given. Then the mass flow of the bottom is given to calculate the boilup or reflux ratios. With these ratios it is possible to replace several duties. This is done to keep the section as flexible as possible. Except for the T23, where a condensor duty is specified because of the fact that at least one (condensor or reboiler) duty has to be specified.

Difficulties in this section occured mainly with the heat balance and the connection of the heaters with the reboilers and condensors of the columns. Therefore these heat streams are not connected to each other. The main goal was to pursue the composition of the mass flows as they are given on the Linde design flow sheets. The duties of the heaters therefore serve only a controlling purpose. Another problem was that the Linde data, first used for the coldbox, did not correspond with the data on the KTI design flowsheets. Hence it was necessary to increase the flows until they matched the KTI design flows.

The results of the design simulation are given in appendix 5. The simulation data correspond with the KTI data. There is only a difference between the CO product stream no. 226 (± 1 kmol N_2 too much) and in the H_2 rich stream no. 228 (too little N_2) coming out of the coldbox.

The heat flow going into the reformer tubes given by Aspen (4.19 MW), does also agree with the KTI value. Because the streams are almost the same as the given design streams by KTI, the already calculated heat transfer coefficient (448.3 W/(m^2K) is maintained (paragraph 3.1.4). The calculated heat transfer coefficients will be compared with each other and be used to make a prediction of the heat flow by other feed streams. Assuming a constant temperature of the outside tube wall (constant ΔT_{ln}).

The CO design production rate, calculated by Aspen is 1225 kg/h.

5.2 Actual

5.2.1 Simulation

The actual amount of CO produced is 1.26 ton/hr, this is about 3.2 % higher than the design production (1.22 ton/hr). With the iteration program described in appendix 3 the necessary increase in the amount of feed is calculated (using the multiplication factor). This calculation leads to a feed increase of ± 2.9 %. Therefore all design feed streams are increased with 2.9 %. Also some block specifications need to be increased, because of the increased feed. Namely one condensor duty, one mass flow over a top of a column and the amount of H_2 recycled (change in splitter). The other block specifications are given in such a way that no change in the specifications is needed when all the feed streams are increased with the same fraction. The most important in and out going streams are given in appendix 5.

The streams that are increased with 2.9 % are : 201, 205, 253, 260, 281 and BIN (stream 251 is not increased with 2.9 %, resulting in a too high temperature of stream 7).
The block specifications that are increased with 2.9 % are : the condensor duty of column T23, the mass flow of CO_2 over the top of column V2106 and the mass flow of H_2 recycled (change in splitter B1).

5.2.2 Calculations using simulated streams

For calculation of the heat transfer coefficient, the stream which enters the reformer is used. The composition of this stream is given in table 5.1 With this stream the composition of the stream half way the reformer is calculated using the iteration program of appendix 3 and by assuming a linear temperature and pressure profile in the refomer. With this composition the heat transfer coefficient is calculated in the same way as carried out in paragraph 3.1.4. This results in a heat transfer coeficient of 458.6 W/(m^2K). The heat flow, calculated by Aspen, in the reformer tubes (H2101) is 4.32 MW. The actual heat transfer coefficient will be compared to the heat transfer coefficient of the reformer tubes using other feed streams in order to make an estimation of the new heat flow.

Table 5.1 Stream composition in the reformer tubes

STREAM Comp.	207 stream entering the tubes (kmol/hr)	stream half way the tubes (kmol/hr)	208 stream going out the tubes (kmol/hr)
H_2	9.09	80.55	153.49
CO	7.11	16.19	55.11
CO_2	31.19	42.91	31.90
N_2	8.92	8.92	8.92
O_2	0.00	0.00	0.00
CH_4	49.13	32.63	4.72
C_2H_6	1.56	0.00	0.00
C_3H_8	0.20	0.00	0.00
C_4H_{10}	0.08	0.00	0.00
C_5H_{12}	0.02	0.00	0.00
C_6H_{14}	0.03	0.00	0.00
MEA	0.00	0.00	0.00
H_2O	155.86	123.35	106.45
AR	0.00	0.00	0.00
T (°C)	487.0 0	673.50	860.00
P (bar)	15.00	13.25	11.50

The equilibrium coefficients of the coke deposition reactions 3.8 and 3.9 are calculated using stream 207, the iteration program of appendix 3 (calculating the composition) and the equations mentioned in chapter 3.1.2, assuming a linear temperature and pressure profile in the reformer tubes. In table 5.2 the thermodynamical equilibrium constants are given for the coke deposition and the calculated ones of the equilibrated gas. To prevent coke deposition the actual values need to be higher than the thermodynamic values. Since the theory used (see 3.1.2) is a rule of thumb, the actual values should be taken as safety reference when the reformer feed is changed.

As can be seen in table 5.2 the current process operates in a safe region since the actual k-values are at least 1.3 times bigger than the thermodynamic k-values.

Table 5.2 Thermodynamic and actual equilibrium constants for the coke deposition reactions.

T (°C)	P (bar)	Therm. $K_{3.8}$ (atm^2)	Therm. $K_{3.9}$ (-)	Actual $K_{3.8}$ (atm^2)	Actual $K_{3.9}$ (-)
487	15.00	0.30	365.00	0.50	620.00
500	14.88	0.41	221.00	0.64	391.00
550	14.41	0.86	40.40	1.53	75.50
600	13.94	1.92	9.97	3.38	17.90
650	13.47	4.06	4.06	7.18	5.35
700	13.00	6.36	1.00	15.10	1.95
750	12.53	13.50	0.30	32.90	0.87
800	12.06	24.50	0.13	77.20	0.48
850	11.59	34.80	0.05	197.00	0.33
860	11.50	40.40	0.04	240.00	0.31

Aspen calculates an actual CO production rate of 1260 kg/hr, which is the same as the given actual production rate.

5.3 Less N_2 in the feed

5.3.1 Simulation

For the simulation a natural gas stream with less N_2 is used. The N_2 is removed using a simulation of a Linde patent (paragraph 8.2.2.2). Using this patent ± 80 % of the N_2 is removed. Because the mole fraction of N_2 isn't large in most of the streams, the other streams and block specifications are kept the same as with the actual simulation. The most important in and out going streams are given in appendix 5.

5.3.2 Calculations using less N_2 in the feed

For the feed with less N_2 also the heat transfer coefficient is calculated using the stream half way given in table 5.3 (see 5.3.1)
This results in a heat transfer coeficient of 450.8 W/(m^{2}K). The heat flow, calculated by Aspen, in the reformer tubes (H2101) is 4.29 MW. Compared with the actual value, the heat transfer coefficient has decreased ± 4 %. This will also decrease the heat flow with ± 4 %, resulting in a heat flow of : 0.96*4.32=4.15 MW. So the calculated heat flow by Aspen will not be reached, resulting in a lower temperature of the stream coming out of the reformer tubes. Which will cause a lower production of CO.

Table 5.3 Stream composition in the reformer tubes

STREAM Comp.	207 stream entering the tubes (kmol/hr)	stream half way the tubes (kmol/hr)	208 stream going out the tubes (kmol/hr)
H_2	8.61	79.90	152.76
CO	6.05	15.78	54.29
CO_2	31.19	42.32	31.64
N_2	1.78	1.78	1.78
O_2	0.00	0.00	0.00
CH_4	49.21	32.64	4.80
C_2H_6	1.56	0.00	0.00
C_3H_8	0.20	0.00	0.00
C_4H_{10}	0.08	0.00	0.00
C_5H_{12}	0.02	0.00	0.00
C_6H_{14}	0.03	0.00	0.00
MEA	0.00	0.00	0.00
H_2O	155.85	123.87	106.69
AR	0.00	0.00	0.00
T (°C)	487.00	673.50	860.00
P (bar)	15.00	13.25	11.50

The equilibrium coefficients of the coke deposition reactions 3.8 and 3.9 are calculated as in chapter 5.2.2 and given in table 5.4.

As can be seen in table 5.4 the process, with less N_2 in the feed, operates in a safe region with k-values, which are almost the same as the actual k-values.

Aspen calculates a CO production rate of 1253 kg/hr. This is lower than the actual production rate (1260 kg/hr) and will decrease further due to the too high heat flow. So the removal of N_2 out of the feed gas is no good solution for increasing the production capacity. An advantage of the N_2 removal is the big increase in purity of the CO product stream.

Table 5.4 Thermodynamic and equilibrium constants for the coke deposition reactions with less N_2.

T (°C)	P (bar)	Therm. $K_{3.8}$ (atm^2)	Therm. $K_{3.9}$ (-)	Less N_2 $K_{3.8}$ (atm^2)	Less N_2 $K_{3.9}$ (-)
487	15.00	0.30	365.00	0.50	629.00
500	14.88	0.41	221.00	0.65	397.00
550	14.41	0.86	40.40	1.56	76.60
600	13.94	1.92	9.97	3.43	18.10
650	13.47	4.06	4.06	7.27	5.41
700	13.00	6.36	1.00	15.20	1.96
750	12.53	13.50	0.30	33.10	0.87
800	12.06	24.50	0.13	77.20	0.48
850	11.59	34.80	0.05	197.00	0.33
860	11.50	40.40	0.04	239.00	0.32

5.4 Capacity increase of 20 % by adding CO_2 to the feed.

5.4.1 Simulation

Using the iteration and the heat duty calculation program of appendix 3 an estimation is made of the feed streams necessary to increase the CO production by 20 %. This is done by assuming a constant heat flow (actual value). Using these streams an estimation is made of the needed changes in the actual streams and block specifications. Extra pressure drops due to the increased mass flow are neglected.
This results in changing the following streams : 201, 205, 251, 253, 260 and 281 (appendix 5).
The changes in block specifications are:
- mass flow of H_2 recycled, splitter B1 (more H_2 needed in the feed)
- condenser duty of block T23 (higher CO flow)
- mass flow of CO_2 over the top of column V2106 (more CO_2 in the stream coming out of the reformer)
- the mass fractions of water (coming out of the steam drum) specified in block SPLIT (stream 208 which must be cooled down by making steam has become bigger)

The bigger H_2 recycle stream is let to the H_2-mix block, which in practise gives a stream to the desulphurizer with a too high fraction of H_2 (more than 10 mole %). An other assumption is the input of CO_2 into the natural gas stream. In practise the CO_2 can better be mixed with the CO_2 recycle stream.

The new block specifications are given in table 5.5 and all the streams are given in appendix 5.

Table 5.5 Changed block specifications.

Block	block type	changed specification	stream	new value
B1	splitter	mass flow	202	97.0 kg/hr
SPLIT	splitter	mass fraction	A C E G	 0.13586 0.16845 0.63000
T23	radfrac	condensor duty		-5923 W
V2106	radfrac	mass flow of CO_2 over the top	213	1662 kg/hr

5.4.2 Calculations using a CO_2 rich feed stream.

Also for the CO_2 rich feed the heat transfer coefficient is calculated (see 5.3.1) using the stream half way the reformer tubes given in table 5.6.
This results in a heat transfer coefficient of 500.2 W/(m^{2}K) due to the higher Reynolds number. The heat flow, calculated by Aspen, in the reformer tubes (H2101) is 4.37 MW. Compared with the actual value, the heat transfer coefficient has increased ± 9 %. This will also increase the heat flow with ± 9 %, resulting in a heat flow of : 1.09*4.32 = 4.71 MW. So the calculated heat flow by Aspen is lower than the calculated one, resulting in a higher temperature of the stream coming out of the reformer tubes. Which will give a higher production of CO. But it must be considered that no temperature approach is used for the CO_2 conversion. With the new CO_2 rich feed streams a temperature approach may be needed, because more CO_2 must be converted in the reformer tubes. When a temperature approach is needed the CO_2 recycle stream will be higher.
The velocity in the tubes has increased compared to the actual velocity, because the number of moles has increased. This can result in a higher temperature approach for both reactions 3.3 and 3.4. This results in a higher recycle stream and a lower CO production rate.

Table 5.6 Stream composition in the reformer tubes

STREAM Comp.	207 stream entering the tubes (kmol/hr)	stream half way the tubes (kmol/hr)	208 stream going out the tubes (kmol/hr)
H_2	52.40	79.90	170.53
CO	19.80	15.78	67.01
CO_2	51.65	42.32	37.07
N_2	8.49	1.78	8.46
O_2	0.00	0.00	0.00
CH_4	46.64	32.64	5.96
C_2H_6	1.43	0.00	0.00
C_3H_8	0.18	0.00	0.00
C_4H_{10}	0.07	0.00	0.00
C_5H_{12}	0.02	0.00	0.00
C_6H_{14}	0.02	0.00	0.00
MEA	0.00	0.00	0.00
H_2O	131.17	123.87	113.04
AR	0.00	0.00	0.00
T (°C)	487.00	673.50	860.00
P (bar)	15.00	13.25	11.50

As can be seen in table 5.6 the stream coming out of the reformer is bigger compared with the actual stream. This may lead to some capacity increase in the MEA section (see paragraph 6.5).

The equilibrium coefficients of the coke deposition reactions 3.8 and 3.9 are calculated as in chapter 5.2.2 and given in table 5.7.

As can be seen in table 5.4 the current process operates in a somewhat less safer region with k-values, which are some smaller than the actual k-values. But with more CO_2 present in the reformer tubes, CO_2 is able to remove coke, so that the somewhat lower k-values can be accepted.
Aspen calculates a CO production rate of 1551 kg/hr, which is an increase of 23 %.

The mentioned influences on the CO production are hard to predict, but taking everything into account, the addition of CO_2 to the feed will be a good solution to increase the capacity of the plant.

Table 5.7 Thermodynamic and equilibrium constants for the coke deposition reactions for the simulation with CO_2 added to the feed.

T (°C)	P (bar)	Theory $K_{3.8}$ (atm^2)	Theory $K_{3.9}$ (-)	20% more CO $K_{3.8}$ (atm^2)	20% more CO $K_{3.9}$ (-)
487	15.00	0.30	365.00	0.43	545.00
500	14.88	0.41	221.00	0.56	344.00
550	14.41	0.86	40.40	1.36	66.70
600	13.94	1.92	9.97	3.00	15.90
650	13.47	4.06	4.06	6.39	4.76
700	13.00	6.36	1.00	13.50	1.73
750	12.53	13.50	0.30	29.20	0.77
800	12.06	24.50	0.13	67.90	0.43
850	11.59	34.80	0.05	172.00	0.29
860	11.50	40.40	0.04	229.00	0.28

5.5 Capacity increase of 20 % by adding CO_2 to the feed and using a pre-reformer.

5.5.1 Simulation

A pre-reformer converts all higher alkanes, with the advantage that in the reformer the k-values can be lowered and that an extra heat flow can be added to the stream after the pre-reformer. A steam to carbon ratio of 0.4 can be taken in a pre-reformer feeded with natural gas [3.9], the ratio used in the simulation is 0.5. In the reformer the k-values are lowered by adding less steam to the feed. This results in a lower CO_2 recycle, a higher CH_4 recycle and a lower mass flow coming out of the reformer. With a pre-reformer the feed can be taken higher, resulting in a ± 5 % higher CO production.

With the capacity increase using the CO_2 rich feed stream, the MEA section has to be changed. This is because of the higher mass flow coming out of the reformer. Using a feed stream with added CO_2 and a pre-reformer it can be possible to have an increased CO production without the need to change the MEA section.

After the desulphurizer block a mixer is placed to add steam to the pre-reformer feed stream. After the mixer a heater is placed to get the wanted temperature (500 °C) at the inlet of the pre-reformer. For the simulation the pre-reformer is put after the heater and is simulated with a Gibbs reactor. The heater can be left out when the right temperatures are chosen in the heat exchangers, heated by the reformer flue gasses. The extra CO_2 is added to stream 205. In practise the extra CO_2 can better be added to the CO_2 recycle stream (temperature of stream 205 is too high).

The following streams are changed compared with the actual simulation : 201, 205, 251, 253, 260 and 281 (appendix 5).
Also some new streams are entered to connect the new blocks namely stream : 142, 143, 144, 146 and 147 (appendix 5).

The block specification which are changed are :
- mass flow and streams of the recycled H_2, splitter B1 (more H_2 needed in the feed)
- condenser duty of block T23 (higher CO flow)
- mass flow of CO_2 over the top of column V2106 (less CO_2 in the stream coming out of the reformer
- the mass fractions of water (coming out of the steam drum) specified in block SPLIT (other streams to warm up)
- boilup ratio of block T22 (to get the CH_4 out of the feed, the CH_4 reclycle is bigger)
- the streams coming in block H_2O-mix (extra H_2 recycle stream is entered)

The added blocks are : B2, B3 and B5 (see appendix 4).

The block specifications are given in table 5.8 and 5.9 and all the streams are given in apppendix 5. In the product stream there is still too much CH_4 present (0.01 kmol), which mean that the boilup ratio of column T22 is still too high.

Table 5.8 Changed block specifications.

Block	block type	changed specification	stream	new value
B1	splitter	mass flow out	150 202 140	80.0 kg/hr 10.7 kg/hr
SPLIT	splitter	mass fraction	A C E G	0.08 0.10 0.704
T23	radfrac	condensor duty		- 6000 W
V2106	radfrac	mass flow of CO_2 over the top	213	1200 kg/hr
T22	radfrac	boilup ratio		6.0
H_2O-mix	mixer	extra stream coming in	140	

Table 5.9 Added block with their specifications

Block	block type	stream in	stream out	specification
B2	mixer	142 144	143	P_{out} = 18.5
B3	rgibbs	147	146	heat duty = 0 P_{out} = 15 bar
B5	heater	143	147	P_{out} = 18.2 T_{out} = 500 °C

5.5.2 Calculations

Also for the CO_2 rich feed combined with a pre-reformer the heat transfer coefficient is calculated (see 5.3.1) using the stream half way the reformer tubes given in table 5.10. This results in a heat transfer coeficient of 462.8 W/(m^{2}K). The heat flow, calculated by Aspen, in the reformer tubes (H2101) is 4.21 MW. Compared with the actual value, the heat transfer coefficient is almost the same. The calculated heat flow by Aspen is somewhat lower than actual heat flow. A temperature approach for the CO_2 reaction maybe needed (see paragraph 5.4.2). But taking everything into account the conversion calculated by Aspen should give a good estimation for the CO production.

As can be seen in table 5.10 the stream coming out of the reformer is looking to the total mass and mole flow, about the same compared to the actual stream. So no capacity increase is needed in the MEA section (see paragraph 6.5).

Table 5.10 Stream composition in the reformer tubes

STREAM Comp.	207 stream entering the tubes (kmol/hr)	stream half way the tubes (kmol/hr)	208 stream going out the tubes (kmol/hr)
H_2	52.67	82.60	170.53
CO	6.92	17.38	63.40
CO_2	41.29	40.92	28.39
N_2	8.59	8.59	8.59
O_2	0.00	0.00	0.00
CH_4	51.79	41.69	8.21
C_2H_6	0.00	0.00	0.00
C_3H_8	0.00	0.00	0.00
C_4H_{10}	0.00	0.00	0.00
C_5H_{12}	0.00	0.00	0.00
C_6H_{14}	0.00	0.00	0.00
MEA	0.00	0.00	0.00
H_2O	122.15	112.42	91.46
AR	0.00	0.00	0.00
T (°C)	487.00	673.50	860.00
P (bar)	15.00	13.25	11.50

The equilibrium coefficients of the coke deposition reactions 3.8 and 3.9 are calculated as in chapter 5.2.2 and given in table 5.11.

As can be seen in table 5.11 the process operates in a less safer region comparing the k-values with the actual k-values. But since the higher alkanes are converted in the pre-reformer, it must be possible to accept the lower k-values.
Aspen calculates a CO production rate of 1507 kg/hr, which is an increase of 20 %.

Table 5.11 Thermodynamic and equilibrium constants for the coke deposition reactions for the simulation using a pre-reformer and CO_2 added to the feed

T (°C)	P (bar)	Theory $K_{3.8}$ (atm^2)	Theory $K_{3.9}$ (-)	20% more CO $K_{3.8}$ (atm^2)	20% more CO $K_{3.9}$ (-)
487	15.00	0.30	365.00	0.43	537.59
500	14.88	0.41	221.00	0.55	337.97
550	14.41	0.86	40.40	1.31	64.70
600	13.94	1.92	9.97	2.86	15.11
650	13.47	4.06	4.06	5.96	4.44
700	13.00	6.36	1.00	12.20	1.57
750	12.53	13.50	0.30	25.48	0.68
800	12.06	24.50	0.13	56.13	0.35
850	11.59	34.80	0.05	134.10	0.23
860	11.50	40.40	0.04	161.02	0.21

The adding of CO_2 to the feed in combination with a pre-reformer seems to be a good solution. Comparing to the solution with only extra CO_2 added to the feed, the advantage of using a pre-reformer is that the capacity of the MEA section need not be changed.

5.6 Conclusions

The capacity of the plant can be increased in two ways :

1. adding CO_2 to the feed

2. adding CO_2 to the feed in combination with a pre-reformer.

For the first option the MEA section must be changed. For the second option a pre-reformer must be installed. Which option is the best will depend on the costs (chapter 9).

6 MEA section

6.1 Introduction

In the MEA-section the CO_2 gas is removed from the process gas. The process gas is counter-currently transported through an absorption column with a monoethanolamine (MEA) stream at a temperature of 40 °C, where the CO_2 is absorbed into the MEA-solution. The CO_2 rich MEA solution is transported to the MEA-stripper. The CO_2 is released from the solution at low pressure and a temperature of 120 °C. The CO_2 stream flows to the compressor where it is compressed and recycled to the reformer. The process gas is compressed and flows to the drying unit.

6.2 MEA

Monoethanolamine used for CO_2-removal works as follows: The hydroxyl group reduces the vapor pressure and increases the water solubility. The amino group provides the necessary alkalinity in water solutions to absorp CO_2.

$$2RNH_2 + CO_2 + H_2O \rightleftharpoons (RNH_3)_2CO_3$$

$$(RNH_3)_2CO_3 + CO_2 + H_2O \rightleftharpoons (RNH_3)HCO_3$$

$$2RNH_2 + CO_2 \rightleftharpoons RNHCOONH_3R$$

Under normal conditions the composition of the equilibrium varies with the partial pressure of the CO_2 over it. But the vapor pressures of these products increase rapidly with temperature, which makes it possible to strip the absorbed gas from the MEA-water solution by the application of heat. As mentioned above monoethanolamine can react directly with CO_2 and has a greater alkalinity which gives it a greater effectiveness then other amines.

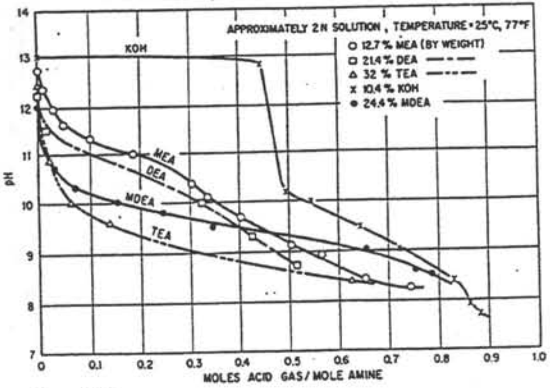


fig. 6.1

6.3 Absorber

The process gas enters the base of the MEA absorber at a temperature of 40°C and a pressure of 10.5 bar. The process gas flows through three packed beds of 2 inch diameter stainless steel Cascade Mini Rings (CMR) with a packing factor of 22. The CO_2 is absorbed in the MEA solution which flows downwards through the packing and absorbes essentially all the CO_2.
The CO_2 reacts with MEA according to the next reaction :

$$HO\text{-}CH_2\text{-}CH_2\text{-}NH_2 + H_2O + CO_2 \rightleftharpoons HO\text{-}CH_2\text{-}CH_2\text{-}NH_3 + HCO_3$$

The MEA solution leaves the base of the absorber at a temperature of 72°C due to the heat of absorbtion. In heat exchanger H-2109 it cools the lean MEA solution from the stripper and heats up to 103 °C.

In ASPEN the actual vapour flows have been calculated together with densities and viscosities of vapour and liquid. This is presented in appendix 6. The maximum possible vapour flow has been determined also using the generalized pressure drop correlation, also presented in appendix 6.

This results in a maximum possible capacity increase, of this absorber, of 109% at 60% flooding with the same packing. Which is more then sufficient for the 20% capacity increase.

6.4 Stripper

The rich MEA solution enters near the top of the MEA-stripper via a flashing liquid distributor and flows down over two packed beds of stainless steel Cascade Mini Rings (CMR) with a packing factor of 29. The solution then flows via a liquid draw off tray into the MEA-reboiler. In this reboiler vapour is generated which flows to the stripper column through the chimney of the liquid draw-off tray and up the tower stripping the CO_2 from the solution. In the top of the stripper the vapour is washed with reflux condensate. The hot lean solution at 120°C flows through the MEA cross exchangers back to the absorber.

In ASPEN the actual flows, densities and viscosities have been calculated based on the Linde data. With these data the maximum possible vapour flow has been determined using the generalized pressure drop correlation, presented in appendix 6.
This results in a maximum possible capacity increase of 17% at 90% flooding, which is very high, with the actual packing. This is just enough for the 20% capacity increase of the plant when using only extra CO_2 in the reformer feed.

6.5 Heat exchangers

When using only extra CO_2 in the reformer feed, the increased flows in the MEA-section make new heat exchanger dimensioning necessary. The new flows are from ASPEN, other data are based on KTI values. The best choice for reasons of efficiency and costs has turned out to be the use of parallel heat exchangers. In appendix 6 this is illustrated with an estimation of the new temperatures using the old heat exchangers with new flows.

The following heat exchangers and condensors should be installed parallel to the existing ones:

heat exchanger parallel to:	H-2108	H-2109 A/B	H-2110	H-2111	H-2112
flow shell side (kg/hr)	3350.4	3350	3848	23775	10152
flow tube side (kg/hr)	13060	3594	1324	1040	403.2
shell outside diameter (mm)	152	135	495	95	181
number of tubes	24	18	40	44	28
temperatures tube side in (°C)	25	72	180	25	102
temperatures tube side out (°C)	35	103	132	35	40
temperatures shell side in (°C)	88	120	120	133	25
temperatures shell side out (°C)	40	88	120	40	35
pressure drop shell (bar)	0.26	0.26	-	0.25	0.4
pressure drop shell/tube (bar)	0.4	0.14	0.24	0.15	0.08
overall heat transfer coefficient (kJ/m^2 °C hr)	2928.8	2573.16	3757.2	2263	483
length (m)	5.5	6	6	3.9	3.0
total surface (m^2)	7.63	12.42	14.2	8	4.9

6.6 Pumps

Introduction

The pumps used in the MEA section are designed for a certain operating point. When more fluid must be pumped, a couple of ways to achieve so are discussed here, with the possibilities :

1. Another pump in parrallel with the original one.
2. Another pump in series with the original one.
3. Parallel pipelines.
4. change the RPM's of the pump.

Before discussing these four possibilities, it is wise to give a brief resume of the most important aspects of a centifugal pump.

Characteristic of the pump.

A characteristic is known as a functionel relationship between two or more for the process relevant variables. The two best-known variables are the suction head H and the volume flow ϕ_v (fig. 6.2). The suction head is the pressure increase in the pump, converted into the height of a column of the pumped fluid:

$$H=\frac{1}{\rho g}(p_2-p_1)=h_{geom} \qquad (6.1)$$

The pressure difference itself is called the manometric head. H is expressed in lengthunits, so in SI units it is in meters. When working with centrifugal pumps, the "characteristic" is meant to be H as a function of ϕ_v.

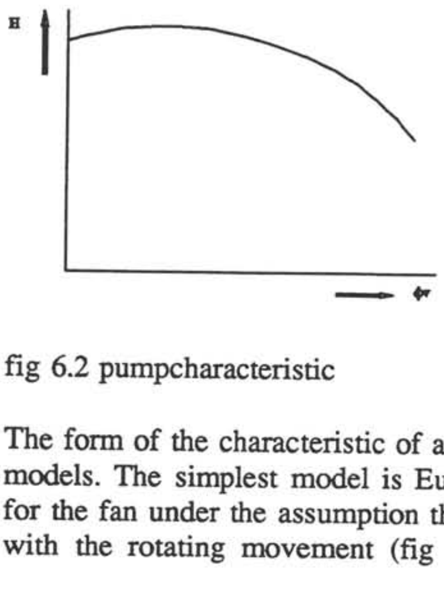


fig 6.2 pumpcharacteristic

The form of the characteristic of a centrifugal pump can be explained with simple physicle models. The simplest model is Euler's, by which the moments of inertia theorem is used for the fan under the assumption that the flow of the fluid is homogeneous and takes along with the rotating movement (fig 6.3). This model results in a lineair characteristic, of which the tangent depends on the fanblade configuration. The requirements aren't coming up in a real fan completely, through which the characteristics descend. On top of that, the fan is situated in a pump, so there will be flowresistance, of which the effect roughly is changing with the square of the volume flow ϕ_v. Flows less and more than the optimal operating point, results in oblique entrance in the fan. This all means that Euler's characteristic will never achieved (fig 6.4).

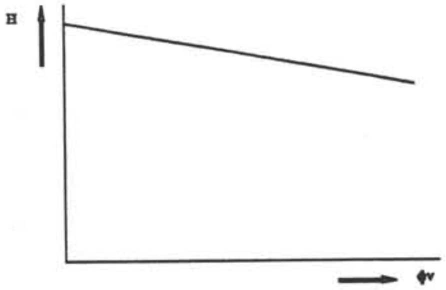


Fig 6.3 Euler's characteristic

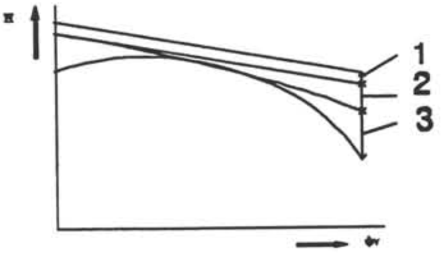


fig 6.4 real characteristic

1 Effect of not homogeneous distibution

2 Effect of flow resistances

3 Effect of obique entrance
(with respect to fan direction.)

Systems characteristics

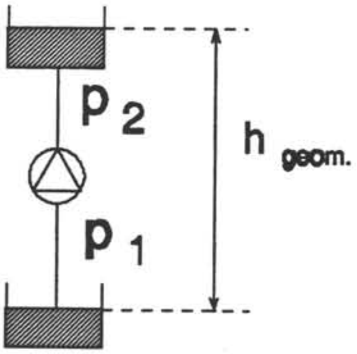
Often there is a functional relationship between pressure drop and volume flow for the system a pump cooperates with. When this relationship is drawn in the H-ϕ_v diagram, the result is an operating point of the pump.

Example 1

Systems with only height difference, without flow resistance in the pipes (fig 6.5 and 6.6).

Here the geometric height h_{geom} is the same as the height H (formula 6.1)

If the height difference doesn't depend on the flow ϕ_v, then the system curve is a horizontal.



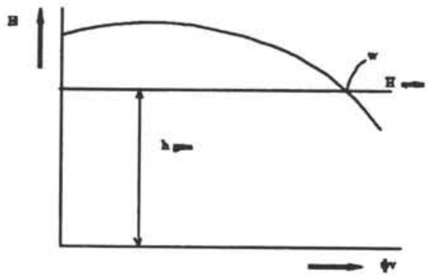


fig 6.5 fig 6.6

system with heightdifference

Example 2

Only flow resistances, no height differences.

Assume the flow resistance can be described by a square resistance law (valid in tubes above Re ≈ 2000):

$$\Delta p=\frac{L}{D}\xi\frac{1}{2}\rho c^2=constant\cdot\varphi_v^2 \tag{6.2}$$

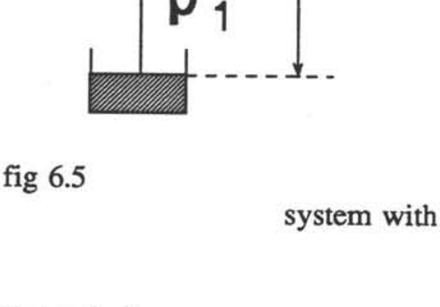
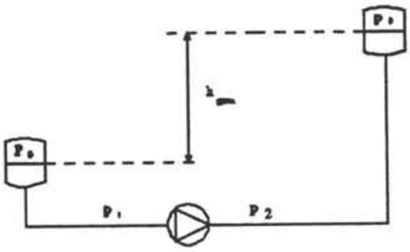


fig 6.7 system with only piperesistance

With this model the pipe characteristic is a parabola with its top in the origin of the axiscross. In fig 6.7 two system curves with different values for the constants are drawn.

Example 3



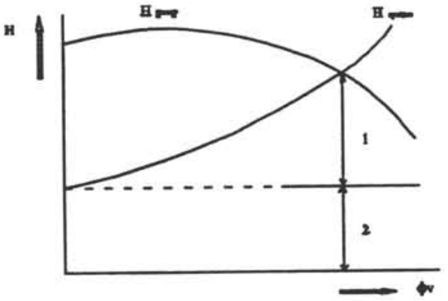


fig 6.8

fig 6.9

System curves for the more common case

More common case: height difference, pressure difference and flowresistance (fig 6.8 and 6.9). This is a combination of example 1 and 2, whereby also different gas pressures p_0 and p_3 above the levels are assumed. So now we have:

$$\frac{p_2-p_1}{\rho g}=H_{pump}=\frac{p_3-p_0}{\rho g}+h_{geom}+\frac{\Delta p_{pipe}}{\rho g} \tag{6.3}$$

Unstable behaviour of a centrifugal pump.

It is possible that a characteristic has a rising and descending part as shown in fig. 6.10. In that case the pump might operate unstable, depending on the coupled system and the position of the operating point. Assume that with the as example drawn system, the system curve exists of a static height (H_{01}) and a resistance height (H_{pipe1}). The resulting operating point is W_1. Here, the value of H_0 depends on the use: The pump must deliver as much as the user can take. Assume, this is not the case and the deliverance of the pump becomes to large. The operating point W moves across the pump characteristic to a higher value of H, causing ϕ_v to decrease. An equilibrium can be found that way, for example at W_2. Decreases the consumption by the user, the pump will search for a new equilibrium, whereby H_0 increases again and ϕ_v decreases. The utmost stable operating point that can be achieved that way, is W^*. when the deliverance of the pump still is too large, H_0 wants to rise further; the pump can deliver less, but at a lower H_0; The pump stops at that point and when no retraction valve is used, even backflowing may occur. When because of this backflowing, H_0 decends the pump will be able to work again. The present operating point lies on the rightside of the characteristic. The value of ϕ_v is however much to big again, and the operating point will again move towards W*, after which the cycle repeats. At this way a pulsing behaviour shows up, not only in the fluid flow, but also in the traction of the pump. The frequency depends on the volume flow and the resevoir dimensions. When the pump load only exists of static height (no pipe resistance), then the ultimate between the stable and instable part of the characteristic lies not near W*, but in the top T of the curve. When the load exists only out of pipe resistance (pump working on a smore valve for example), then the pipe curve always has a point of intersection with the pump characteristic.

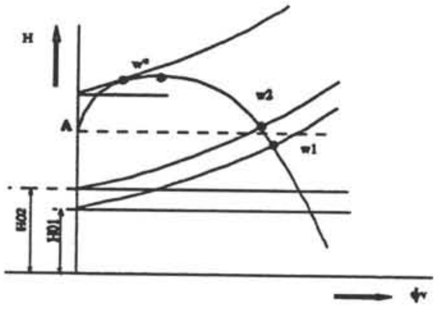
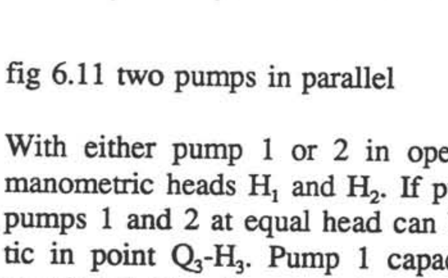


fig 6.10 pump characteristic with chance for instability.

ad 1) Pump operating in parallel

Where it is necessary to increase the amount of liquid to be pumped, two or more pumps are often installed beside one another. This condition has been sketched in fig 6.11.



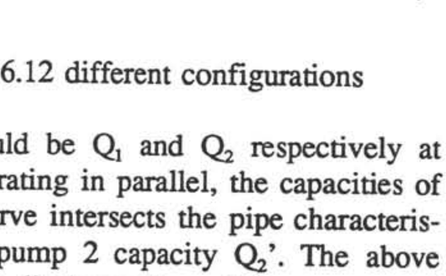


fig 6.11 two pumps in parallel

fig 6.12 different configurations

With either pump 1 or 2 in operation, capacities would be Q_1 and Q_2 respectively at manometric heads H_1 and H_2. If pumps 1 and 2 are operating in parallel, the capacities of pumps 1 and 2 at equal head can be added. The new curve intersects the pipe characteristic in point Q_3-H_3. Pump 1 capacity is now Q_1' and pump 2 capacity Q_2'. The above mentioned pipe characteristic refers only to the common discharge line of the pumps and hence the friction of the individual suction and discharge lines should be substracted from the Q-$H_{tot.}$ curve by the methode described under 3.1 before determining operating points for pumps 1 and 2.

ad 2) Pumps operating in series

If the manometric head of one pump appears to be too low to displace a certain quantity of liquid through a given pipeline, more pumps can be installed in the same pipe line to increase the pressure. The discharge of the first pump is connected to the suction of a second pump. Depending on local conditions, these pumps can either be placed close to each other (in the same room) or far apart. It is unusual to install pumps in series in new installations since a multy-stage pump is usual preferred. If two pumps, 1 and 2 with identical Q-$H_{tot.}$ curve are installed, capacity will amount to Q_1 when either pump 1 or 2 is operated seperately. When both pumps are operated in series, the joint Q-$H_{tot.}$ curve is found by adding the manometric head at equal capacities. The intersection with the pipe characteristic now shows operating point Q_2 with series-operation (fig 6.12)

ad 3) Parallel pipelines

If the capacity of one pipeline becomes too low - e.g. because of plant enlargement - a second pipe can be placed parallel to the existing one.

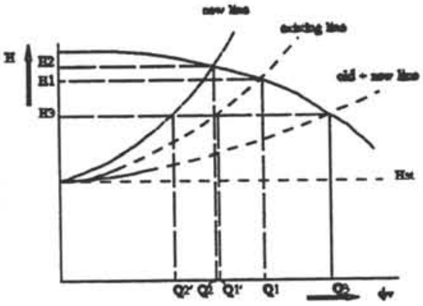


fig 6.13 different piperesistances

An increase in capacity is provided that can be calculated as follows: in graph (6.13) a pump in the existing pipeline is operating at capacity Q_1 and $H_{tot.}$ H_1. If the pump operates on the new line only, capacity is Q_2 at $H_{tot.}$ H_2. Pipe characteristic of the total system can be found by adding capacities of the old and new pipeline (at equal friction).
$Q_1' + Q_2' = Q_3$. The intersection of this characteristic with pump Q-$H_{tot.}$ curve gives operating point Q_3 - H_3. Capacity per pipeline can be found by reading same for the particular pipe at head H_3 (Q_1' and Q_2').

ad 4) Change the RPM's of the pump

For centrifugal pumps, there is a relation between manometric head H and the rotationfrequency n. At different rotationfrequencies the same centrifugal pump has different pump charateristics. The one belonging to the higher rotationfrequency lies above, the one belonging to the lower rotationfrequency lies under the normal Q-H_{tot} curve (fig 6.14).

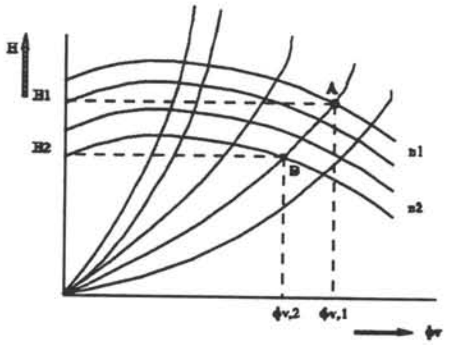


fig 6.14 different rpm's

These characteristics are determined by a congruence law, that is why the shapes are alike. For fluids with low viscosity the following relations exist:

$$\frac{\varphi_{v,2}}{\varphi_{v,1}} = \frac{n_2}{n_1} \qquad (6.4)$$

$$\frac{H_{tot,2}}{H_{tot,1}} = \frac{n_2^2}{n_1^2} \qquad (6.5)$$

$$\frac{P_2}{P_1} = \frac{n_2^3}{n_1^3} \qquad (6.6)$$

Here P is the power needed to pump. The index 1 relates to the original situation. This congruence law can be tested when the new rotation frequency does not deviate from the original rotation frequency.

Power for the pumping

The power the electro engine has to deliver can be calculated as follow:

$$-P_{axis}=\frac{v\,(p_2-p_1)\,\varphi_m}{\eta}=\frac{\rho g H \varphi_v}{\eta} \qquad (6.7)$$

Here η is the total efficiency of the pump, ϕ_m is the massflow.
The massflow will rise 15% so this means that the power increase per pump will also be around 15%. The cheapest and easiest way to increase the flow will be the latter described way, so with a higher rotation frequency. Questions remaining now are: can the electro engine handle the power, and doesn't the flow resistance become too huge in the pipes?

Calculations have been made for the pumps in the MEA section, with two massflows: ϕ_{m1} and $\phi_{m2}(=1.2*\phi_{m1})$. The efficiency was set on η=0.8. With formula 6.7, the power needed was calculated, by assuming that only the massflow would change; the rest like pressures, viscosities and mixture ratios are constant. We just want to see if the pumps can handle the flowincrease, so we need to have a estimation of the powerconsumption. These were the results:

Table 6.1: calculations results.

	ϕ_1	ϕ_2	p_{in}	p_{out}	ν	P_{KTI}	$P_{+20\%}$
	kg/s	kg/s	bar	bar	cP	kW	kW
N2101A/B	6.10	7.32	1.5	13.7	9.8e-4	9.1	10.9
N2102A/B	0.27	0.33	0.5	0.7	1.0e-3	0.02	0.02
N2103	0.63	0.76	0.6	0.7	9.8e-4	0.01	0.01

There will be no problems for the pumps to increase the flow. Only pump N2101 has to pressurize the fluid, the other two pumps have to displace fluid more than pressurize it. Because no extra data then the sheets are known, nothing can be said about the point of instability of the pumps.

6.7 Process gas drying.

The process gas from the MEA absorber contains CO_2 and H_2O, which would freeze in the cold box. The dryer removes these components to a level of 0.1 ppm volume.

The process gas from the MEA section has a temperature of 40 °C and a pressure of 9.4 barg. Any entrained condensate in the gas is separated in a K.O. drum. After this the gas is filtered, compressed, cooled and again sent through an K.O. drum. The gas leaving this K.O. drum (temperature 35 °C, pressure 27.5 barg) is sent to one of the three mole sieve beds, which will further remove the H_2O and the CO_2. One adsorbent bed is in line taking fresh feedgas to adsorb all carbon dioxide and water. The gas from this bed is then routed through a second bed, used as a guard bed, before flowing to the cold box. The third bed is in regeneration. In appendix 6 the cycle sequence is showed.

The process gas dryers are mole sieve beds. Molecular sieves are called zeolites. Commercial molecular sieve zeolites are usually synthetic. They are crystalline framework aluminosilicates containing alkali metal cations. The structure extends in three dimensions by a network of ALO_4 and SiO_2 tetrahedra linked to each other by sharing of oxygen atoms. Molecular sieves possess the high porosity that is characteristic of all adsorbents. In addition, the ordered crystalline structure. of the molecular sieve provides pores of a constant size.

The pore size of molecular sieves can be enlarged or diminished by appropriate cation exchange. Therefore many commercial types are available with pore openings ranging from 0.3 nm to about 1.0nm. This property gives molecular sieves unique advantages in certain applications because many gases or liquids can be excluded fom the microporous structure. Larger pore molecular sieves can also be used to simultaneously dry and purify streams.

Because of the ordered structure, molecular sieves have excellent capacity at low water concentrations and do not exhibit a capillary condensation pore-filling mechanism at high water concentrations. Molecular sieves are also inert to most fluids and are physically stable when wetted with water. Strong inorganic acids or alkalies should be avoided as well as temperatures above 700 °C.

For the generation of the process gas dryers, the hydrogen rich gas from the cold box is heated to 200 °C by steam and passed across the bed at low pressure to drive off the CO_2 and H_2O. The regeneration contains the following steps:

- Depressurisation step.
  The bed is reduced slowly in pressure to the same pressure level as the regeneration gas.

- Heating step.
  A flow loop of regeneration gas is established and the heating cycle is started.

- Cooling step
  The regenerated bed goes on to cooling. The generation gas now bypasses the regeneration heater and the cold gas slowly cools the bed.

- Purge step
  The regenerated bed goes onto a purge step. This is to slowly purge the bed of its regeneration gas volume so that when it actually goes into line there is no significant change in the quality of gas flowing to the cold box.

- Repressurisation step.
  The regenerated bed is now repressurized to operating pressure.

If the production capacity of the plant is increased by using only extra CO_2 in the reformer feed, then the CO_2 and H_2O amount sent to the dryers will be somewhat greater. This will result in a shorter adsorbtion time, so the guard- or the regeneration time must be decreased. At first it is necessary to decrease the regeneration time, which maybe possible by using more H_2 to regenerate the dryer and by speeding up the separate regeneration steps. If it is still necessary to decrease the guard time to cope with the decreased absortion time the risk of freezing in the cold box will be greater. So the twenty precent capacity increase may leed to a higher risc of freezing in the cold box.

6.8 Conclusion

The capacity increase for 20% more CO production by adding CO_2 to the reformer is possible with the existing MEA equipment, although the 90% flooding in the stripper is high. The heat exchangers in the MEA section need parallel heat exchangers. The dryer section need not to be changed, although the risk of freezing in the coldbox could be greater. Further stretching would require an other stripping column. The columns in the coldbox all have enough overcapacity and also the pumps do not need to be changed.

When using a pre-reformer in combination with adding extra CO_2 there will be no need to change anything because the flows are the same or less and the CO_2 content is about the same.

Literature

[6.1] Olujić, Ž., 'Introduction to design of Equilibrium Separation Processes'. Laboratory for Process Equipment TU Delft, 1992.

[6.2] Coulson, J.M. and Richardson, J.F., 'Chemical Engineering Volume 6', Pergamon 1991.

[6.3] Kohl, A. and Riesenfeld, F., 'Gas Purification', 4th edition, Gulf Publishing Company, 1985.

[6.4] Design and operating manual carbon monoxide plant II, G.E.P., KTI

[6.5] Kirk-Othmer, 'Encyclopedia of Chemical Technology', third edition, volume 8

7 CRYOGENIC SEPARATION

7.1 Introduction

The process gas coming from the drying unit containing H_2, CO, N_2 and CH_4 goes to the coldbox, the cryogenic separation. This separation is based on the difference in boiling points of CO and H_2 + CH_4. The process gas is cooled to a temperature of -203/-193 °C by heat exchangers. For this process, the required refrigeration can be obtained by H_2 expansion and a CO recycle loop. The cold box consists of condensators, flash drums, CO/CH_4 splitters and a CO wash column. Because of the close physical properties the N_2 can not be completely separated from the CO.

7.2 Columns

Feed gas coming from the drying unit is precooled against separation products in heat exchanger E-21. In the reboiler E-22 of the column T-22 the feed gas is further cooled down by producing rectification vapour in the column T-22, and then is fed into the lower part of the column T-21.

In this column, a methane rich liquid is produced in the bottom and a methane-free liquid is produced in the top. In the top cooler E-23 L and U, the top gas of T-21 is cooled down to 201°C by condensing a maximal amount of carbon monoxide. The hydrogen-rich gas is warmed up in E-23 U, enters the first stage of the piston expander EM-21 and is warmed up a third time in E-23 U. After passing E-23 L, it is warmed up in E-21 and leaves the plant. A part of the liquified carbon monoxide is used as reflux for T-21 to wash out the methane from the gas stream.

The remaining part of the carbon monoxide is taken from a chimney tray in the upper part of T-21 and expanded into the H_2 flash column T-24, where the dissolved hydrogen is boiled out.

The methane rich bottom product of T-21 is expanded into the other H_2 flash column T-23, where the dissolved hydrogen is also boiled out. The top products of the two H_2 flash columns, mainly hydrogen are fed to the tail gas. The bottom liquid of T-23 is expanded and used as refrigerant in one pass of the condenser E-23 L.

It is then fed into the middle section of the CO/CH_4 splitter T-22. The expanded bottom liquid of the other H2 flash column T-24 is mixed together with the two expanded carbon monoxide streams from the reboilers E-22 of the CO/CH_4 separation column T-23. Afterwards this stream is used firstly as refrigerant in the condensor E-25 of the column T-24 and enters then the CO/CH_4 splitter as reflux.

The bottom liquid of the column T-22 consisting mainly of methane represents the major part of the tail gas to which the head product of the H_2 flash columns T-23 and T-24 are added. It is warmed up in E-21 and leaves as tail gas. The top product of T-22 represents the carbon monoxide product.

The carbon monoxide recycle is first cooled down against separation products in the heat exchanger E-21 is split into three streams. Two streams provide heat to the reboiler E-22 of T-22 and reboiler E-24 of T-23. The third stream is injected into the H_2 flash column

T-24 as stripping gas. The two carbon monoxide streams from the reboilers E-22 and E-24 are expanded, and mixed to the bottom liquid of T-24.

7.3 Conclusion

The columns all have enough capacity for the 20% capacity increase by either using extra CO_2 in the feed or by using a pre-reformer in combination with the extra CO_2 in the feed. Appendix 7 contains the calculations.

8. NITROGEN REMOVAL

In this chapter the advantages of the removal of nitrogen from the natural gas feed are discussed. The different methods to achieve this are described and simulated where possible.

8.1. Advantages of removal of nitrogen from natural gas feed

The feed of the plant, natural gas from Groningen, contains about fourteen volume percent nitrogen. Because the nitrogen is an inert gas it will flow through the plant without being used anywhere. The energy that is needed to pressurize, to heat and to cool the nitrogen during the process are wastes of energy. When we release the flows from nitrogen they can contain more usefull components, which results in more feedstock and probably in a capacity increase. When the nitrogen is totally or partially removed from the feed gas then the product will have a higher purity than the actual one which has a molar ratio carbon monoxide/nitrogen of 9/1.

After separating the nitrogen from the natural gas there will be two flows, a nitrogen-rich flow and a nitrogen-poor flow. The latter will be the feed of the existing CO plant, the nitrogen rich flow can be fed in the natural gas net of the total plant. This is possible because the amount of gas that the CO plant takes from the gas net of the total plant is about ten percent. So when the nitrogen-rich flow, which is very small compared to the total gasnet is mixed with the natural gas of this gasnet the result will be an increase of the nitrogen that is negligible small.

8.2. Available separation technology

This paragraph will study the different methods that can be applied for the nitrogen separation, which in practice means the separation of nitrogen from methane, because methane is the most important component in natural gas. The following methods will be discussed:

-Absorption
-Cryogenic separation
-Membranes
-Pressure Swing Adsorption

8.2.1. Absorption

Generally absorption is a very suitable method for separating one component. The absorbent is a large molecule that binds the specific component that has to be removed. The problem in this case is that such a molecule is not yet available for nitrogen separation from methane. So absorption is not suitable for this proces.

8.2.2. Cryogenic separation

The most applied method for nitrogen removal from a gas which contains methane is cryogenic separation. Cryogenic separation is separation at low temperatures in order to liquefy one or more components or to create low or high solubilities of one component in another. This paragraph describes two methods of cryogenic separation. The first is an installation with one column, the second uses three columns.

8.2.2.1. Method I

The first method is described in two German patents from 1970 of Messer Griesheim GmbH [lit. 8.1, 8.2]. It is based on a nitrogen containing natural gas that is separated in a nitrogen-rich flow and a nitrogen-poor flow, which contains almost all the methane, by one column. It is not known if this installation is operating in practice. The description of this method is the following. Figure 8.1 shows the flowsheet on the next page.
The natural gas enters the plant in pipe 1. In heat exchanger 1 the flow is cooled by the leaving products and then heats the bottom of the column in reboiler 2 in order to create a boil up. Then the flow (3) is flashed in valve 3 to column pressure of about 28 bar and fed into the column. Via pipe 5 the nitrogen-rich flow is withdrawn from the top of the column. This stream can be pure nitrogen, depending on how far the rectification is raised. In this case this is not necessary and also to expensive. The nitrogen-rich flow passes heat exchanger 4, where it is heated, and is then expanded in turbine 5, in which it is cooled deeply. The created coldness is used in heat exchanger 6 in the middle of the column in order to create a reflux, necessary for the destillation. The rest of the coldness is withdrawn from the nitrogen rich fraction in heat exchanger 7 and 1, after which it leaves the plant through pipe 10. The nitrogen poor flow is withdrawn from the bottom of the column (pipe 11) after which it is splitted (8) in two flows. The largest flow (90%) is flashed in valve 9 in order to create coldness and is then heated by the entering gas. Then it leaves the plant through pipe 14 at a pressure of about 7 bar.
A part of the bottom products flows through pipe 15 and is cooled, after which it is flashed to about 2 bar. This flow is used as an open cycle in order to create a reflux in the top of the column. It is flashed in valve 10 to about 2 bar and is then evaporated in heat exchanger 11, which results in the desired reflux. The pressureless nitrogen-poor stream in pipe 19 flows through heat exchangers 4 and 7 in which it is heated in countercurrent flow with the cooling bottom products. In heat exchanger 12 the cycle medium is brought to about 5 °C and is then compressed to column pressure by compressor 13. After flowing through water cooler 14 and heat exchanger 12 the cycle medium is fed into the column as vapour flow 25.

The way this patent is simulated with Aspen Plus is described in Appendix 8, which also contains the results of the simulation.

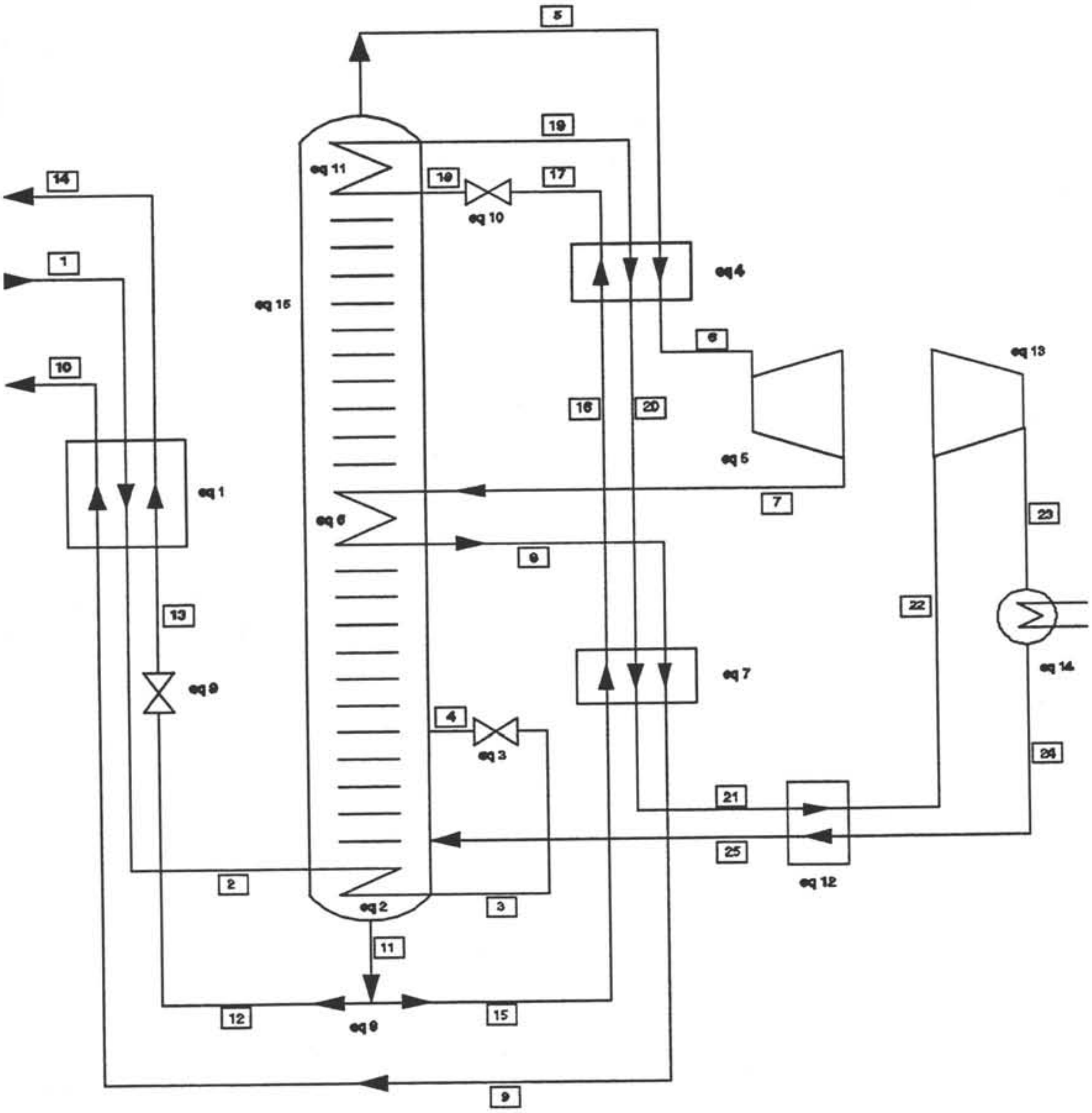


Fig. 8.1. Flowsheet of method I.

8.2.2.2. Method II

The second method is described in a Dutch patent from 1972 of Linde A.G., Germany [lit. 8.3]. The invention is related to a process for separating nitrogen from natural gas by rectification at low temperatures. The carbon dioxide, together with the two or more C-atoms containing hydrocarbons and a part of the methane, is separated by rectification as a high boiling fraction at medium pressure level. The CO_2-free fraction is separated in a nitrogen and a methane fraction by further rectification. After heat exchanging with the hot stream which enters the system, the latter two streams are taken from the system as high boiling fractions. It is not known if this installation is operating in practice. The description of this method is given in the following. Figure 8.2 shows the flowsheet on page 8-6.

In compressor 1 the natural gas is compressed to 48 bars. Assuming that the natural gas contains no water, so the dryers (2) are not needed, the gasmixture is cooled in heat exchanger 3, so that the higher hydrocarbons (C_5+) are almost completely condensed. In separator 4 the liquefied higher hydrocarbons are separated. The vapour fraction is condensed in heat exchangers 5 and 6. After being flashed in valve 7, the mixture enters the medium-pressure column (33 bars) 8.

The bottom product of this column has the following composition: 3 mole-% N_2, 91.5 mole-% CH_4, 3.6 mole-% C_2H_6, 0.5 mole-% C_3H_8, 0.1 mole-% C_4H_{10} and 1.3 mole-% CO_2. This fraction is a product and carried off at 175 K via pipe 9, vapourized and heated in heat exchangers 5 and 3 and delivered at 32 bars.
The overhead product of column 8, containing 36 mole-% N_2 and 64 mole-% CH_4, is carried off via pipe 10 at a temperature of 164 K. In heat exchanger 11 this vapour fraction is partially condensed at 151 K. The liquid fraction contains 68 mole-% CH_4 and is gathered in separator 12. The liquid partially returns to column 8 via pipe 13 as a CO_2-wash stream. After being flashed, the vapour fraction enters colomn 15 via pipe 14 at 28 bars. The bottom temperature of this column is 148 K; the percentage nitrogen of the vapour is 30 mole-%.

The remaining part of the vapour from separator 12 is carried off via pipe 16 and together with the bottoms of column 15 cooled in heat exchanger 17 at 112 K and enters via valve 18 the low-pressure column 19 at 1.5 bars. The wash stream needed for this column is gained in column 15. At the top of this column, liquefied nitrogen containing 5 mole-% CH_4 with a temperature of 123 K is carried off via pipe 20 and partially returns via pipe 21 to column 15 as a methane-free wash stream. The remaining part is cooled in heat exchanger 22 to 86 K and after being flashed, enters column 19 as a wash stream.

The liquefied CH_4-fraction at the bottom of column 19 still contains 3 mole-% nitrogen and is almost CO_2 free (50 ppm). This fraction, with a temperature of 109 K, leaves column 19 via pipe 23, compressed with pump 24 to 13 bars and heated in heat exchanger 17 to 146 K. At point 25 almost completely condensed circulation-methane is added. This stream is compressed by compressor 26 to 36 bars, cooled in heat cexchangers 3 and 5, condensed in heat exchanger 6, subcooled in heat exchanger 27 to 160 K and flashed in valve 28 to 13 bars, taking a temperature of 151 K. The united CH_4-streams are vapourized in heat exchanger 11 in countercurrent flow with condensed CO_2-free overhead product from column 8, and

heated to 158 K. After heating in heat exchangers 27, 5 and 3, the stream is taken from the system at ambient temperature. The amount circulation-methane is taken at point 33 and sucked by compressor 26. The CO_2-free methane fraction is mixed with the higher hydrocarbons from separator 4, and taken from the system via pipe 30. The percentage carbon dioxide and higher hydrocarbons in stream 30 is 2 mole-%.
The separated nitrogen leaves the top of column 19 as a vapour fraction at a temperature of 83 K and a percentage of N_2 of 99.5 mole-%. This stream is heated in heat exchangers 22, 17, 11, 27, 5 and 3 to ambient temperature and taken from the system via pipe 32 at atmospheric pressure.

The way this patent is simulated with Aspen Plus is described in Appendix 8, which also contains the results of the simulation.

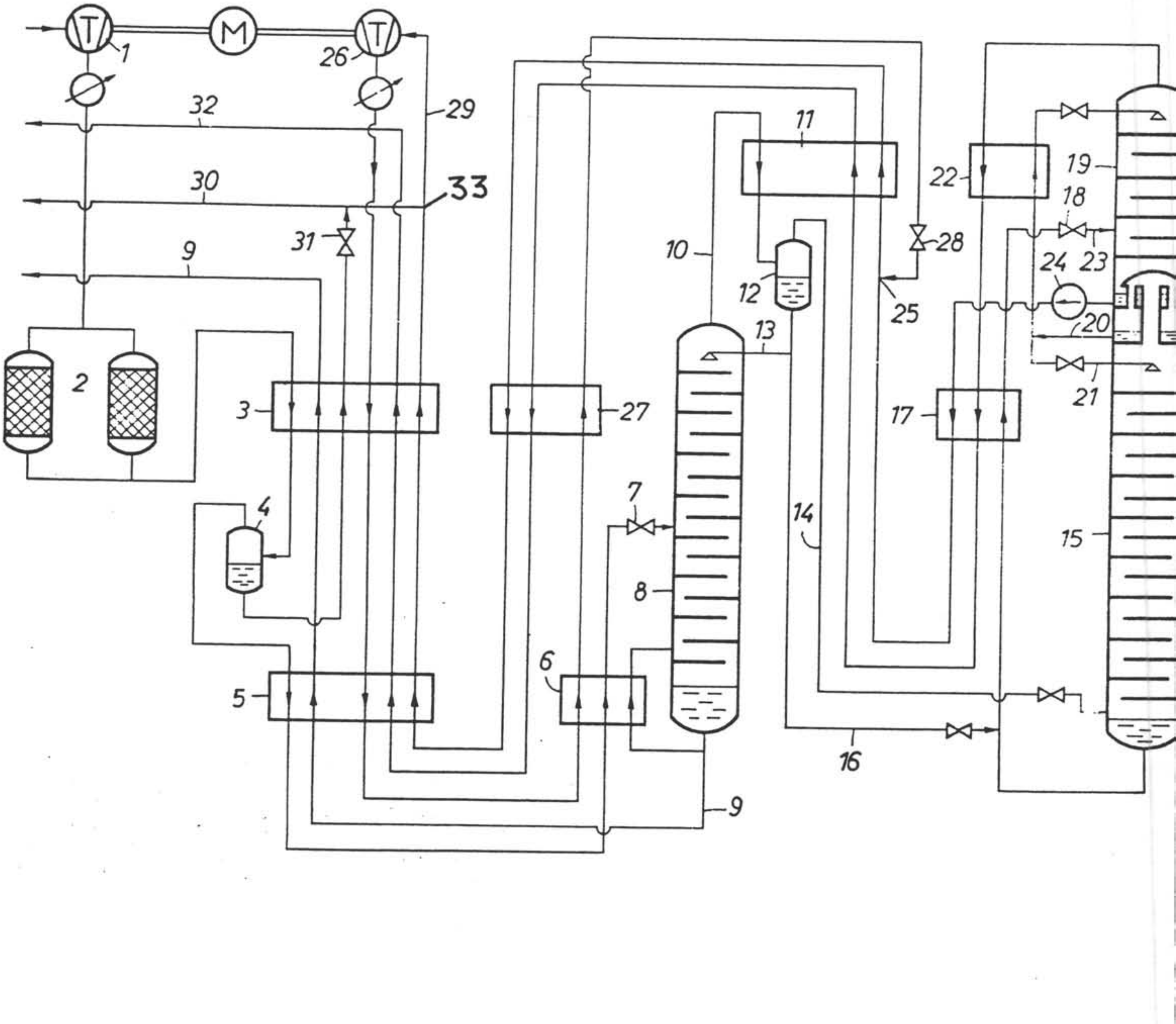


Fig. 8.2. Flowsheet of method II.

8.2.3. Membranes

A very actual way of gas separation is separation by membranes. Membranes are materials with a certain porosity, which gives them the ability of working as a sieve. For the purpose of liquid separation membranes are already being used for a long time, but gas separation by membranes in a commercial way is a recent method.

The principle of gas separation by membranes is simple. When a component has to be removed from a gas mixture in a certain room a membrane can be placed in this room in such a way that two separated rooms are formed. When the pressure in both rooms is equal, no separation will occur. The membrane behaves the same for all gas particles from both sides. Even when one component goes much easier through the membrane than the other components, this counts for both sides and netto nothing happens. Only when a difference in pressure is created between both rooms, for example by making one vacuum, separation will occur. Then there is a stream in one direction and the component that goes easy through the membrane will reach the vacuum room faster then other components, so the concentration of this component in the vacuum will increase. When the vacuumpump is set off, the separation stops and after a while the begin situation is reached again. So only when there is a difference in pressure over the membrane gas separation will occur. The different gasses flow netto to the room with the lowest concentration, but each in it's own tempo. This depends on the properties of the membrane, the type of gas and the interaction between these two factors. The passage of the gasmolecules through the solid material of the membrane is attended by forming and breaking up weak physical-chemical connections which vary by the the different components that are used.
In fact two processes are important: the solution of the gas in the solid material and the transport of the gas through it. Essential is the first step: the binding of the gas on the surface of the solid membrane. The next step is breaking up the first connection and forming new one's deeper in the membrane.
If the forces of the connections are small, few gas will dissolve, while the diffusion through the membrane passes relatively fast. When the connections are too strong, then the gas molecules never leave there places and no diffusion will take place. The transport velocity through the membrane depends on the combination of these effects. This explains that a physical-chemical active compound like water easier passes the membrane than an inert gas, like nitrogen. The processes are of course dependent on temperature.
For the amount of gas (F) that passes the membrane per second a simple relation counts:

$$F=\frac{P*O*\Delta p}{d} \tag{8.1}$$

This means that the gas stream is proportional to the surface O of the membrane and to the pressure difference Δp over the membrane and inversely proportional to the thickness (d) of the separating layer. The constant of proportion P contains the structure properties of the membrane and the hidden interaction processes and is called the "constant of permeability". This constant is a function of temperature.
For a given membrane material P varies with different gasses. The ratio of the P-values of

two different gasses is called the selectivity (α) of this couple. For a given gas P varies with different membrane material.

There are two classes of membranes: organic and anorganic membranes. Organic membranes are generally polymers. For gas separation polymeric membranes with pores are not usefull because of their bad selectivity. Better useful are the polymeric membranes which are close, but they can not be seen as simple sieves anymore. In fact this is a process where gas dissolves in the polymer and the gas molecules whip from one hole to another.
There are some polymeric materials that are already commercial for gas separation: polydimethylsiloxane (PDMS), polydimethylfenyleenoxide (PPO), cellulose acetate and polysulfone. The constant of permeability and the selectivity are very different for each of this materials.
For practical uses it is necessary to have a great pressure difference over the membrane, that is as thin as possible, in order to get a gas throughput as great as possible. The thickness of the membrane is the crucial factor in this process, because with a thinner membrane the pressure drop decreases, which makes the process cheaper, with regard to the energy demand of pumps or compressors. The problem however is the mechanical strength of the membrane, that of course decreases by making it thinner. This problem was solved by making an asymmetric membrane, that means asymmetric in the structure of the pores. Such a membrane consists of a very compact top layer, with a thickness of a few micrometres or less, that has good selectivity properties, layed on a thicker support layer with a thickness of about a tenth millimetre, that takes care of the mechanical strength. This support layer has a very open pore structure and a resistance for the gas that can be neglected.

Our question was what the possibilities are of a membrane with regard to nitrogen separating from natural gas, or practically the same, with regard to separating nitrogen from methane. This means we looked for a membrane that permeates nitrogen better than methane, thus a membrane with a selectivity $\alpha(N_2/CH_4)$ greater than one. A membrane that permeates methane better than nitrogen is also possible, but since the amount of methane is much greater than the amount of nitrogen in the natural gas (43.3 kmol CH_4 versus 7.5 kmol N_2 per hour) this is not practical, except for a selectivity that is very much smaller than one. For moderate selectivities the most practical way to separate two components is to let the smallest amount of the two permeate the fastest in connection with the process time.
Methane has a higher solubility than nitrogen in most liquids and polymers, so we expect that most membranes have a $\alpha(N_2/CH_4)$ less than one. This proved to be true [lit. 8.4]; cellulose acetate has α=0.73 and polysulfone has α=1.0. So with cellulose acetate nitrogen and methane can be separated, but this process won't be a very fast one, for the reasons described above.
At this moment the technology is not yet able to separate nitrogen and methane in a commercial way, but some companies, like Separations Technology Associates [lit. 8.5], are active in developing such membranes.

8.2.4. PRESSURE SWING ADSORPTION

Introduction

Separation of gasses accounts for the major production costs in chemical, petrochemical and related industries. There has been a growing demand for economical and energy-efficient gas separation processes. Although cryogenics remain the most widely used process for this purpose, the last two decades have seen a tremendous growth in research activities and commercial applications of adsorption-based gas separation processes [lit. 6]. The increasing interest in this area is also reflected in the large number of research articles and patents published in the field of adsorption separation. Such a growing relevance of this area can be attributed to the following factors:

- Development of synthetic and more selective adsorbents.
- An improved theoretical understanding of adsorption from gaseous mixtures.
- A better understanding of multicomponent adsorber dynamics.
- Development of an efficient pressure swing cycle.

The basic principle of PSA

Separation by an adsorptive process is based on the selective accumulation of one or more components of a gas mixture on the surface of a microporous solid. When a gaseous mixture is exposed to an adsorbent for a sufficient time, an equilibrium is established between the adsorbed phase and the gas phase. The adsorbed phase often has a composition different from that of the bulk phase. The gas phase becomes richer in the less selectively adsorbed component, as depicted in Figure 8.3 on the next page.

The attractive forces responsible for adsorption are of the van der Waals type. Desorption can be achieved either by increasing the temperature of the system or by reducing the adsorbate pressure. The desorption step also regenerates the adsorbent. Thus, the adsorptive separation process consists of a cyclic sequence of adsorption and desorption steps. When desorption is achieved by decreasing the pressure, the process is called pressure swing adsorption (PSA).

One of the components is selectively adsorbed at higher partial pressure and desorbed subsequently by lowering the partial pressure. The change in the partial pressure of the component can be caused either by decreasing the total pressure, by changing the composition of the gaseous mixture, or by doing both simultaneously. Figure 8.4 on the next page shows the amount of gas adsorbed as a function of partial pressure at a particular temperature. The amount adsorbed decreases along the curve from point A to point B with a decrease in the partial pressure of the component.

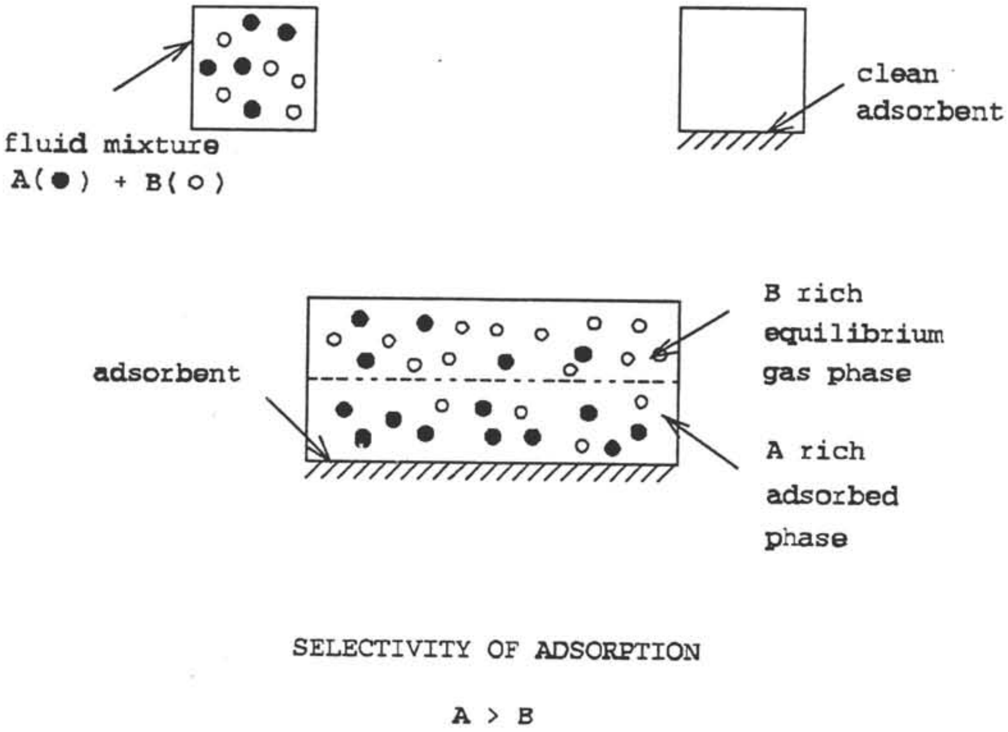


Fig. 8.3. Principle of adsorptive separation.

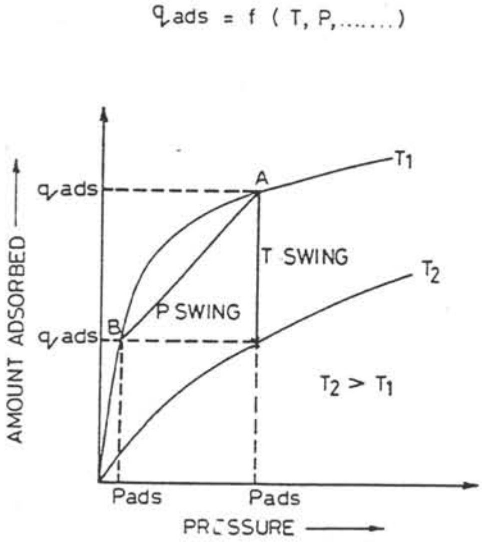


Fig. 8.4. Adsorption isotherms showing pressure and temperature swings.

The adsorption capacity available for separation in PSA is the difference in the capacities for the given component at the two pressures. However, in practice, due to the heat of adsorption, there is an associated change in the temperature of the system and hence the working PSA capacity is slightly different, as depicted in Figure 8.5.

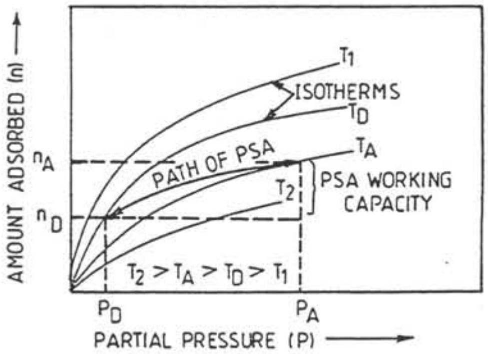


Fig 8.5. Adsorption isotherms showing pressure and temperature swings and PSA working capacity.

The primary steps in PSA

The PSA system in its basic form consists of two beds which are alternately pressurized and depressurized according to a programmed sequence. A two-bed system is shown in Figure 8.6 on the next page. The basic steps of the PSA process are shown in Figure 8.7 on page 8-13 and summarized in the following.

1. Feed pressurization

The feed gas is compressed into an adsorbent-fixed bed from one end, with the other end being closed. The gas freed from the adsorbed components is accumulated at the closed end.

2. Product release

At the upper operating pressure, the adsorbate-free gas, usually the product, is withdrawn from the far end of the bed while feed flow is maintained. Three distinct regions develop inside the adsorbent bed, as shown in Figure 8.7 on page 8-13.

- Near the feed entry the bed is saturated with the adsorbate and the gas phase has the composition of the feed.
- Near the exit the bed is still adsorbate free and the gas phase has the product composition.
- The region lying between the above two ends is called the mass transfer zone. This is where adsorption is occurring, and the gas phase composition changes rapidly along the axial position. The adsorption front moves along the bed as more feed

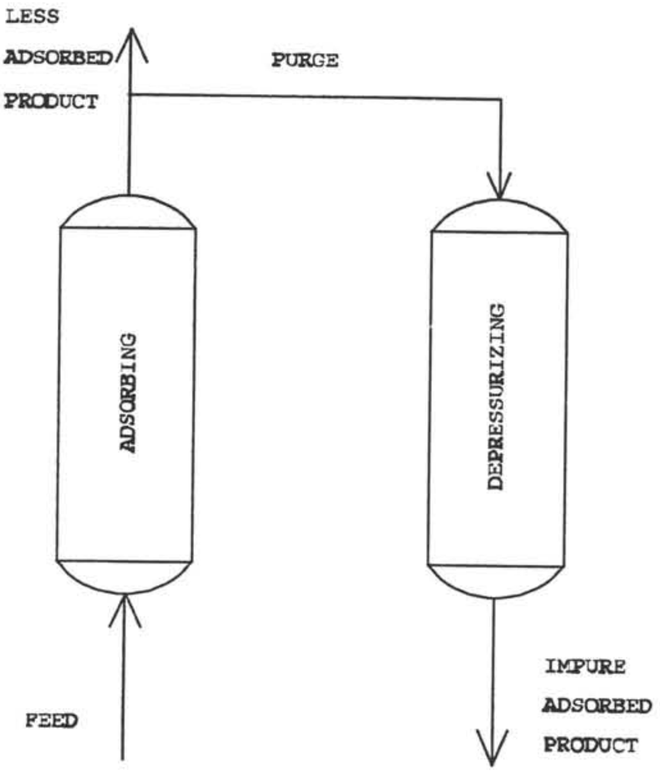


Fig. 8.6. Schematic diagram of a two-bed PSA process.

is introduced. Eventually the bed is completely saturated, with the mass transfer zone having reached the end of the bed, at which point the feed is said to breakthrough into the product stream.

3. Depressurization

To regenerate the saturated bed, the next step involves reducing the operating pressure (blowdown or depressurization). The adsorbate is largely desorbed into the gas phase, released as a waste stream, or collected as a product in case it is valuable.

4. Low pressure purge

To complete the regeneration of the bed, the adsorbent is purged with product quality gas at low pressure, usually countercurrent to the feed flow from the product end. In this case also, distinct regions form and the purge gas will eventually breakthrough the waste.

PSA is well suited to rapid cycling, and it generally operates at a relatively low adsorbent loading because selectivity is greatest in the Henry's law region. A high pressure operation is desirable because it minimizes the purge loss, but this gain is offset by the greater blowdown losses for a high pressure system. A low temperature operation is needed to maximize capacity and selectivity, but cooling below the ambient temperature is generally not economical. Some of the points that make separation by PSA economically attractive are the following:

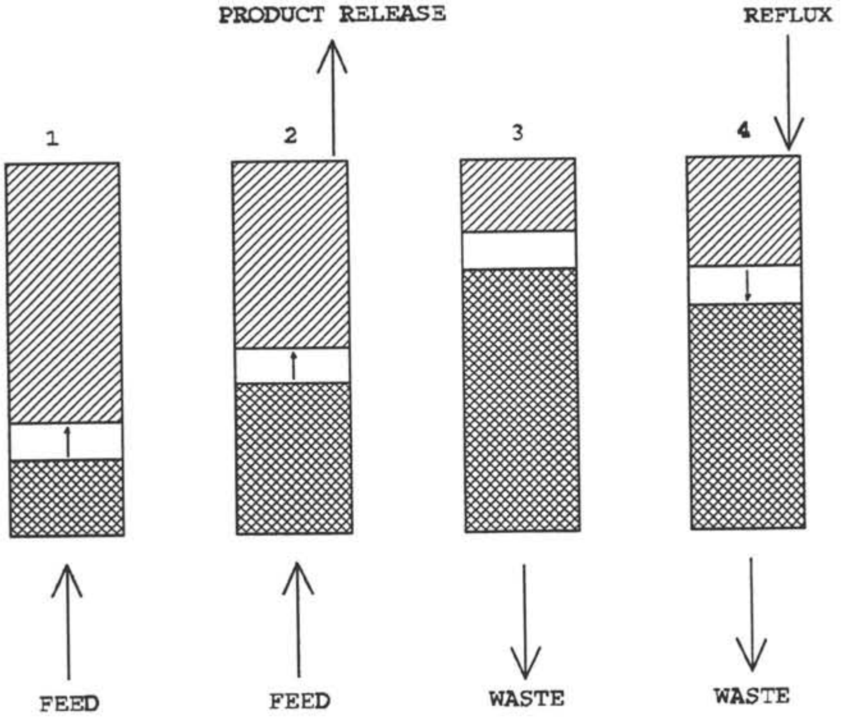


Fig. 8.7. The basic steps in a PSA process.

- A high concentration of the desired and less strongly adsorbed component in the gas mixture.
- Moderate purity requirement for the desorbed product.
- A low heat adsorption (less than 30 kJ/mol) of adsorbable component to facilitate rapid desorption.
- A linear adsorption isotherm for the strongly adsorbed component.
- Small adsorption/desorption pressure ratio.

Major developments in the PSA process

One of the major disadvantages of the earliest PSA system was low recovery of the product gas. For example, in the separation of air for oxygen production, the recovery was rarely above 25% in a simple two-bed system. To overcome this disadvantage, a variety of process modifications have been made. A critical review of the literature during the past two decades shows that the major part of research in this area has been directed towards improving the process economy by enhancing the product recovery. Some of the most important developments are briefly described in the following.

Pressure equalization step

The major operating cost in PSA is the energy required for pressurization of the feed. In the early PSA systems a large part of this energy was lost during blowdown. Berlin[lit. 2] suggested a pressure equalization step to conserve this energy. After the first bed has been purged and the second bed has completed the adsorption step, instead of blowing down the second bed directly, both the beds are interconnected to equalize the pressure. The first bed is partially pressurized with the product-rich gas from the outlet of the second bed. Following pressure equalization, the beds are disconnected and the first bed is pressurized with the feed gas while the second bed is vented to complete blowdown. Inclusion of this step in the PSA process sequence has not only minimized energy losses but also resulted in a substantial increase in recovery.

Multibed system

More complex processes, including three- and four-bed systems, have been developed to take advantage of the pressure equalization step. A four-bed PSA system is shown in Figure 8.7 on the next page. In this system, one bed is in the adsorption step and the other three beds are in various stages of repressurization, depressurization or purging. The principle is an extension of the Berlin [lit. 2] system.

The process operates at two intermediate pressures between the feed pressure and the exhaust pressure (usually atmospheric). At the end of the adsorption step, bed 2, which is at high pressure, is connected at the discharge end to column 4, which has just completed the purge step and is essentially at atmospheric pressure, and the pressures are equalized. In this way the product-rich gas is conserved and used for partial pressurization of bed 4. Final repressurization of bed 4 is accomplished by using product gas from bed 1, and the feed is connected to the inlet of column 4. A fraction of the remaining gas from bed 2 is used for reverse-flow purging of bed 3. When the pressure in bed 2 has fallen to required level, beds 2 and 3 are disconnected and the residual gas from bed 2 is vented from the bed inlet. Bed 2 is then purged in reverse flow with gas from bed 1 and repressurized to the first intermediate pressure with gas from bed 4, which has just completed the adsorption step. The final repressurization is accomplished by using product gas, and the feed is then connected to the inlet of bed 2.

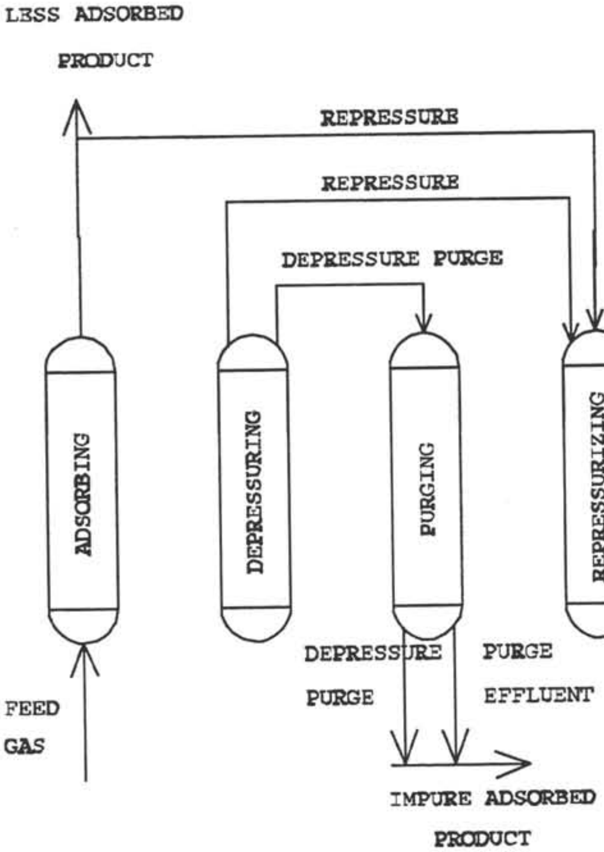


Fig. 8.7. Schematic diagram of a four-bed PSA process.

The advantages over the two-bed process at the cost of a more complex flow sheet are the following:

- Considerable reduction in power consumption.
- High product recovery.
- High purity product.
- Constant product flow rate.

The use of more than one type of adsorbent in a single PSA unit, a guard bed to remove impurities, and rapid cycling to improve the adsorbent productivity are some of the other recent improvements. Other developments in the process include vacuum swing adsorption (VSA), polybed PSA (up to 10 beds), and multiproduct recovery.

Adsorbents used in PSA

The choice of an adsorbent for PSA application is governed by its adsorption capacity and selectivity for the desired component. The selectivity or the separation factor of component A over B is given by

$$\alpha_{A/B}=\frac{x_A y_B}{y_A x_B} \tag{8.2}$$

where x and y are the adsorbed and the gas-phase concentrations. Simulation studies for countercurrent adsorption separation processes reveal that for the process to be economical, the minimum acceptable intrinsic separation factor for the desired component is about 3. With a separation factor of less than 2, it is difficult to design a satisfactory process.

A study by T.C. Frankiewicz and R.G. Donnelly [lit. 7] shows that nitrogen is weakly adsorbed on the surfaces of numerous zeolites. Methane is a weakly polarizable molecule which, as a result of this polarizability, is also weakly adsorbed on zeolites. In general, the heat of adsorption for CH_4 is equal or slightly greater than the heat of adsorption for N_2 and as a result an adsorption separation of these gasses either does not occur or happens by a weakly selective CH_4 adsorption. In the 1950s, there was discovered that N_2 could be selectively adsorbed from a CH_4/N_2 mixture by cooling a 4A molecular sieve to between 0°C and -78°C. However, this system was limited by slow kinetics, a weak selectivity and the need to thermally regenerate the sorbent.

In the begin 1980s, the naturally occurring zeolite clinoptilolite (clino) was found which can selectively adsorb N_2 in the presence of CH_4 near ambient temperature. The zeolite designated ZBM-15 has the largest ability to separate a N_2/CH_4 mixture.

Given the ability of the clino ZBS-15 to effect CH_4/N_2 separation, the named study reviews the results from several series of pressure swing CH_4/N_2 separation experiments and shows how to design a process to use this effect. An economic evaluation suggested the process would be economically viable for small plants ($2x10^6$ ft^3/day).

The pressure swing separation of CH_4 and N_2.
In order to investigate the process aspects of the pressure swing separation of CH_4 and N_2 the apparatus depicted in figure 8.8 on the next page, was constructed. Valves V1 through V5 are fitted with electric switching mechanisms that are interfaced to a computer. The two pressure transducers, three mass flow meters, and column temperature are also monitored by the same computer. All gas effluent from the apparatus through vent or vacuum is sampled through a molecular leak valve for analysis by the quadrupole mass spectrometer. The mass spectrometer in turn reports these compositions to the computer. Once a run is initiated, the apparatus is under complete control of and monitored by the computer.
The back pressure regulator (BPR) is set to give the desired pressure in the adsorption column (C1 or C2) being used. Although it is possible with this apparatus to involve both columns

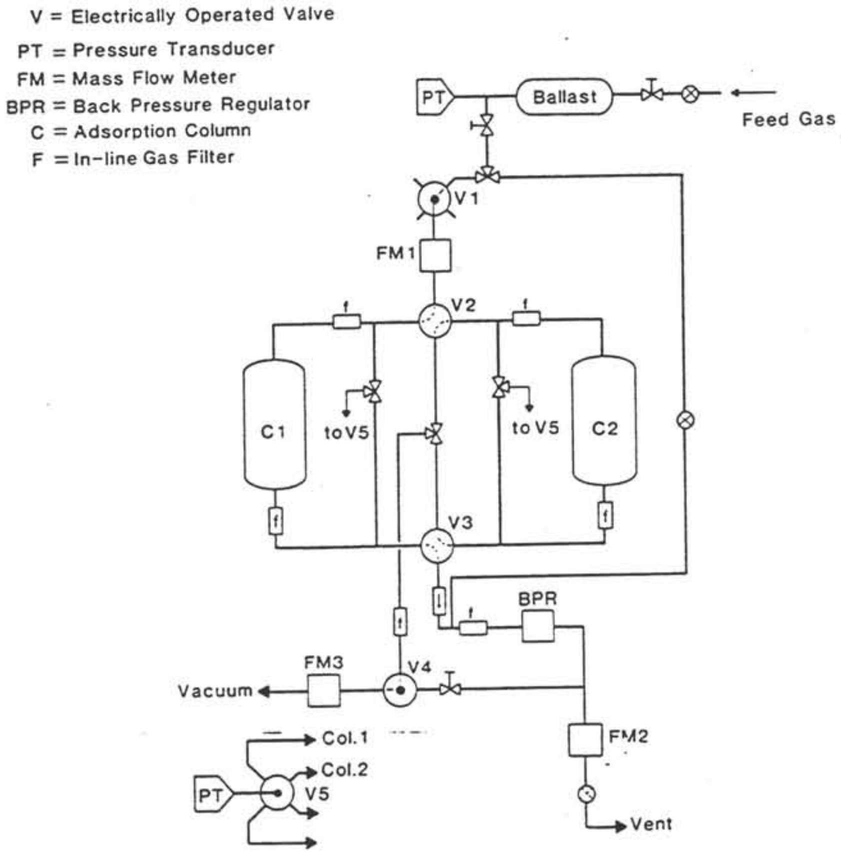


Fig. 8.8. A schematic drawing of the computer controlled pressure swing apparatus.

alternately in a separation experiment, this was not done during the experiments described. so that all vent and vacuum regeneration gasses could be analized for every cycle in the run. During a pressure swing run, gas enters the adsorption column, C1 or C2, through valve V2. Valve V3 is set to allow gas to exit the selected adsorber through the back pressure regular (BPR) as soon as the desired operating pressure is achieved. For depressurization, V3 is switched to allow the column exit gas to bypass the BPR and be vented through valve V4. V4 is a vacuum/vent selector and V5 allows a single pressure transducer to monitor system pressures at up to four selected points.

A sample data plot is shown in figure 8.9 on the next page. Feed gas is 40% N_2 and 60% CH_4. A mass balance is calculated for CH_4 and N_2 for each step in the process as well as for the complete adsorption cycle. The mass balance includes a Van der Waals calculation of the amount gas stored in column voids and the volume of gas adsorbed on the zeolite.

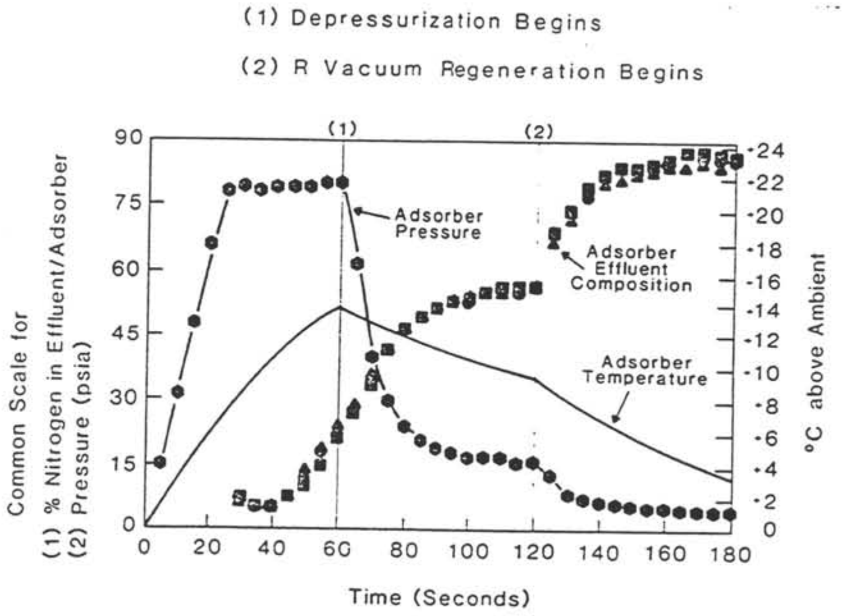


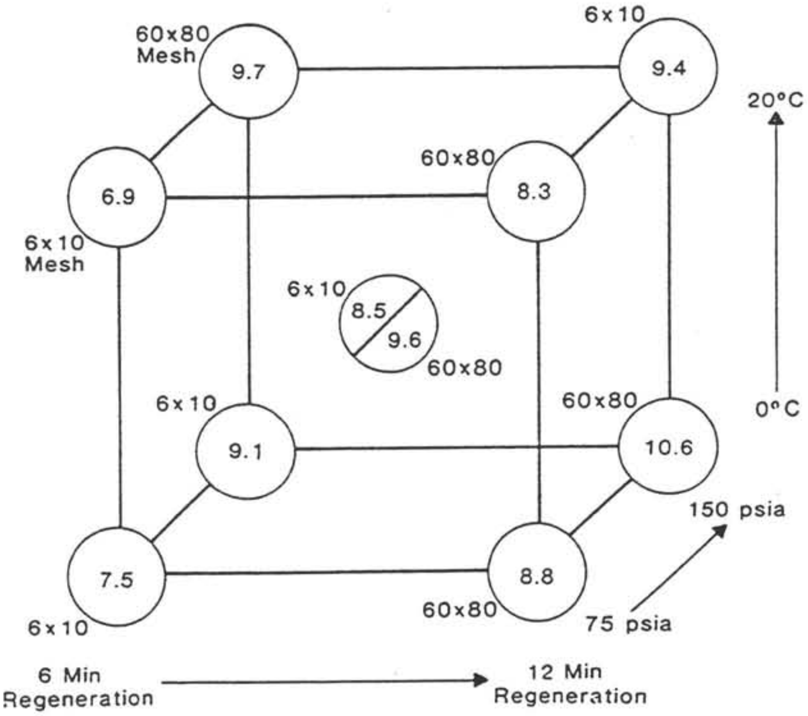
Fig. 8.9. Adsorber parameters are plotted versus time for a pressure swing run. Note the common scale for $\%N_2$ and adsorber pressure.

Table 8.1 on the next page lists the independent variables and their respective ranges which were included in the described study. Dependent variables can be defined in numerous ways depending upon the objectives of the particular experimental series being conducted. Typically, a pressure swing adsorption cycle program is input to the apparatus's computer control program, e.g., per figure 8.9, and the cycle repeated under computer control until the experimental objective is achieved. For this work, 6 to 24 cycles were normally used with total run times up to 8 hours.

Figures 8.10 on the next page and figure 8.11 on page 8-20 illustrate changes in two dependent variables: dynamic N_2 adsorption capacities and CH_4/N_2 separation factors. Independent variables are column temperature, operating pressure, and time allowed for vacuum regeneration. This experimental series used a constant feed rate of 6.0 l/min over a time of 1.00 min into a 1 inch diameter x 24 inch long adsorber filled with 180 g of zeolite. Column depressurization took place for 1.00 min. and this was followed by a variable length vacuum regeneration.

Table 8.1. Operational variables and variable ranges studied for the pressure swing separation of CH_4 and N_2.

Gas Feed Rate	16.7 - 50.0 scc/g. of zeolite-min.
Feed gas composition	10 - 40% N_2
Adsorber Temperature	0° - 55°C
Operating Pressure	75 - 300 psia
Adsorber Granule Size	.18 - 3.5 mm
Column Regeneration	0 - 20 min. vacuum or CH_4 purge



P_{Total}	P_{N_2}	Theor. Cap.
80 psia	32 psia	8.2 scc/g
112 psia	45 psia	9.8 scc/g
150 psia	60 psia	11.2 scc/g

Fig. 8.10. Average SCC of N_2 adsorbed per gram of the clino ZBS-15 for a 3 variable factorial design experimental series. Feed was 33.3 SCC/g of zeolite per cycle of 40% N_2/60% CH_4 gas.

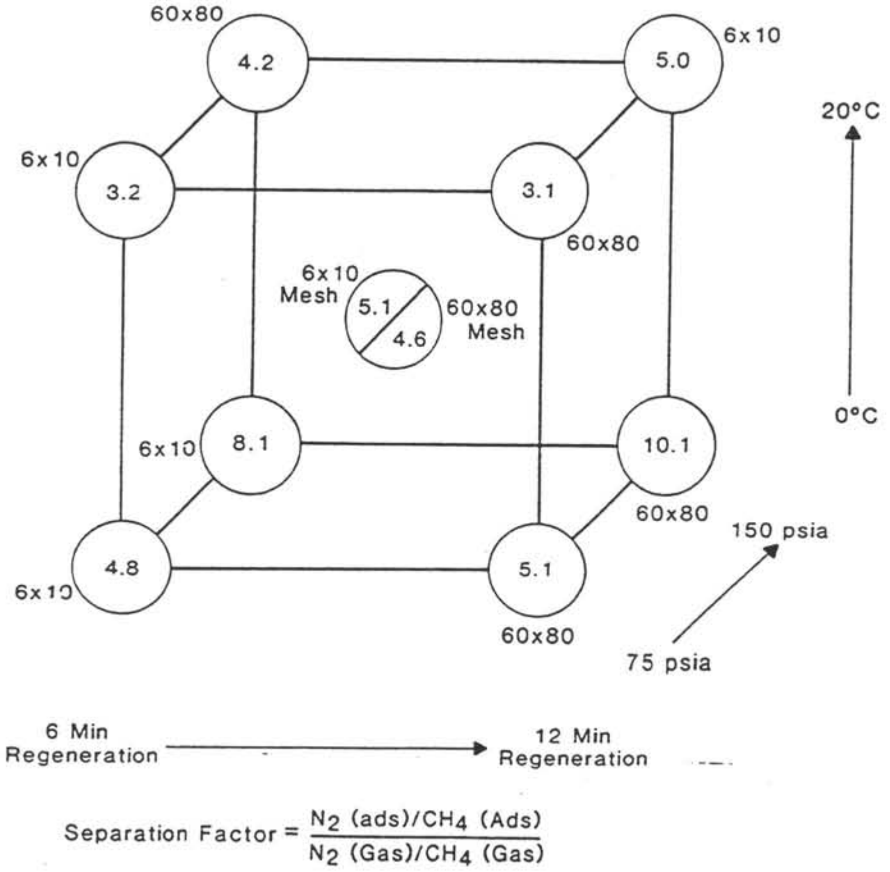


Fig. 8.11. CH_4/N_2 separation factors for a 3 variable factorial design experimental series. Feed was 33.3 SCC/g of zeolite per cycle of 40% N_2/60% CH_4 gas.

Adsorbent particle sizes, although not a design variable, did affect some results for hydrodynamic reasons. As can be seen from the centerpoints, a slight deterioration in column performance resulted with the switch from 60x80 to a 6x10 mesh adsorbent. Although this effect was real and reproducable, the effects on the three design variables were generally more significant.

At the bottom of figure 8.10, capacities derived from the clino N_2 adsorption isotherms are also listed. The factorial design results suggest that over 90% of the theoretical N_2adsorption capacity can be dynamically used in a pressure swing process provided adsorbent regeneration is adequate. The column temperature does not strongly effect dynamic N_2 adsorption capacity, but does influence N_2/CH_4 separation factors in the process. This results from a slowing of CH_4 kinetics as temperature is decreased.

The longest step in the pressure swing cycle for CH_4/N_2 over clinoptilolite is regeneration. Because this step involves vacuum and represents unproductive time in the process, regeneration was closely studied. Regeneration times were varied from 10 sec. to 20 min. and regeneration mode was changed from vacuum (approx. 20 torr system pressure) to quiescent to CH_4 purge. The results for 5 of these runs are summarized in figure 8.12 for a 20% N_2, 80% CH_4 feed gas. It appears that a vacuum regeneration time of at least 6 minutes is required to maintain product quality over multiple cycles. Other modes of regeneration were not succesful and it appears that a process design cannot reasonably incorporate anything but vacuum regeneration.

Process design and economics

Using the detailed mass balance data for the experiments described above, a commercial process design was developed and subjected to an economic analysis. The process involves the use of 10 adsorbed beds sized to handle 2.0 or 20.0 x 10^6 SCF/day of feed gas containing 20-30% N_2 and 70-80% CH_4. The product varies from 90-95% methane depending upon the feed composition. Pressure swing separation costs were found to be \$ 0.35/10^6 Btu for the larger plant and \$ 1.20/10^6 Btu for the smaller plant. Corresponding costs for cryogenic separation of the same feedstocks were estimated to be \$ 0.29/10^6 Btu for the 20.0 x 10^6 SCF/day plant and \$ 1.66/10^6 for the smaller plant.

Thus pressure swing separation of CH_4/N_2 appears to be viable for small plants.

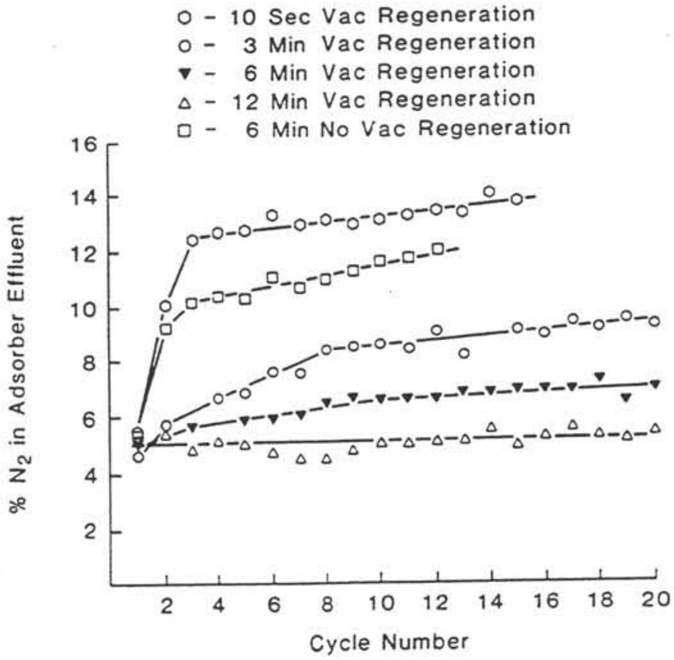


Fig. 8.12. Product quality from an adsorber varies as the regeneration time is varied. Feed gas is 20% N_2/80% CH_4.

Potential adsorbents

Although there is some room for improvement in the PSA process, the potential gains in process economics in the future are likely to come from the development of new and improved adsorbents. Major advances have been made in the synthesis of new zeolite structures since the development of the first synthetic zeolite A. The development of silicate, ZSM type, metallosilicates, aluminophosphates ALPOs, silicoaluminophosphates SAPOs, metalloaluminophosphates MeAPOs, particularly the more recent synthesis of VPI-5, aluminoborates, and beryllophosphates shows that the field of zeolite synthesis is yet to reach its maturity even after the considerable synthetic efforts of the last 40 years. At present, mainly A, X, mordenite, and some natural zeolites are being commercially used as adsorbents in the separation of gasses by PSA. The commercial potentials of such zeolites as silicates, ZSM type, and the ALPOs are yet to be explored. These present interesting and varied surfaces, and they call for extensive studies from the adsorption point of view. For example, silicate has a highly hydrophobic surface, while A and X are strongly hydrophilic in nature. ALPOs have an intermediate hydrophilicity. This class of zeolites may become specialized adsorbents for separation processes. Recent studies have shown that silicalite is a potential adsorbent for the separation of N_2/CH_4 and CO_2/CH_4, with selectivities for N_2 and CO_2 being more than 3, as shown in Table 8.2.

Table 8.2. Separation factors for sorption of CO_2, N_2, and CH_4 on silicate.

Temperature (K)	CO_2	CO_2/CH_4	CH_4/N_2
273	20	3.5	3.5
283		3.0	2.8
298		2.7	2.7
323		2.5	2.2
343	4	2.0	-

8.3. Conclusion

In order to remove nitrogen from the natural gas feed, we studied four different methods.

The first, absorption, is a suitable method for separating one specific component. For our situation it is not, because there is no suitable absorbent available for N_2/CH_4 separation.

The second method, cryogenic separation, is a method that is very often used in the separation of nitrogen from methane. Two possibilities were studied: a method which makes use of one column, and a method that uses three small columns. Both methods were patented more than twenty years ago.
The first method is able to remove about 81 percent of the nitrogen. The removed nitrogen including a little methane and some other components are mixed with the total gas net of the entire plant. The difference in concentrations will be very small, so they don't have consequences for other processes. This method costs about 8 million Dfl. No costs for the fact that the method is patented have to be calculated, because the patent is older than twenty years, so the patent is not protected anymore.
The second cryogenic method removes 79.6 percent of the nitrogen; 3.3% of the N_2 remains in the feed. The methane-purity raised from 81.3% to 91.8%, and only 0.03 kmol/hr CH_4 (0.068% of the total feed) remains in the removed nitrogen stream. The latter stream is mixed with the total gas net. Like the first method, no costs for the fact that the method is patented have to be calculated, because the patent is older than twenty years.
The costs of both methods could not be estimated, since the heat exchanging surfaces of the multi-flow heatexchangers, which are necessary for cost calculatings, could not be estimated. Because in both methods various multi-flow heat exchangers are used, the calculating of the costs of the plants became impossible.

The third nitrogen-removing method that was studied is separation by membranes. Compact polymeric membranes are able to separate nitrogen from methane, but since their selectivity is not good enough, the separation is slow and not very suitable. This is also the reason of the fact that membranes for N_2/CH_4 separation are not commercial yet.

The last investigated method is pressure swing separation. According to the experiments described, pressure swing adsorption is viable for small plants ($2x10^6$ ft^3/day, which is about 0.6 m^3/sec.). Since the present CO-plant has a lower capacity, is pressure swing adsorption a possible method to remove nitrogen from natural gas.

Literature

[8.1] Messer Griesheim GmbH, Frankfurt, West-Germany Patent 2,022,954 (2 Dec. 1971).

[8.2] Messer Griesheim GmbH, Frankfurt, West-Germany Patent 2,055,229 (18 May 1972).

[8.3] Linde A.G., Wiesbaden, Dutch Patent 7205577 (9 November 1972).

[8.4] E.W. Funk and N.L. Norman, Purification of natural gas by membranes, Gas Separation Technology,

[8.5] E.J. Hoffman, K. Venkataraman and J.L. Cox, Membrane separation for subquality natural gas, Energy Progress, March 1988, Vol.8, No. 1.

[8.6] R.V. Jasra, N.V. Choudary and S.G.T. Bhat, Separation of gases by pressure swing adsorption, Separation science and technology, **26**(7), pp. 885-930, 1991.

[8.7] T.C. Frankiewicz and R.G. Donnelly, Methane/Nitrogen separation over the zeolite clinoptilolite by the selective adsorption of nitrogen, American Chemical Society, 1983.

9. PLANT COST CALCULATIONS

9.1. Investment cost

There are several methods to determine the investment cost. An more accurate method needs more detailed information than a method that is not so accurate. The following methods in order of accuracy can be used:

- sales method (first indication)
- scale up method (to determine the influence of capacity)
- 'step' method (to compare different pathways), Zevnik-Buckanan, Wilson, Taylor, etc.
- 'factor' method (a global absolute determination), Lang, Holland, Miller, Guthrie, etc.
- office type (a more detailed absolute method)
- detailed method

The factor method is used here to compare new possibilities for the CO plant (improvements) with the already existing plant and to determine the investment cost. The method requires only the available information about the process equipment, furthermore it is relatively easy and quick to use.

9.1.1. The factor method

The investment cost of a plant, determined with the factor method, is based on the purchase costs of the most important pieces of equipment of the process, these are:

- furnaces
- pressure vessels
- columns
- heat exchangers
- compressors
- pumps

To determine the purchase costs of these pieces of equipment the equations of Dr. Ž. Olujić (Lit.9.1) are used; for comparison the prices from Webci (Lit.9.2) are used.
The purchase cost equipment (PCE) is multiplied with two factors, the f_a factor, to determine the Physical Plant Cost (PPC), and the f_b factor, to estimate the Fixed Capital (FC). Thus:

$$PPC = f_a * PCE$$
$$FC = f_b * PPC$$

The f_a and the f_b factor can be found in Table 9.1 (Lit.9.3). For the CO plant no storage facilities are needed, and, as the process streams are all fluids, the f_a factor equals 3.25 and f_b equals 1.45. To determine the total investment cost the working capital (5 to 30% of the fixed capital) must be added to the fixed capital.

Table 9.1. Typical factors for the estimation of project fixed capital cost

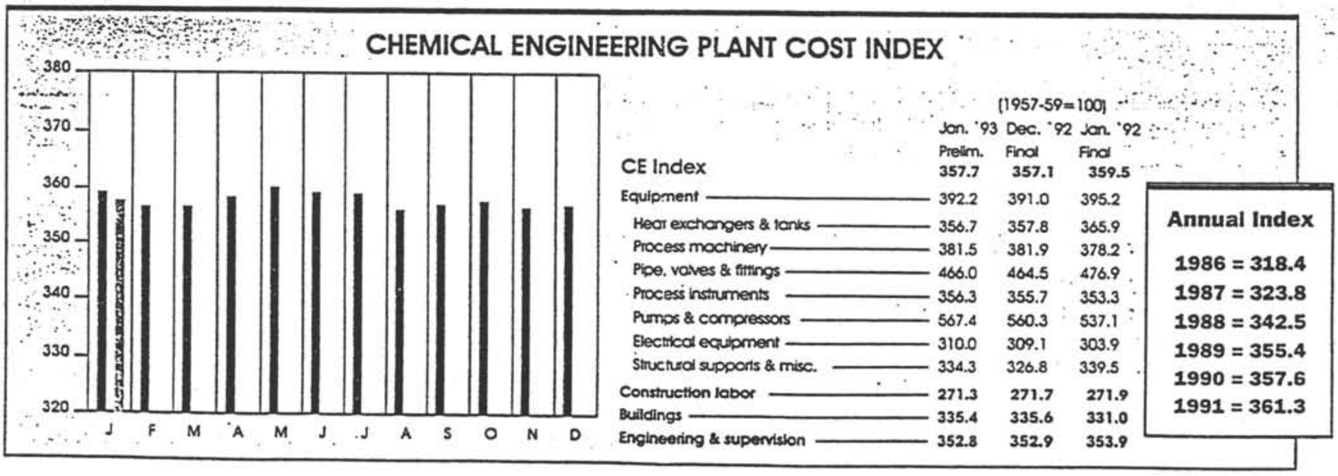
Item	Process type		
	Fluids	Fluids–solids	Solids
1. MAJOR EQUIPMENT, TOTAL PURCHASE COST	PCE	PCE	PCE
f_1 Equipment erection	0·4	0·45	0·50
f_2 Piping	0·70	0·45	0·20
f_3 Instrumentation	0·20	0·15	0·10
f_4 Electrical	0·10	0·10	0·10
f_5 Buildings, process	0·15	0·10	0·05
*f_6 Utilities	0·50	0·45	0·25
*f_7 Storages	0·15	0·20	0·25
*f_8 Site development	0·05	0·05	0·05
*f_9 Ancillary buildings	0·15	0·20	0·30
2. TOTAL PHYSICAL PLANT COST (PPC) PPC = PCE $(1 + f_1 \ldots + f_9)$ = PCE ×	3·40	3·15	2·80
f_{10} Design and Engineering	0·30	0·25	0·20
f_{11} Contractor's fee	0·05	0·05	0·05
f_{12} Contingency	0·10	0·10	0·10
FIXED CAPITAL = PPC $(1 + f_{10} + f_{11} + f_{12})$ = PPC ×	1·45	1·40	1·35

* Omitted for minor extensions or additions to existing sites.

9.1.2. The purchase cost of the equipment

The purchase cost estimation by Dr. Ž. Olujić is given in US dollars ($). The correlations use an I factor to correct for the annual inflation. This index I can be found in the Chemical Engineering Plant Cost Index of the Journal 'Chemical Engineering' (see Table 9.2).

Table 9.2. The chemical engineering plant cost index.



CHEMICAL ENGINEERING PLANT COST INDEX

(1957-59=100)

	Jan. '93 Prelim.	Dec. '92 Final	Jan. '92 Final
CE Index	**357.7**	**357.1**	**359.5**
Equipment	392.2	391.0	395.2
Heat exchangers & tanks	356.7	357.8	365.9
Process machinery	381.5	381.9	378.2
Pipe, valves & fittings	466.0	464.5	476.9
Process instruments	356.3	355.7	353.3
Pumps & compressors	567.4	560.3	537.1
Electrical equipment	310.0	309.1	303.9
Structural supports & misc.	334.3	326.8	339.5
Construction labor	**271.3**	**271.7**	**271.9**
Buildings	**335.4**	**335.6**	**331.0**
Engineering & supervision	**352.8**	**352.9**	**353.9**

Annual Index

1986 = 318.4
1987 = 323.8
1988 = 342.5
1989 = 355.4
1990 = 357.6
1991 = 361.3

For the different pieces of equipment the following I values were found (December 1992):

Table 9.3. The I values of different pieces of equipment

Type of equipment	CE index
Furnace	357.8
Pressure vessel	357.8
Column	357.8
Internals	357.8
Packing	391.0
Heat exchanger	357.8
Compressor and pump	560.3
Driver	381.9

9.1.2.1. The furnace

The correlation developed for furnaces includes both the furnaces for heating the process fluids and the cracking and the reforming furnaces:

$$C_{fu} = C_{fuo} * F_m * F_p * F_t * (I/336.2) \qquad (9.1)$$

Here C_{fuo} (US \$) is the base cost (mid 1985), F_m (-) the material of construction factor, F_p (-) the design pressure cost factor, I (-) the Chemical Engineering Plant Cost Index and 336.2 the CEPC index for this type of equipment in 1985. The corresponding cost factors can be found in the following table, and the base cost is correlated against the heat transfer duty ($3000 < Q(kW) < 150000$):

$$C_{fuo} = \exp(5.639 + 0.85*\ln Q) \qquad (9.2)$$

Table 9.4. Cost factors of furnaces

Material of construction	F_m	Design pressure (bar)	F_p	Type of furnace	F_t
Carbon steel	1	10	1	Heater	1
Alloy steel	1.36	50	1.1	Pyrolysis	1.1
Stainless steel	1.6	100	1.25	Reformer	1.5

9.1.2.2. The pressure vessel

Pressure vessels are columns, drums, tanks and reactor shells. The cost of a pressure vessel is calculated from:

$$C_{pv} = C_{pvo} * F_m * F_p * (I/336.2) \qquad (9.3)$$

The correlation for the base cost is:

$$C_{pvo} = (a + b*l)*d^{1.1} \qquad (9.4)$$

where l (m) is the length or height of the vessel and d (m) the corresponding internal diameter. The values of the coefficients a and b are given in Table 9.5.

Table 9.5. Vessel coefficients.

Vertical vessels	a	b	Horizontal vessels	a	b
1.5 < l(m) < 5	1500	1100	1.5 < l(m) < 6	890	705
5 < l(m) < 90	1294	1141	6 < l(m) < 25	512	768

Table 9.6. Cost factors for material of construction and design pressure

Material of construction	F_m	Pressure (bar)	F_p
Carbon steel (CS)	1	1 - 5	1
CS, SS-lined	2.3	5 - 10	1.1
Stainless steel (SS)	3.7	10 - 20	1.2
CS, Monel-lined	3.9	20 - 30	1.4
Monel	6.4	30 - 40	1.6

9.1.2.3. The column

The shells of columns may be considered as vertical pressure vessels, therefore correlation (9.3) can be used for prediction of the corresponding price. In addition the cost of column internals has to be estimated. Hence, the correlation for the cost of a distillation, absorption or desorption column is:

$$C_{co} = C_{pv,vert} + C_{int} \qquad (9.5)$$

where index 'vert' denotes vertical pressure vessel and index 'int' the cost of column internals which differs for tray and packed columns.

9.1.2.3.1. Correlations for cost of trays

The cost of trays may be estimated by:

$$C_{int} = N_{tr} * C_{tr} * F_m * F_{nt} * F_{tt} * (I/336.2) \qquad (9.6)$$

where N_{tr} (-) is the number of trays in the column, F_{nt} (-) cost factor for the number of trays and F_{tt} (-) cost factor for the tray type. C_{tr} (US \$) is the base cost for a valve tray of carbon steel, which may be estimated for columns with internal diameters d (m) from 0.3 to 4 m by:

$$C_{tr} = 58.7 + 88.4*d + 52.9*d^2 \qquad (9.7)$$

Values of characteristic cost factors are given in Table 9.7.

Table 9.7. Characteristic cost factors of trays.

Tray type	F_{tt}	Material of construction	F_m	Number of trays	F_{nt}
Sieve	1	CS	1	20	1
Valve	1.45	SS	1.7	10	1.5
Bubble cap	2.90			7	2
Grid	0.90			4	2.5
				1	3

9.1.2.3.2. Cost of packings

The prices for random packings obtained in 1990 are ± 5000 f/m^3 or ± 2940 \$/m^3 (1 \$ = *f*1.7) for pall rings (stainless steel) with a diameter of 50 mm. For distributers the prices are ± 6000 f/m^3 or ± 3530 \$/m^3. For cost updating the given prices must be multiplied with (I/393), where I is the CE index of packings (I=391).

9.1.2.4. The heat exchanger (shell and tube)

The cost of a shell and tube heat exchanger is calculated from:

$$C_{he} = C_{heo} * F_p * F_t * (I/336.2) \qquad (9.8)$$

C_{heo} (US \$) is the base cost, which is given as a function of the transfer area A (m^2).

$$C_{heo} = \exp(a + b*\ln A) \qquad (9.9)$$

The values of coefficients a and b as well as the values of corresponding cost factors are given in Tables 9.8 and 9.9.

Table 9.8. The coefficients of shell and tube heat exchangers.

Material of construction Shell/Tube		a	b
CS/CS	$10 < A(m^2) < 900$	7.085	0.656
CS/Brass	$10 < A(m^2) < 900$	6.980	0.7133
CS/SS	$10 < A(m^2) < 900$	6.587	0.9955
SS/SS	$10 < A(m^2) < 60$	7.439	0.8861
SS/SS	$60 < A(m^2) < 900$	8.6063	0.601

Table 9.9. The cost factors of shell and tube heat exchangers.

Design pressure (bar)	F_p	Type of heat exchanger	F_t
1 - 10	1	Kettle reboiler	1.4
10 - 20	1.1	Floating head	1
20 - 30	1.25	U-tube	0.85
30 - 50	1.3	Fixed tube	0.8
50 - 70	1.5		

9.1.2.5. The compressor

The cost of gas transporting equipment does not include a driver, whose cost must be estimated separately. The correlation includes the cost of the base device and a material of construction cost factor:

$$C_{com} = C_{como} * F_m * (I/418.3) \qquad (9.10)$$

where the base cost C_{como} is correlated against the power consumption (kW):

$$C_{como} = [\exp(a + b*\ln P)] * 0.6 \qquad (9.11)$$

The values of the coefficients corresponding to the common compressor types and the cost factors for the material of construction are given in Table 9.10.

Table 9.10. Coefficients and cost factors of the compressor.

Type of compressor	a	b	Type of compressor	F_m		
				CS	SS	Ni-alloys
Axial, centrifugal, reciprocating (30 < P < 10000)	6.628	0.968	Axial	1	5.8	14.1
			Centrifugal	1	4.5	10.5
			Reciprocating	1	5	12
Rotary (30 < P < 1000)	7.817	0.618	Rotary	1	4	9

9.1.2.5.1. The driver (electric motor)

For standard electric motors the following correlation may be used:

$$C_{em} = C_{emo} * F_t * F_{red} * (I/331.2) \tag{9.12}$$

where F_{red} is a factor which takes into account the cost of the reduction in the number of revolutions. Common value is 1 but in the cases when the reduction is needed then the value 1.35 should be used. The values of the F_t factor are 1.4 for explosion proof motors and 0.75 for open drip proof motors. The reference price is for a totally enclosed electric motor and is correlated against the required brake power ($0.5 < P(kW) < 5000$):

$$C_{emo} = \exp\,[5.33 + \ln P *(0.3 + \ln P * (0.162 - 0.014 * \ln P))] \tag{9.13}$$

9.2. Operating costs

An estimation of the operating costs is needed to judge the viability of a project and to chose between possible alternative processing schemes. Generally the operating costs are divided into two groups, the fixed costs and the variable costs.

Fixed costs:

1. Maintenance (labour and materials)
2. Operating labour
3. Laboratory costs
4. Plant overheads
5. Capital charges
6. Rates (and any other local taxes)
7. Insurance
8. Licence fees and royalty payments

Variable costs:
1. Raw materials
2. Miscellaneous operating materials
3. Utilities
4. Shipping and packaging

The costs listed above are direct costs of producing the product at the plant site. In addition to these costs, the site will have to carry its share of the Company's general operating expenses. These will include:

1. General overheads
2. Research and development costs
3. Sales expense
4. Reserves

All these various components of the operating costs are summarized in Table 9.11. This table will be used to estimate the total production costs.

Table 9.11. Summary of the operating costs.

Variable costs	*Typical values*
1. Raw materials	from flow-sheets
2. Miscellaneous materials	10 per cent of item (5)
3. Utilities	from flow-sheet
4. Shipping and packaging	usually negligible
Sub-total A	....
Fixed costs	
5. Maintenance	5–10 per cent of fixed capital
6. Operating labour	from manning estimates
7. Supervision	20 per cent of item (6)
8. Plant overheads	50 per cent of item (6)
9. Capital charges	15 per cent of the fixed capital
10. Insurance	1 per cent of the fixed capital
11. Rates	2 per cent of the fixed capital
12. Royalties	1 per cent of the fixed capital
Sub-total B	....
Direct production costs A + B	....
13. Sales expense	20–30 per cent of the direct production cost
14. General overheads	
15. Research and development	
Sub-total C	....
Annual production cost = A + B + C =	....

$$\text{Production cost £/kg} = \frac{\text{Annual production cost}}{\text{Annual production rate}}$$

9.3. Calculations of the investment cost

9.3.1. Design process

The purchase costs of the equipment are given below. The prices calculated with the method of Dr. Ž. Olujić are compared with the Webci prices (guilders are converted to US dollars, 1 dollar equals 1.7 guilders).

Table 9.12. The purchase cost of the furnace (reformer).

Equipment code	Number	PCE according to Olujić (10^3 x \$)	PCE according to Webci (10^3 x \$)
H-2101	1	857.5	857.5
TOTAL PCE		857.5	857.5

Webci has no prices for furnaces, so the same prices as Olujić are taken.
The price for the catalyst in the reformer is 30 guilders per litre or 18 \$ per litre. The total price is 1560 x 18 (\$) = 28 x 10^3 US \$.

Table 9.13. The purchase costs of the catalyst.

TOTAL PCE (10^3 x \$)	28

Table 9.14. The purchase costs of the pressure vessels.

Equipment code	Number	PCE according to Olujić (10^3 x \$)	PCE according to Webci (10^3 x \$)
V-2101	1	5.7	11
V-2102	2	8.1	12
V-2103	1	5.2	13
V-2104	1	19.3	14
V-2107	1	12.7	15
V-2108	1	11.0	15
V-2109	1	8.1	14
V-2110	1	15.5	10
V-2111	1	2.0	10
V-2112	1	8.1	12
V-2113	2	6.9	14
V-2114	2	5.2	14
V-2115	1	5.2	11
V-2116	1	3.0	10
V-2117	3	3.3	11
V-2119	1	1.8	10
TOTAL PCE		148.3	253

Table 9.15. The purchase costs of the columns without trays and packings.

Equipment code	Number	PCE according to Olujić (10^3 x \$)	PCE according to Webci (10^3 x \$)
V-2105	1	24.1	83
V-2106	1	57.6	131
V-2118	3	12.1	38
T-21	1	89.0	68
T-22	1	23.0	54
T-23	1	14.1	37
T-24	1	13.1	37
TOTAL PCE		257.2	524

Table 9.16. The purchase costs of the trays of the columns.

Equipment code	Number	PCE according to Olujić (10^3 x \$)	PCE according to Webci (10^3 x \$)
V-2105	1	0.5	0.4
V-2106	1	3.3	2.1
V-2118	3	0.7	-
T-21	1	5.9	2.2
T-22	1	13.4	3.0
T-23	1	8.9	1.4
T-24	1	8.9	1.4
TOTAL PCE		43.0	10.5

Table 9.17. The purchase costs of the packings (Pall rings and distributors) of the columns.

Equipment code	Number	PCE according to Olujić (10^3 x \$)	PCE according to Webci (10^3 x \$)
V-2105	1	19.1	27.0
V-2106	1	19.9	25.7
V-2118	3	-	-
TOTAL PCE		39.0	52.7

The purchase cost of MEA in the columns V-2105 and V-2106 is calculated by subtracting the packing volumes (11.7 m^3) from the column volumes (22.31 m^3) and adding 10% for the MEA in the pipes. The price of MEA is ƒ1.94/kg or 1.14 $/kg, so the total purchase cost of MEA is 13 x 10^3 $.

Table 9.18. The purchase cost of MEA.

TOTAL PCE (10^3 x $)	13

Table 9.19. The purchase costs of the heat exchangers.

Equipment code	Number	PCE according to Olujić (10^3 x $)	PCE according to Webci (10^3 x $)
H-2102	1	3.4	10
H-2103	1	15.2	27
H-2104	1	7.0	20
H-2105	2	5.4	12
H-2106	1	8.9	16
H-2107	1	13.3	18
*H-2108	1	14.1	32
*H-2109A	1	12.3	25
*H-2109B	1	25.0	30
*H-2110	1	59.0	78
*H-2111	1	36.2	45
*H-2112	1	18.4	30
H-2113	2	6.6	15
*H-2114	2	5.1	14
*H-2115	3	8.5	18
*H-2116	1	4.6	13
*H-2117	1	4.5	13
H-2118	2	7.1	16
H-2119	2	4.1	12
*H-2120	1	3.7	14
E-21	1	14.5	21
E-22	1	42.7	25
E-23L	1	126.7	53
E-23U	1	184.9	88
E-24	1	10.2	16
E-25	1	10.2	16
E-27	1	10.2	16
TOTAL PCE		706.8	797

The heat exchangers denoted with * are U-tubes, and their prices are 10-15% more expensive than the prices for heat exchangers given by Webci. Therefore 15% is taken into account in the prices of the U-tubes.

Table 9.20. The purchase costs of the compressors and ventilators.

Equipment code	Number	PCE according to Olujić (10^3 x $)	PCE according to Webci (10^3 x $)
K-2101	2	12	12
K-2102	2	7	7
K-2103	4	102.6	94
K-2104	3	151.9	126
K-2105	4	72.6	62
TOTAL PCE		1194.6	1041

K-2101 and K-2102 are ventilators. Olujić has no prices for these equipment, therefore the same prices as Webci are taken.

Table 9.21. The purchase costs of the drivers.

Equipment code	Number	PCE according to Olujić (10^3 x $)	PCE according to Webci (10^3 x $)
K-2103	4	19.2	31
K-2104	3	26.7	35
K-2105	4	14.2	15
TOTAL PCE		213.7	290

The purchase costs, the fixed capital and the investment cost of the whole plant (design) are given in Table 9.22.

Table 9.22. The investment costs of the design plant.

10^3 x US $	according to Olujić	according to Webci
Total PCE	3502	3867
Total PPC PPC=f_a*PCE	11380	12568
Fixed Capital FC=f_b*PPC	16501	18223
Working Capital (10%)	1650	1822
Investment cost	18151	20046

9.3.2. The new process (only extra CO_2)

For the new process a CO_2 storage tank is needed with a volume of 15 m^3 and several heat exchangers have to be expanded by adding some new heatexchangers. The purchase costs can be found in the Tables 9.23 and 9.24.

Table 9.23. The purchase cost of a storage tank.

Equipment code	PCE according to Olujić (10^3 x \$)	PCE according to Webci (10^3 x \$)
CO_2 storage tank	11.7	29

Table 9.24. The heat exchangers.

Equipment code	Number	Extra transfer area (m^2)	PCE according to Olujić (10^3 x \$)	PCE according to Webci (10^3 x \$)
H2108 extra	1	7.63	4.1	13.5
H2109A extra	1	6.21	3.9	12.9
H2109B extra	1	6.21	4.4	18.3
H2110 extra	1	14.2	10.1	25.0
H2111 extra	1	8.0	5.7	19.6
H2112 extra	1	5.0	3.3	12.2
H2113 extra	2	3.0	2.3	9.7
H2114 extra	1	2.0	1.9	10.8
H2115 extra	1	2.0	2.2	10.8
H2115 extra	2	3.5	3.0	11.5
H2116 extra	1	1.5	1.8	10.8
H2117 extra	1	1.5	1.5	10.8
H2118 extra	2	7.0	4.0	11.5
H2119 extra	1	4.0	2.8	10.0
H2120 extra	1	1.5	1.4	10.8

The other equipment remains the same. The investment cost is shown in Table 9.25.

Table 9.25. The investment cost.

10^3 x US $	according to Olujić	according to Webci
Extra PCE	73	260
Extra PPC (f_a = 2.55)	187	663
Extra FC (f_b = 1.45)	271	961
Total fixed capital	16772	19184
Investment cost	18449	21102

9.3.3. The new process (using extra CO_2 and a pre-reformer)

For the new process a CO_2 storage tank is needed with a volume of 15 m^3 and and a pressure vessel with catalyst. The total amount of catalyst needed per year remains the same, because due to the pre-reformer the life time of the catalyst in the reformer increases. The purchase costs can be found in the Tables 9.26 and 9.27.

Table 9.26. The purchase cost of a storage tank.

Equipment code	PCE according to Olujić (10^3 x $)	PCE according to Webci (10^3 x $)
CO_2 storage tank	11.7	29

Table 9.27. The purchase cost of a pressure vessel

Equipment code	PCE according to Olujić (10^3 x $)	PCE according to Webci (10^3 x $)
pre-reformer vessel	12.0	20

The other equipment remains the same. The investment cost is shown in Table 9.28.

Table 9.28 The investment cost.

10^3 x US $	according to Olujić	according to Webci
Extra PCE	24	49
Extra PPC (f_a = 2.55)	61	125
Extra FC (f_b = 1.45)	88	181
Total fixed capital	16589	18404
Investment cost	18640	20244

9.4. Calculation of the operating costs

9.4.1 Design process (KTI)

The annual operating costs are calculated by using Table 9.11 and the investment cost determined by Olujić. The operating time is 95% of one year, 345 days/year or 8280 hours/year.

A. The variable costs:	
1.Raw materials	
- Natural gas 0.19 Dfl/Nm^3 or 0.00277 \$/mol	
53.1 kmol/h x 8280 h/y x 0.00277 \$/mol	1218 x 10^3 \$
- Boiler feed water 1.15 Dfl/m^3 or 0.68 \$/m^3	
6.466 m^3/h x 8280 h/y x 0.68 \$/m^3	36 x 10^3 \$
2.Miscellaneous materials	165 x 10^3 \$
3.Utilities	
- Electricity for compressors	
2260 kW x 8280 h/y x 0.064 Dfl/kWh (or 0.038 \$/kWh)	704 x 10^3 \$
- Degradation costs of the catalyst	
1/5 y^{-1} x 28,000 \$	6 x 10^3 \$
- Degradation costs of MEA	
0.4 y^{-1} x 11670 kg x 1.14 \$/kg	5 x 10^3 \$
4.Shipping and packaging - not applicable	

Subtotal A	2134 x 10^3 \$

B. The fixed costs:	
5.Maintenance	1650 x 10^3 $
6.Operating labour	
Four manpower are needed to operate the plant continuously. One continuous manpower costs ƒ350,000 per year or 206,000 $ per year.	824 x 10^3 $
7.Supervision	165 x 10^3 $
8.Plant overheads	412 x 10^3 $
9.Capital charges	2475 x 10^3 $
10.Insurance	165 x 10^3 $
11.Rates	330 x 10^3 $
12.Royalties	165 x 10^3 $
Subtotal B	6186 x 10^3 $
Direct production costs A + B	8320 x 10^3 $
C. Share of the Company's general operating expenses (25% of the direct production costs)	
13.Sales expense	
14.General overheads	
15.Research and development	
Subtotal C	2080 x 10^3 $
Annual operating costs (A + B + C)	10400 x 10^3 $
Production cost (1221.4 kg CO/h)	1.03 $/kg.

9.4.2. The new process (using only extra CO_2)

For the variable costs just the prices for raw materials and miscellaneous change:

1. Raw materials
   - Natural gas: 50.1 kmol/h x 8280 h/y x 0.00277 $/mol = 1149 x 10^3 $
   - Carbondioxyde: 14.2 kmol/h x 44.0 kg/kmol x 8280 h/y x 0.185/1.7 $/kg = 584 x 10^3 $
2. Miscellaneous materials = 168 x 10^3 $

Subtotal A = 2652 x 10^3 $

For the fixed costs only the costs for operating labour, supervision and plant overheads don't change. The other costs will be:

5. Maintenance = 1677 x 10^3 $
9. Capital charges = 2516 x 10^3 $
10. Insurance = 168 x 10^3 $
11. Rates = 335 x 10^3 $
12. Royalties = 168 x 10^3 $

Subtotal B = 6265 x 10^3 $

The direct production costs (A + B) are 8917 x 10^3 \$, therefore the subtotal of C (25% of the direct production costs) is 2229 x 10^3 \$.

The annual operating costs for the new process are 11146 x 10^3 \$ and the production cost for CO will be (55.402 kmol CO/h x 28 kg/kmol x 8280 h/y)$^{-1}$ x 11146 x 10^3 \$/y = 0.87 \$/kg.

9.4.3. The new process (using extra CO_2 and a pre-reformer)

For the variable costs just the prices for raw materials and miscellaneous change:

1. Raw materials
   - Natural gas: 50.2 kmol/h x 8280 h/y x 0.00277 \$/mol = 1151 x 10^3 \$
   - Carbondioxyde: 13.9 kmol/h x 44.0 kg/kmol x 8280 h/y x 0.185/1.7 \$/kg = 550 x 10^3 \$
2. Miscellaneous materials = 168 x 10^3 \$

Subtotal A = 2620 x 10^3 \$

For the fixed costs only the costs for operating labour, supervision and plant overheads don't change. The other costs will be:

5. Maintenance = 1660 x 10^3 \$
9. Capital charges = 2488 x 10^3 \$
10. Insurance = 166 x 10^3 \$
11. Rates = 332 x 10^3 \$
12. Royalties = 166 x 10^3 \$

Subtotal B = 6213 x 10^3 \$
The direct production costs (A + B) are 8833 x 10^3 \$, therefore the subtotal of C (25% of the direct production costs) is 2208 x 10^3 \$.

The annual operating costs for the new process are 11041 x 10^3 \$ and the production cost for CO will be (53.809 kmol CO/h x 28 kg/kmol x 8280 h/y)$^{-1}$ x 11041 x 10^3 \$/y = 0.89 \$/kg.

LITERATURE

9.1. Olujić, Ž., 'Approximate Design and Costing of Equipment used in Absorption, Destillation, Extraction and Stripping processes'. Laboratory for Process Equipment, TU Delft, 1991.

9.2. Webci, Wubo, 'DACE-prijzenboekje', 16th edition. Dutch Association of Cost Engineers, Leidschendam, 1992.

9.3. Richardson, J.F., Coulson, J.M., 'Chemical Engineering - volume 6'. Pergamon, New York, 1983.

9.4. Montfoort, A.G., 'De Chemische Fabriek'. Faculteit der Scheikundige Technologie en der Materiaalkunde, TU Delft, 1990.

10 ALTERNATIVE METHODS FOR CO-PRODUCTION

10.1 Possibilities for CO-production

10.1.1 Coal Gasification

Another process to make CO is coal gasification. In this process solid coal is reformed into gaseous CO and sometimes, depending on the feed, H_2 which has to be separated later in the process. Coal is gasified in either by partial combustion or by CO_2-hydro-gasification. Very often a process is a combination of both modes, depending on the product desired. The main reactions that take place in a coal gasifier are :

$C + H_2O$	$\rightleftharpoons$	$CO + H_2$	Hydrogasification
$CO + H_2O$	$\rightleftharpoons$	$CO_2 + H_2$	Hydrogasification
$C + \frac{1}{2} O_2$	$\rightleftharpoons$	CO	Partial oxidation
$C + CO_2$	$\rightleftharpoons$	$2\ CO$	CO_2 gasification

The product needed is CO, thus when you look at the reactions it is obvious that reactions with O_2 and CO_2 are preferred. In practice gasification of coke can be carried out in a fixed bed slagging gasifier which is continuously operated at slightly above atmospheric pressure. A possible scheme is illustrated in fig.10.1.

The feed needed for this process contains O_2 ,CO_2, sized coal and flux (typically limestone). Flux is added to the coal in order to obtain favorable ash melting temperatures and slag viscosities. The solid feed is fed to the reactor via a fully automatic controlled system consisting of conveyors, bunkers, chutes and locks. The gaseous feed (CO_2 and O_2) is injected in the reactor's bottom section via a mixing tube. The generated gas ascends countercurrently to the coal bed and the crude gas leaves the reactor at about 870 °C at the top with a CO concentration of 90-92 % depending on feedstock qualities. Some coke fines are also carried over from the reactor along with the crude gas stream. These fines are separated in a cyclone and recycled to the reactor. After the cyclone the crude gas is passed through a scrubber where it is water saturated and cooled. Here the gas is not only cooled but also residual traces of dust are being removed. Finally, the crude gas is cooled to 35 °C. At the bottom liquefied coke ash (slag) is removed batchwise with a automatic deslagging system. Of course the gasproduction continuous during deslagging.

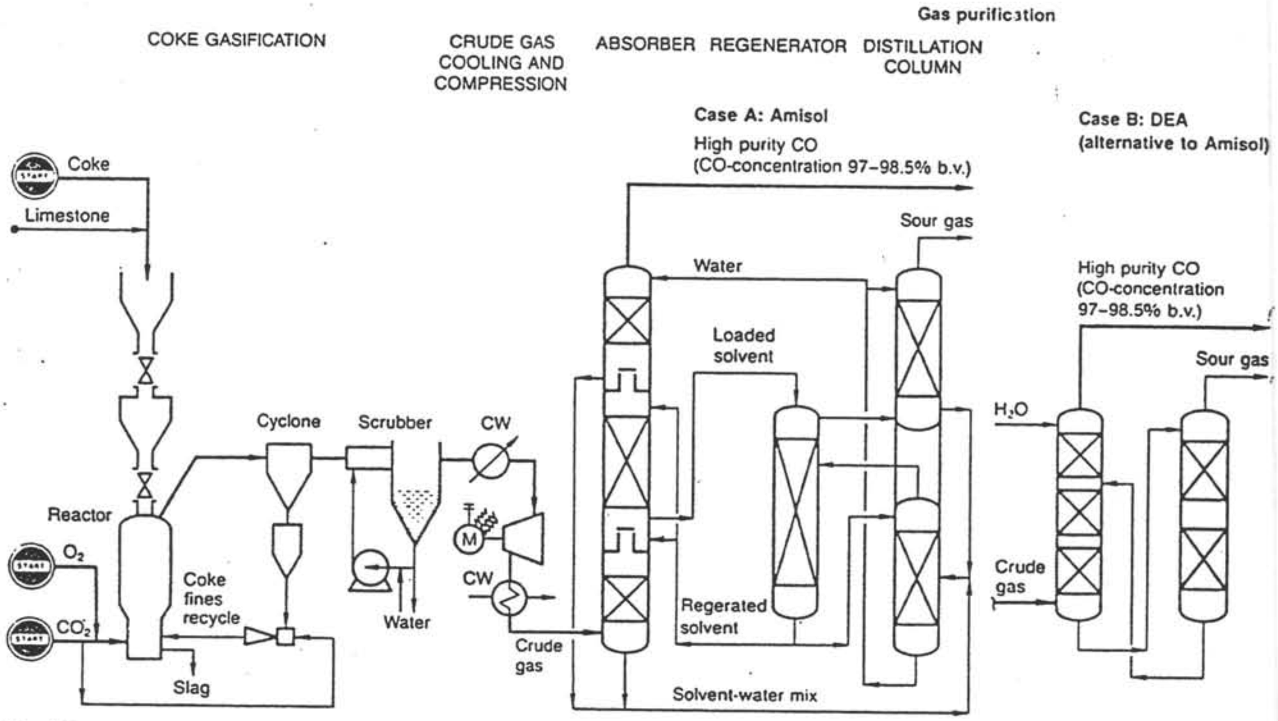


fig.10.1 : scheme for coke gasification and gas purification units.

After the reactor the crude gas contains about 90-92 % CO. To remove the CO_2 there are some different methods. In [1] there are two options mentioned, the Amisol process and the DEA process. The Amisol process is more expensive but applied if there are stringent requirements with respect to sulfur compounds. The Amisol is capable of removing all sulfur compounds down to a level of less than 0.1 ppm total sulfur.

The Amisol process works with a mixture of two solvents, consisting of diethylamine (chemical solvent) and methanol (physical solvent). The DEA process on the other hand has only a chemical solvent diethanolamine in water. This is a cheaper process which can be selected when a sulfur concentration of approx. 500 ppm is acceptable.

After the CO_2 removal a CO concentration of 97 to 98.5% by volume is available. This CO makes a good feedstock for most syntheses. This process is commercially proven by Lurgi GmbH ,Frankfurt, Germany. Both investment and operating costs are rather competitive in comparison to processes based on natural gas. Investment costs come out rather low because:

* After the reactor the CO concentration is much higher in comparison to the CO concentration for processes based on natural gas. 90 to 92 % for the coke process versus 28 % for the natural gas process. This makes the gas volume to be handled much lower; hence smaller equipment size will do latter in the process.
* Normally no gas separation unit is required as a CO concentration of 98+ % can be achieved just by removal of CO_2 and sulfur compounds.

Also the operating costs are rather low because of:

- Low specific consumption figures for coke, O_2 and CO_2 due to the high selectivity for CO of the gasification process.
- Low specific utility consumption rates like electricity and cooling water. This is also based on the high selectivity for CO, plus the fact that a gas separation unit is not normally required.

The costs for producing one ton of CO are given below in table 10.1 and are for a CO plant with a capacity of minimal 6.5 ton/hour. When in a natural gas plant the hydrogen only can be used as fuel, the gasification process is 70 to 100 % below the cost of CO production in a natural gas plant. lit.[10.1]. The reason of not seriously being a candidate for an alternative production process is the minimum capacity for being competitive. It is only economical attractive with a production of at least 6.5 ton/hour. The current capacity for the two GEP plants is about 2.2 ton/hour.

Of course there are other reactor types which are not of the moving bed type but are entrained flow reactors. They operate at higher temperatures with greater mass flow; hence the entrained flow reactors are only economical at higher capacity.

Table 10.1: Cost in DM for the production of one ton CO (1986).

coke	0.36 t	DM 300 / t	108
oxygen	200 Nm^3	DM 0.16 / t	32
CO_2	250 Nm^3	DM 0.14 / t	35
limestone	0.02 t	DM 100 / t	2
electrical power	75 kWh	DM 0.12 / t	9
cooling water	18 m^3	DM 0.1 / t	2
labor	6 pers.	DM 60.000/year	7
capital investment			65
total production cost for one ton CO			260

10.1.2 The CO_2 reformer

For the alternative CO production plant a reformer is used which has the same principle as the reformer of the existing plant. The reformer consists of the same compositions as the existing reformer: vertical tubes with catalyst, heaters in the wall but the reformer has a different feed composition due to different feed and different recycle streams.

The total feed to the reformer (feed + reflux) is given in table 10.2.

Table 10.2 : feed composition alternative reformer

reformer feed	kmol/h
CH_4	40.75
CO_2	58.33
N_2	13.6
H_2O	113.0

In the reformer the following reactions describe the CO-conversion:

1) $CH_4 + H_2O \rightleftharpoons CO + 3H_2$
2) $CO + H_2O \rightleftharpoons CO_2 + H_2$

with:

$$K_1 = \exp\left[-\frac{27464}{T} + 30.707 \right] \tag{10.1}$$

$$K_2 = \exp\left[\frac{4084}{t} - 3.765 \right] \quad \text{(only for T > 773 K)} \tag{10.2}$$

The calculations for this equilibrium reactions are calculated with mercury at 860 K. The result of these calculations is the output of the reformer (table 10.3).

Table 10.3: alternative reformer output

reformer output	kmol/h
CH_4	1.942
CO_2	42.15
N_2	13.6
H_2O	90.38
CO	55.00
H_2	100.2

To prevent coke forming in the reformer, according to group 1, a equation which shows a coke forming value is mentioned:

$$\frac{1/2CO_2 + H_2O}{CH_4} > 3.0 \tag{10.3}$$

For this situation the coke forming value is 3.5, which is good enough.

10.2 Membranes for H_2 separation

Below are some possible H_2 membrane applications:

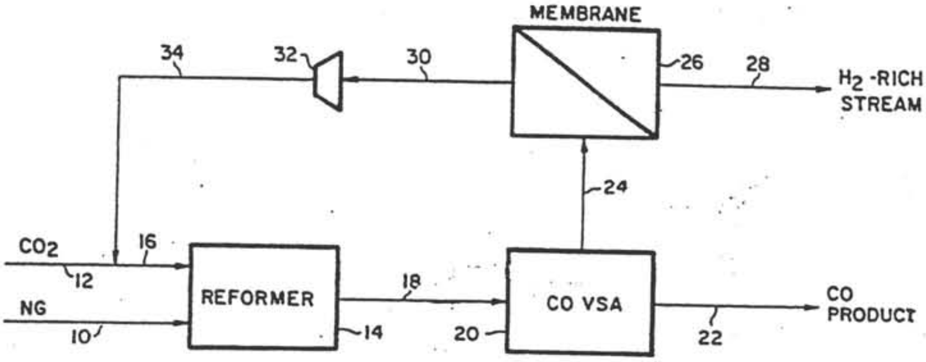


fig. 10.4: H_2 membrane system: first CO recovery

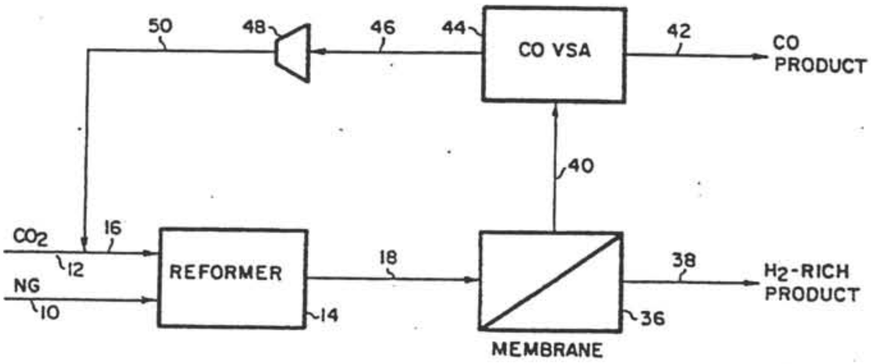


fig. 10.5: H_2 membrane system: first H_2 recovery

The difference between the alternative processes above in fig. 10.4 and fig. 10.5 is that the hydrogen and carbon monoxide separation stages are reversed. When the H_2 membrane separation comes before the CO removal, the membrane stage sees a heightened partial pressure of carbon monoxide and therefore more carbon monoxide is lost through the membrane as permeate in the hydrogen-rich stream. Thus recovery of carbon monoxide in fig. 10.5 is much lower than the recovery of CO in fig. 10.4. (92 % vs 99 %). That is the reason why in the next alternatives always first CO recovery takes place and later the H_2 recovery.

In this membrane process the carbon monoxide lean gas mixture enters a H_2-rejection membrane stage in which H_2 permeates through a membrane to the low pressure side of the membrane as permeate, while the remaining gas mixture passes over the surface of the membrane as the reject stream. A preferred membrane that is selective for hydrogen over the remaining constituents of the gas mixture comprising CO, CO_2, CH_4, N_2, Ar is polymeric cellulose acetate or polysulfone. It should be noted that, as an alternative, the feed stream to the membrane can be boosted in a compressor to aid the H_2 separation in the membrane.

The advantage of using a H_2 membrane separation unit is the high product purity (95-99%) and the high recovery (85%). The right feed condition necessary for a high recovery is a high feed concentration. The H_2 concentration after the CO separation is about 69 %, which is not extremely high.
The disadvantages of using a H_2 membrane unit is the large pressure drop on the product side. Also a H_2 membrane has a poor CO_2 and H_2O separation selectivity. Because the H_2 rich stream consists (except H_2) mainly of CO_2, a membrane system is not recommendable.

A recent (1990) study lit.[10.4] of separating H_2 from coal-gas has indicated that for 99.5 % purity membrane, the separation efficiency is only 40 %. This is the result of bad feed conditions.

10.3 PSA for CO - H_2 separation

The design of the H_2 PSA system

Separation by an adsorptive process is based on the selective adsorption of one or more components of a gas mixture on the surface of a microporous solid. When a gaseous mixture is exposed to an adsorbent for a sufficient time, the gas phase becomes richer in the less selective adsorbent. Desorption can be achieved either by increasing the temperature or by reducing the adsorbate pressure. Thus, the adsorptive separation process consists of a cyclic sequence of adsorption and desorption steps. When desorption is achieved by decreasing the partial pressure of the selective component, the process is called pressure swing adsorption (PSA). A modern pressure swing adsorption system is made up of four or five pressure vessels containing an appropriate adsorbent (adsorbent beds) with interconnecting piping and valving with an automatic control device as shown in fig.10.6

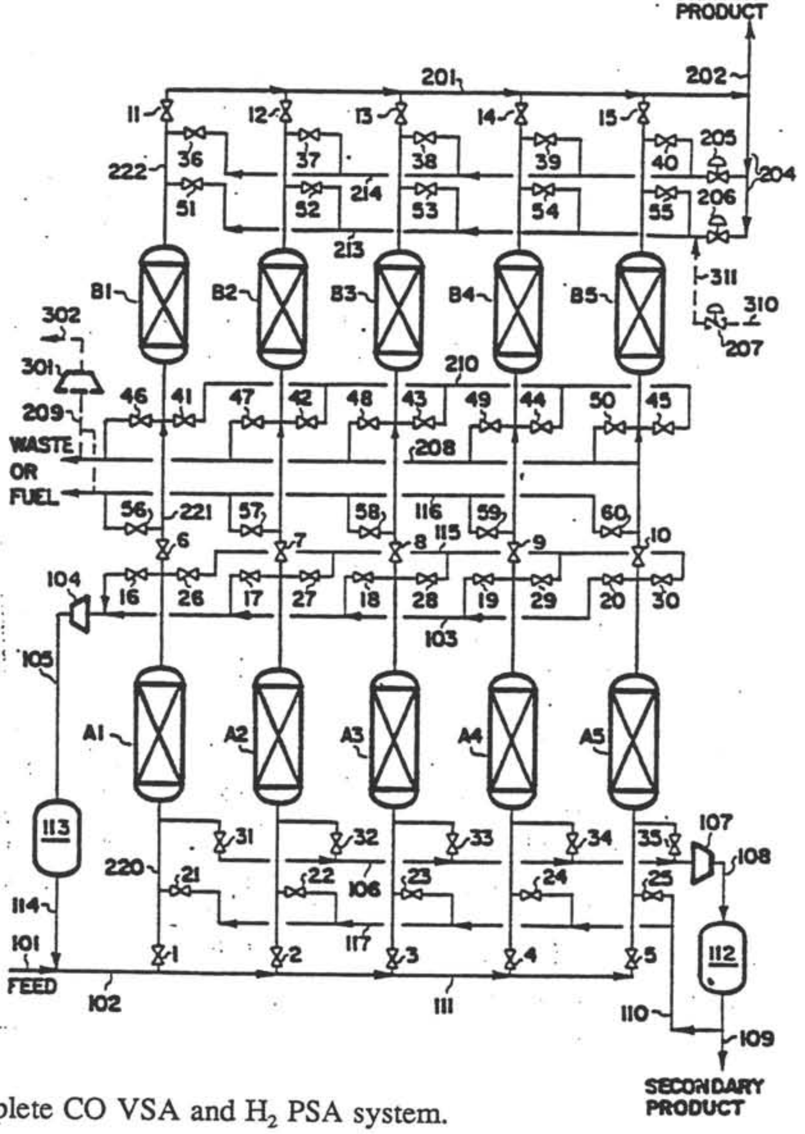


fig 10.6 : complete CO VSA and H_2 PSA system.

In the A-beds the H_2 adsorbent is placed and in the B-beds the CO adsorbent is placed. Hence the primary product is Carbon Monoxide and the secondary product is hydrogen.

The adsorbent - in this case of the type 5A Zeolite sieves - is selected on the basis of the application requirements. This zeolite has a greater affinity for carbon-dioxide, methane and carbon monoxide than for hydrogen.

With the equation according to White lit.[10.5], the fluidization limit for packed beds is determined, and with that the minimal column diameter. The maximum interstitial velocity according to White:

$$v_s(\max) = -\frac{\mu E_1}{2\rho_0 E_2} + \sqrt{\left(\frac{\mu E_1}{2\rho_0 E_2}\right)^2 + \frac{\rho_a g}{\rho_0 E_2}} \qquad (10.4)$$

with:

μ = viscosity in Pa s
ρ_o = density of the gas in kg/m^3
ρ_a = density of the adsorbent (zeolite 5A) in kg/m^3

and:

$$E_1 = 1471\frac{(1-\epsilon)^2}{\epsilon^3 D_p^{\,2} g} \qquad E_2 = 17.16\frac{(1-\epsilon)}{\epsilon^2 D_p g} \qquad \begin{matrix}(10.5)\\(10.6)\end{matrix}$$

with:

ε = total void factor
D_p = particle diameter

From the maximum velocity, the minimal column diameter is determent with the minimal area :

$$A = \frac{\omega_0}{\rho_0 v_s} \qquad (10.7)$$

with:

ω_0 = mass flow in kg/s

An estimation of the column height can be determined from the amount adsorbents necessary for the adsorption of the residual components.

$$L = \frac{1}{A\rho_a n_k} * \sum \frac{\phi_{mol,i}\, t_c}{(Q_{a,i})_{P_{ads}} - (Q_{a,i})_{P_{des}}} \tag{10.8}$$

with:

n_k = number of beds
t_c = cycle time in sec.
$\Phi_{mol,i}$ = flow of component i in mol/s
$Q_{a.i}$ = amount adsorbed component i in mol/kg
P_{ads} = adsorption pressure
P_{des} = desorption pressure

The pressure drop over the bed is calculated with the modified Sabri-Ergun equation lit.[10.6]:

$$\frac{\Delta P}{L} = E1\mu v_s + E2\rho_0 v_s^2 \tag{10.9}$$

The results from these equations can be found in the appendix 10.(page A10-1)

The equipment costs for a H_2 VSA system, the so called Purchased Cost Equipment (PCE), are:

==========> fl. 1.12 * 10^6

The total investment costs are determent by the factoring method. The so called Fixed Cost (FC) are:

==========> fl. 5.26 * 10^6

The calculations of these costs can be found in appendix 10 (page A10-3)

The design of the CO VSA adsorption system

This Vacuum Swing Adsorption system is located before the H_2 PSA system and after the dryers to remove the water. The adsorbent in this case is an adsorbent consisting of a silica and/or alumina carrier with an amount of cupric salt in the range of 1 to 5 mmols/g and a reducing agent to convert cupric ion into cuprous ion in the range of 0.01 to 0.3 g/g carrier. The adsorbent has a adsorption capacity of 21.7 cc/cc adsorbent at atmospheric pressure and releases 9.9 cc/cc adsorbent at 0.04 bar lit.[10.8], 9.9 cc / cc adsorbent is the same as 3.6 mol CO/gr. Because CO is the only component that has to be adsorbed, the beds are smaller than in the H_2-PSA system.

With the equation of White (10.4) the fluidization limit for packed beds is determined and with those results the minimum column diameter.

From the maximum velocity, the minimal column diameter is calculated, using equation 10.4. An estimation of the column height is calculated with equation 10.8 with only CO is adsorbed.

The result of the design of the CO VSA system is in appendix 10.(page A10-2)

The equipment costs for a CO VSA system, the so called Purchased Cost Equipment (PCE), are:

==========> fl. 0.877 * 10^6

The total investment costs are determent by the factoring method. The so called Fixed Cost (FC) are:

==========> fl. 4.13 * 10^6

Of course the costs of a combined CO-VSA and H_2-PSA system are lower because piping and control system are combined. The combined equipment costs (PCE) are:

==========> fl. 1.83 * 10^3

The total investment costs for a combined CO-VSA and H_2-PSA system are:

==========> fl. 8.61 * 10^3

The calculation of these cost can be found in appendix 10 (page A10-3/4)

10.4 COSORB® for CO-raw gas separation

10.4.1 The COSORB® Process

Absorption of carbon monoxide is important in the processes for purification of CO as well as in the removal of CO from various gas streams. The COSORB® Process for the recovery and purification of carbon monoxide from synthesis gases and industrial waste gas streams was developed during the late 1960's and early 1970's. The process utilizes a proprietary COSORB® Solvent composed of a pi bond complexing compound, copper aluminum tetrachloride, dissolved in an aromatic solvent base. The first commercial COSORB® plant was successfully started up at the Dow Chemical Company Plant in Freeport, Texas, U.S.A. in early 1976. Since this early success, the COSORB® Process has enjoyed wide acceptance in the chemical process industry. The COSORB® Process has been applied to numerous diverse feed gases containing carbon monoxide and other inert gases to produce a high purity carbon monoxide product.

The COSORB® Process is based on the selective complexation of carbon monoxide in a liquid solvent (toluene) . The solvent has an aromatic base with an active component referred to as $CuAlCl_4$. The high selectivity of this solvent for carbon monoxide at ambient temperature and the ease of decomplexation at a higher temperature are the basis for the simplicity of the process. The solvent can effectively remove carbon monoxide from gaseous streams at any practical operating pressure. The COSORB® process is essentially a simple absorption/desorption process for carbon monoxide, similar to a carbon dioxide removal process. Its development followed a rather conventional pattern. Extensive vapor liquid equilibrium data were collected in the laboratory . This was followed by bench scale laboratory evaluations of the process. These data were then utilized as the basis for the design and simulation program (appendix 10) of the COSORB® unit.

The basic design of a COSORB® unit is illustrated in Fig. 10.7 and consists of four sections: 1) Feed gas preparation , 2) the COSORB® solvent-CO complexer and COSORB® solvent-CO decomplexer circuit, 3) aromatic recovery from the product gas streams, and 4) the compression and power recovery of the product streams.

The feed gas preparation section consists of the process steps required to remove the irreversibly reactive compounds from the feed gas prior to its contact with the COSORB® solvent. Water is usually removed by a combination of refrigeration and molecular sieves. After conventional treatment for the removal of sulfur compounds, the sulfur compounds are reduced to acceptable levels by treatment with activated carbon. In those cases where hydrogenation of the feed gas is required, zinc oxide beds may be used to reduce sulfur compounds to an essentially "zero" level upstream of the hydrogenation catalyst.

The complexor and decomplexer section of the COSORB® process consists two major columns, which are either packed or trayed columns, with internals identical to standard absorption and stripping columns. The feed gas is countercurrently contacted with the COSORB® solvent in the complexor, and the CO is released from the COSORB® solvent in the decomplexor.

The other common components in a carbon monoxide-rich stream, carbon dioxide, methane, hydrogen, nitrogen and oxygen are physically absorbed.

Since there is a low physical absorption of these inert gases, only a fraction of the inert gases in the feed gas will be absorbed in the COSORB® solvent and then exit with the solvent from the complexor. These physically dissolved gases will be produced with the decomplexed CO product. However, these impurities may be removed from the COSORB® solvent by various combinations of flashing, stripping and complexation in an inert-removal column upstream of CO production in the decomplexor. The design requirements of this third column are determined by the feed compositions and product purity requirements.

The carbon monoxide-rich solvent flows from the bottom of the absorber to a flash unit and then to a heat exchanger and is heated against recycling lean solvent, and where it gives up a large fraction of the dissolved carbon monoxide to the gas phase. The inerts are preflashed, and the final carbon monoxide product is taken overhead of the stripper. The aromatic base of the solvent is generally the stripping medium. The hot lean solvent flows through the heat exchanger, where it is cooled and then recycled to the absorber. The complexor, decomplexor and optional inerts-removal column overhead streams require further treatment to reduce losses of the volatile aromatic base of the COSORB® solvent. Aromatic recovery in the complexor and decomplexor overhead streams is accomplished by a combination of compression, refrigeration and treatment with activated carbon. The inerts column overhead stream is small and is generally sufficient for economical recovery of the aromatics. A turbine compressor compresses the carbon monoxide by making use of pressure from the feed gas to the absorber. With this approach, the stripper could be operated, for example at five psig. Carbon monoxide product of 99% is easily attained in this system. The loss of the aromatic base of the solvent is reduced by use of recovery facilities on the carbon monoxide product stream and the hydrogen-rich stream.

The COSORB® plant can be built with carbon steel. The gas feed must be substantially free of water, hydrogen sulfide, and sulfur dioxide, as these compounds all irreversibly react to a significant extent with the solvent and produce traces of hydrogen chloride in the product streams. In those instances where downstream processes are sensitive to parts-per-million levels of hydrogen chloride , the complexer and decomplexer overheads may require treatment to remove hydrogen chloride to below detectable limits.

Packed towers are more then adequate to allow the separation to produce high-purity carbon monoxide at multimillion-pound-per-day rates. The only utilities necessary are cooling water, low pressure steam, and power sufficient to pomp the solvent from the stripper to the absorber.

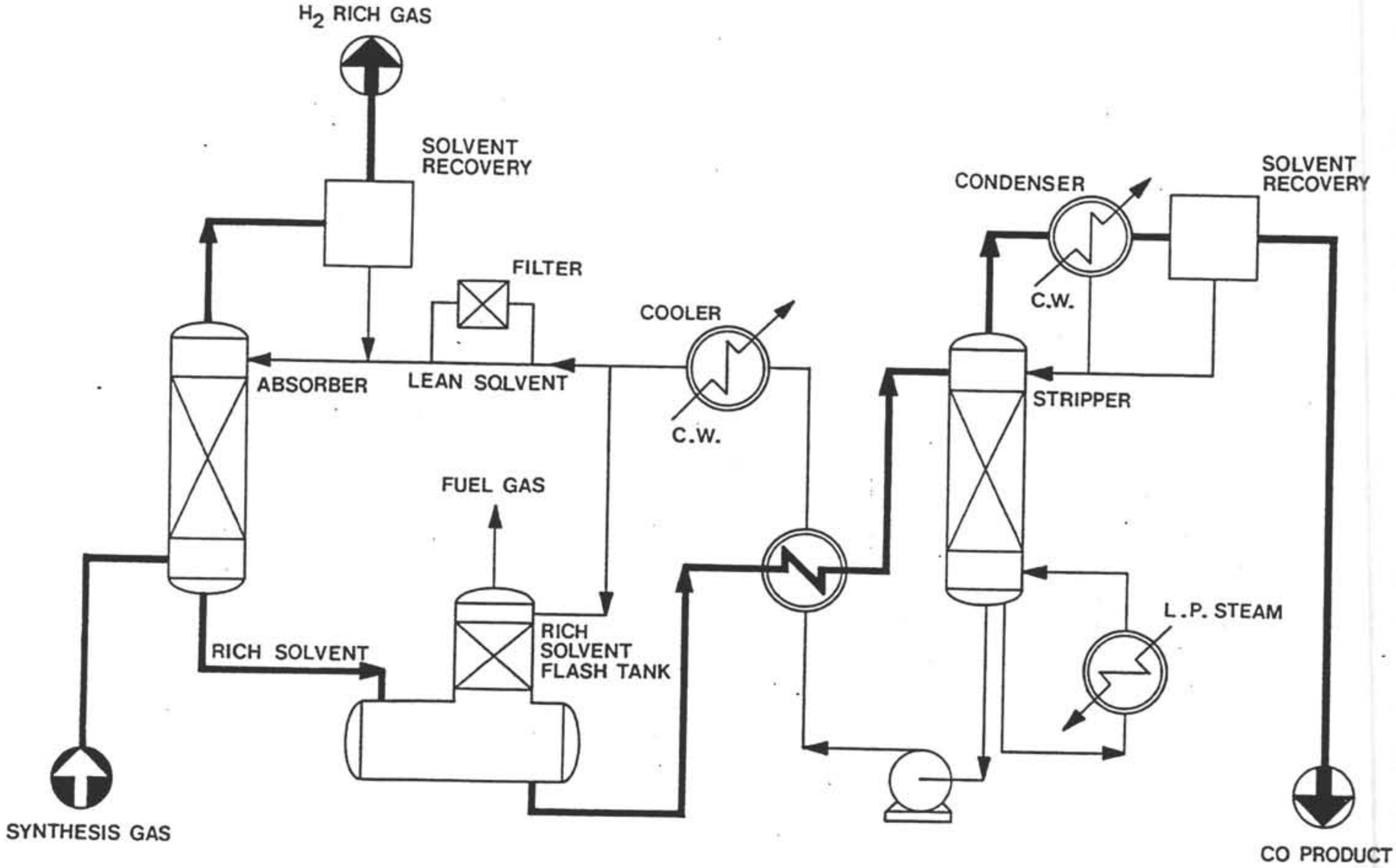


Figure 10.7 Cosorb process for recovering carbon monoxide from industrial gases

10.4.2 Simulation of the COSORB® unit (Non-isothermal gas absorption)

10.4.2.1 Introduction

Gas Absorption with chemical reaction induces the absorption rate which is expressed by means of "enhancement factor" corresponding to the liquid film resistance. The enhancement factor differs by different systems and different operation conditions. The molecular interaction energy of chemical absorption-complexing is often much greater then that of *Van der Waals* force in physical absorption, but still less than covalent energy. And since complexing absorption is reversible, it is easy for desorption (regeneration), therefore it is a highly selective, widely useful and practical separation process which involves large heat effects such as heat of reaction, heat of solution, sensible heat transfer between liquid and gas phase. In this case , the computation and design of these absorbers have to consider of chemical equilibrium, phase equilibrium, mass transfer and heat transfer.

10.4.2.2 Fundamental Theory

COSORB® Solvent utilizes the pi complex bonding between the aromatic solvent, e.g. , toluene, to the metal salt adduct of cuprous chloride and aluminum chloride ($CuAlCl_4$) to achieve very high concentrations of the solid $CuAlCl_4$ in the aromatic liquid. The species in COSORB® Solution are C_7H_8:$CuAlCl_4$ + approximately 1.5 C_7H_8; Thus an overall total molar ratio toluene/copper = 2.5. The pi complexed copper is capable of further complexing with electron donating ligands, such as carbon monoxide, which can donate pi electrons to form additional pi complex bonds to the copper(I) metal. Of key importance to the COSORB® process is the fact that the additional pi bond can be made at ambient temperature and low CO partial pressure and be broken simply by elevating the temperature. The mixture of C_7H_8:$CuAlCl_4$ plus 1.5 free C_7H_8 is simply convenient vehicle to transport the copper(I) metal and its inherent complexing nature from the CO Absorber to the CO Stripper and back again. COSORB® Solvent, as defined, has physical properties much like the toluene portion of the solvent and thus exhibits reasonable heat transfer and good mass transfer characteristics.

The absorption of carbon monoxide in CuCl-$AlCl_3$-toluene complex solution can be described as a stoichiometric reaction as follows :

$$\text{CO} \quad + \quad CuAlCl_4\text{-toluene} \quad \Longleftrightarrow \quad CuAlCl_4(\text{CO})\text{-toluene} \qquad (10.10)$$

This reversible reaction can be represented by the following scheme :

$$A(g) \quad + \quad B(l) \quad \Longleftrightarrow \quad E(l) \qquad (10.11)$$

The theory of gas absorption with fast reversible reaction has been described by Onda (1970) lit. [10.10] and the relevant equations applicable to the present case are described in detail by Gholap and Chaudhari (1988) lit. [10.11]. The ratio of chemical absorption rate and that of physical absorption namely "enhancement factor" (E) expresses the effect of chemical reaction to the absorption, and it differs by different systems, operating and boundary conditions. The equations for enhancement regime and the following condition must be satisfied :

$$3 \leq E \leq E_{\infty} \tag{10.12}$$

where E_{∞} is the enhancement factor for instantaneous reversible reaction and Danckwerts and his coworkers (1970) lit. [10.12] have declared the enhancement factors by the film theory, where

$$E = 1 + \frac{K_{eq}*[CuAlCl_4]_{Bulk}}{(1 + K_{eq}*[CO]^*)} \tag{10.13}$$

Where, K_{eq} is the true equilibrium constant and
$[CO]^*$ is the concentration of A at the gas-liquid interface and
$[CuAlCl_4]_{Bulk}$ is the concentration of Copper in the bulk

The K_{eq} as function of the temperature is obtained from the literature Golaph and Chaudhari (1992) lit. [10.13] using the plot data of that publication.

In chemical absorption, the overall gas phase mass transfer coefficient Kog can be expressed in the form :

$$K_{og}*a = \frac{1}{\dfrac{1}{k_{g,CO}*a} + \dfrac{1}{E*H*k_{l,CO}*a}} \tag{10.14}$$

Where, E is the enhancement factor and H is the Henry constant obtained by physical absorption. In this case physical solubility in toluene has been aided from Seidell (1940) lit. [10.14].

The gas and liquid mass transfer coefficient have been obtained from the Onda model from Coulson (1983) lit. [10.15]

The mass-transfer coefficient in the liquid phase, k_{lCO} is given by the dimensionally consistent equation :

$$k_{l,CO}*\left(\frac{\rho_l}{g*\mu_l}\right)^{\frac{1}{3}} = 0.0051*\left(\frac{L}{a_w*\mu_l}\right)^{\frac{2}{3}}*\left(\frac{\mu_l}{\rho_l*D_{l,CO}}\right)^{\frac{-1}{2}}*(a_p\ *d_p\ )^{-2} \qquad (10.15)$$

The mass-transfer coefficient in the gas phase, k_{gCO} is given by the dimensionally consistent equation :

$$k_{g,CO}*\left(\frac{R*T}{a_p*D_{g,CO}}\right) = 5.23*\left(\frac{G}{a_p*\mu_g}\right)^{0.7}*\left(\frac{\mu_g}{\rho_g*D_{g,CO}}\right)^{\frac{1}{3}}*(a_p\ *d_p\ )^{-2} \qquad (10.16)$$

The wetted area is provided by :

$$a_w\ =a_p*(1-\exp(-1.45*\left(\frac{L}{a_p*\mu_l}\right)^{0.1}*\left(\frac{a_p*L^2}{g*\rho_l^2}\right)^{-0.05}*\left(\frac{L^2}{a_p*\sigma*\rho_l}\right)^{0.2}*\left(\frac{\sigma}{\sigma_c}\right)^{-0.75} \qquad (10.17)$$

For the viscosity of the liquid we used an complex equation :

$$\mu_l\ =\ Exp\left[-4.12227\ -\ 2.3403*Exp(C_2*Ra^3)\ +\ D_2*Ra^2\ +\ E_2*Ra+\ B_2\right] \qquad (10.18)$$

Where,

$$B_2\ =\ \frac{\left(1051.795\ +\ 2026.852*Exp(F_2*Ra^2\ +\ G_2*Ra\right)}{T_l} \qquad (10.19)$$

C_2 = -5.08093E-2
D_2 = 12.2693E-2
E_2 = -6.78159E-2
F_2 = -9.6315E-2
G_2 = 8.026396E-2

Ra is the molar ratio toluene/copper and
Lo is the molar loading carbon monoxide/copper

For the density of the liquid we used the equation :

$$\rho_l = 1000*\left[\left(\frac{1.5562}{Ra + 1}\right) + 0.1881\right] - \left[\left(\frac{0.0002614}{Ra + 1}\right) + 0.0009207\right]*$$

$$(T_l - 273.15) - \left(\frac{Lo*0.06}{Ra}\right) \qquad (10.20)$$

The diffusion coefficient of carbon monoxide in the liquid and gas phase is respectively obtained from the Wilke and Chang equation and the Gilliland equation :

$$D_{g,CO} = \frac{1.173*10^{-13}*\sqrt{M_{avr,l}}*T_l}{\mu_l*(0.0307)^{0.6}} \qquad (10.21)$$

$$D_{g,CO} = \frac{1.013*10^{-7}*T_g^{1.75}*\sqrt{\frac{1}{M_{CO}} + \frac{1}{M_{avr,g}}}}{P*\left(18.9^{\frac{1}{3}} + 10.5^{\frac{1}{3}}\right)^2} \qquad (10.22)$$

For the mean viscosity of the gas phase we used the next equation :

$$\mu_l = 0.0172 + (T_{g2} - T_{gl})*10^{-4} \qquad (10.23)$$

For the density of the gas phase we uses the Redlich & Kwong approach :

$$\rho_g = \frac{M_{avr,g}}{V_1} \qquad (10.24)$$

$$V_1 = \frac{R*t_g}{P} + b_{RK} - \frac{a_{RK}*(V_1 - b_{RK})}{\sqrt{T_g}*P*V_1*(V_1 + b_{RK})} \tag{10.25}$$

$$a_{RK} = 0.42748*R^2*\frac{T_{c,mix}^{2.5}}{P_{c,mix}} \qquad b_{RK} = \frac{0.08664*R*T_{c,mix}}{P_{c,mix}} \tag{10.26}$$

In this simultaneous mass and heat transfer process, analogy between mass and heat may be used to obtain the heat transfer coefficient. Since the liquid film resistance in the heat transfer process may be neglected, the interface temperature is very close to the liquid film temperature, so the heat transfer coefficient is obtained as follows :

$$\left(\frac{h_g*a}{k_{g,CO}*a}\right) = C_{pg}*(Le)^{\frac{2}{3}} = C_{pg}*\left(\frac{\lambda_g}{\rho_g*C_{pg}*D_{g,CO}}\right)^{\frac{2}{3}} \tag{10.27}$$

For the heat conductivity of the gas phase the next equation has been obtained :

$$\lambda_g = \mu_g*\left(C_{pg} + \frac{10.4}{M_{avr,g}}\right) \tag{10.28}$$

Meanwhile, for sake of the similarity between mass and heat transfer, mass flow rate not only affects on the mass transfer coefficient, but also affects the heat transfer coefficient. If in the chemical reaction absorption which involves appreciable concentration change, the result of this influence should be considered, and the heat transfer coefficient h_g should be modified to h_g':

$$h_g' = -G_B*\left(\frac{(C_{pCO}*\left(\frac{dY_{CO}}{dZ}\right) + C_{pTol}*\left(\frac{dY_{Tol}}{dZ}\right)}{1 - \exp\left[G_B*\frac{C_{pCO}*\left(\frac{dY_{CO}}{dZ}\right) + C_{pTol}*\left(\frac{dY_{Tol}}{dZ}\right)}{h_{g,CO}}\right]}\right) \qquad (10.29)$$

The evaporation and condensation of the volatile solvent (toluene) may evaporate or condense along with temperature change in the packed column. This changeable phenomenon also influences the heat transfer process and has already been included in Eq. (10.29). In fact, the liquid layer on both the inner and outer surface of packings are available to the evaporation process, so the available wet surface is much larger then that of physical absorption, and the resistance of the liquid phase would be very small. However, in physical absorption the thickness of the liquid layer and the flow rate at each point of the wet surface of the packings are different, so the thin liquid layer or low mobility part of the liquid film would be saturated and might be hardly absorb the solute (carbon monoxide). That is the reason why there would be lager liquid resistance. Therefore, the liquid resistance of evaporation and condensation of toluene in comparison with that of absorption, can be neglected, so k_{gTol} is able to be obtained from Eq. (10.30) :

$$\frac{k_{g,Tol}}{k_{g,CO}} = \frac{D_{g,Tol}}{D_{g,CO}} \qquad (10.30)$$

According to the performance of the process described, assumptions for the mathematical model have been reasonably illustrated :

(1) For sake of the complexing absorption is a fast reaction, the bulk concentration may be considered as equilibrium concentration, and the concentration at the interface may be considered as the equilibrium concentration in physical absorption.

(2) Since the liquid resistance can be ignored in the heat transfer process, the temperature of the interface is the same as that of the bulk of the liquid.

(3) Since the liquid resistance can be ignored during toluene is evaporating, the partial pressure of toluene may approach to its vapor pressure.
In addition, backward mixing along axis would not be taken into account; the surface of heat transfer is the same as that of mass transfer.

10.4.2.3 Mathematical Modelling

(1) Equation of mass transfer rate :

1 Mass transfer of carbon monoxide :

$$N_{CO}*a*dz = K_{og}*a*P*(Y_{CO} - Y_{COe})*dz = -G_B*dY_{CO} \tag{10.31}$$

From This equation, the rate of change of carbon monoxide concentration in differential packings is as follows :

$$\frac{dY_{CO}}{dz} = \frac{-Kog*a*P*(Y_{CO} - Y_{COe})}{G_B} \tag{10.32}$$

2 Mass transfer of toluene :

From Eq. (10.32), the rate of change of toluene concentration in differential packings is as follows :

$$N_{Tol}*a*dz = k_{gTol}*a*P*(Y_{Tol} - Y_{Tole})*dz = -G_B*dY_{Tol} \tag{10.33}$$

Where k_{gTol} can be obtained from Eq. (10.30).
Hence, the change rate of toluene concentration in differential packings is :

$$\frac{dY_{Tol}}{dz} = \frac{-k_{gTol}*a*P*(Y_{Tol}-Y_{Tole})}{G_B} \tag{10.34}$$

(2) Enthalpy balance, in differential packings : (Fig.10.8)

1 For gas phase (I) :

OUT = IN - CONVERSION

IN : Input rate of enthalpy = G_B*H_G
OUT : Output rate of enthalpy =

$$G_B*(H_G + dH_G) - (G_B*dY_{CO})*[C_{pCO}*(t_G - t_0) + H_{OS}] +$$

$$-(G_B*dY_{Tol})*[C_{pTol}*(t_G - t_0)*H_V \tag{10.35}$$

where the last two terms of heat transfer are caused by mass transfer and :

$$H_G = C_{pB}*(t_G-T_0) + Y_{CO}*[C_{pCO}*(t_G-t_0)+H_{OS}] + Y_T*[C_p*(t_G-t_0)+H_V] \tag{10.36}$$

$$dH_G = C_{pB}*dt_G + Y_{CO}*C_{pCO}*dt_G + [C_{pCO}*(t_G - t_0) + H_{OS}]*dY_{CO} +$$

$$Y_{Tol}*C_{pTol}*dt_G + [C_{pTol}*(t_G - t_0) + H_V]*dY_{Tol} \tag{10.37}$$

CONVERSION : the rate of heat transfer from gas to liquid phase =

$$q_G*a*dz = h_G*a*(t_G-t_L)*dz \tag{10.38}$$

therefore,

$$-G_B*(C_{pB} + C_{pCO}*Y_{CO} + C_{pTol}*Y_{Tol})*dt_G = h_G*a*(t_G - t_L)*dz \tag{10.39}$$

Then the temperature profile of gas phase along the packings height is as follows :

$$\frac{dt_G}{dz} = \frac{-h_G*a*(t_G - t_L)*(C_{pB} + C_{pCO}*Y_{CO} + C_{pTol}*Y_{Tol})}{G_B} \tag{10.40}$$

If mass transfer flux is considerably large, h_G has to be modified as h_G'.

2 For liquid phase (II) :

OUT = IN - CONVERSION

IN : Input rate of enthalpy =

$$(L + dL)*(h + dh_L) + (-G_B*Y_{CO})*[C_{pCO}*(t_G - t_0) + H_{OS}] +$$

$$(-G_B*dY_{Tol})*[C_{pTol}*(t_G - t_0) + H_V] \qquad (10.41)$$

OUT : Output rate of enthalpy = $L*h_L$

CONVERSION : rate of transfer from liquid phase to gas phase =

$$-q_G*a*dz = -h_G*a*(t_G - t_L)*dz \qquad (10.42)$$

Then

$$L*C_q*(\frac{dt_L}{dz}) = G_B*(C_{pB} + C_{pCO}*Y_{CO} + C_{pTol}*Y_{Tol})*(\frac{dt_G}{dz})$$

$$+ G_B*[(C_{pCO}*(t_G - t_0) + H_{OS}]*(\frac{dY_{CO}}{dz})$$

$$+ G_B*[C_{pTol}*(t_G - t_0) + H_V]*(\frac{dY_{Tol}}{dz}) \qquad (10.43)$$

Where t_0 is the reference temperature. As a result, the temperature profile along the packings in the liquid phase dt_L/dz can be obtained from Eq. (10.32), (10.34), (10.40).

(3) The overall material balance and heat balance :

Overall material balance :

$$L_1 * X_{CO1} - L_2 * X_{CO2} = G_B * (Y_{CO1} - Y_{CO2}) \qquad (10.44)$$

Where subscript 1 denotes the bottom and 2 denotes the top of the column,

$$Y_{CO} = \frac{y_{CO}}{(1 - y_{CO} - y_{Tol})}, \quad G_B = G_1 * (1 - y_{CO1} - y_{Tol1}) \qquad (10.45)$$

From the overall heat balance, the temperature of the column bottom t_{L1} can be obtained :

$$Cp_{ql} * (t_{L2} * L_2 - t_{L1} * L_1) =$$

$$(G_2 * C_{pg2} * T_{g2} - G_1 * C_{pg1} * Tg_1) + H_{OS} * G_B * (Y_{CO2} - Y_{CO1}) + H_V * G_B * (Y_{Tol2} - Y_{Tol1}) \qquad (10.46)$$

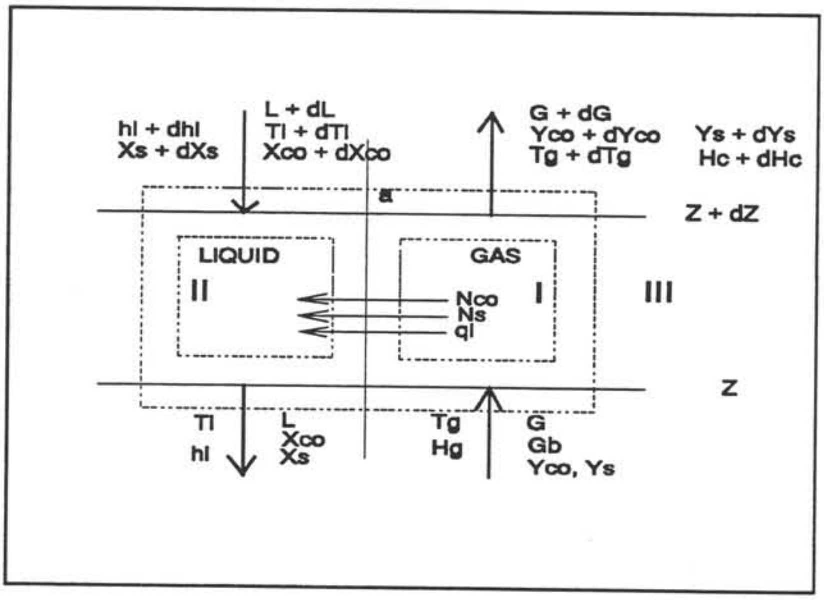
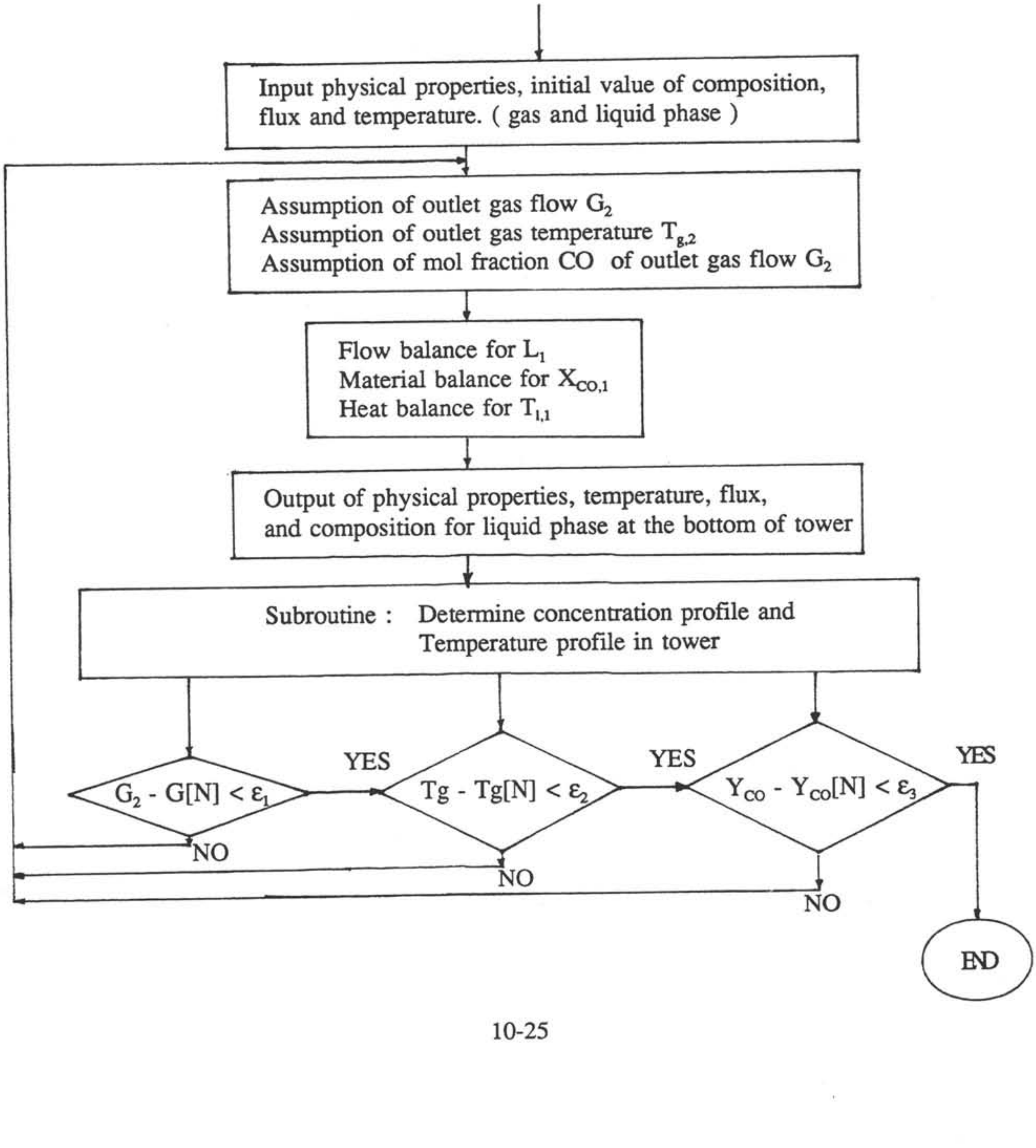


Figure 10.8 Mass and heat transfer in differtial packings of the absorber.

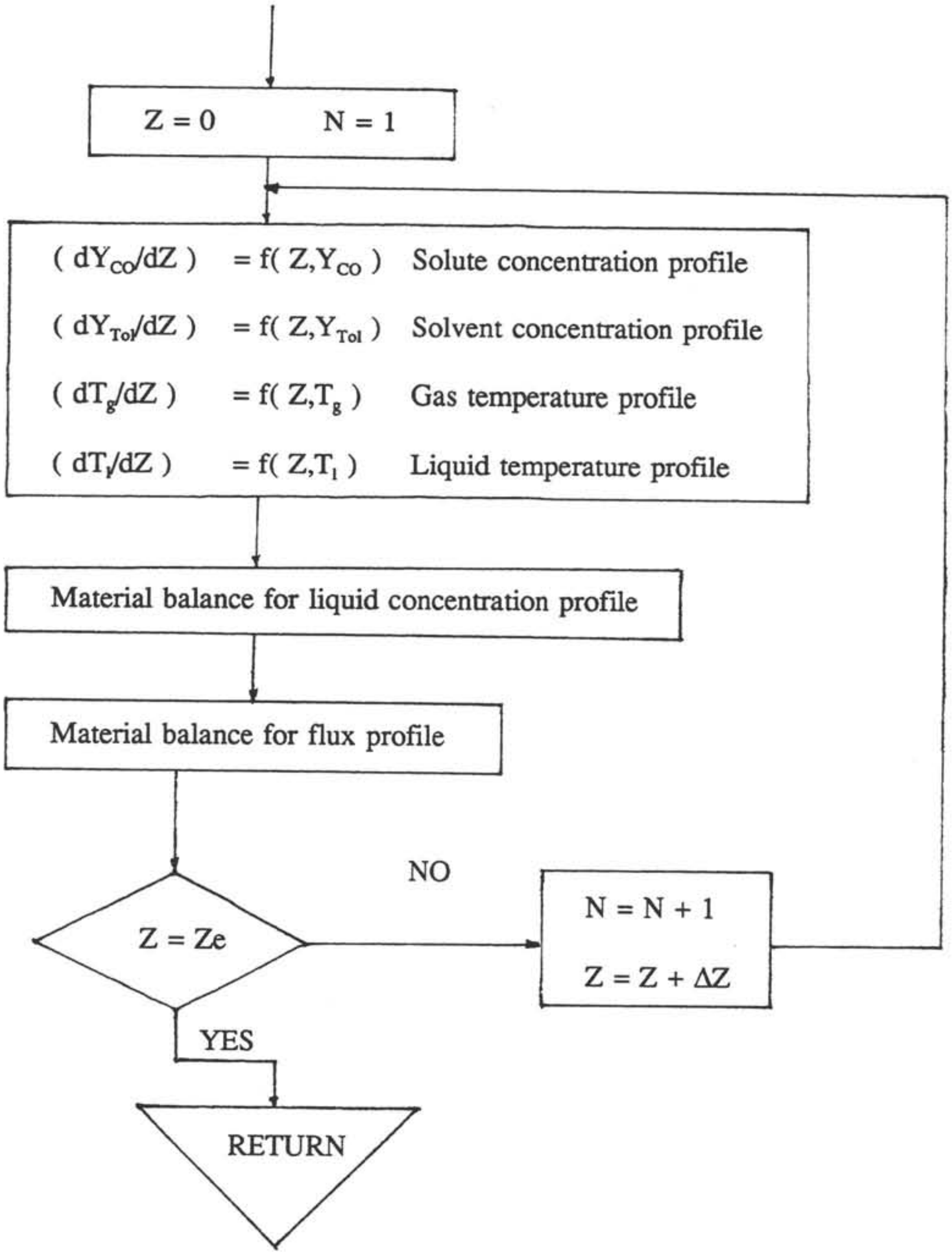
10.4.2.3 Computing and simulation

From the initial conditions, the flux of both gas and liquid phase, their concentration and temperature and from the known parameters-enthalpy of complexing, enthalpy of solvent evaporation, the specific heat, density, molar weight of gas and liquid mixture , diffusivity, enhancement factor, etc., the liquid flux, temperature and composition for the bottom of the tower can be determined from the total heat and total mass balance. Furthermore, with the aid of forth-order Runge-Kutta approach, Eqs. (10.32), (10.34), (10.43) have been solved, from which the temperature profile and concentration profile along the packed tower has also been obtained.

The flow diagram for computing the carbon monoxide absorber tower have been shown in the following algorithms (The turbo Pascal program is printed in appendix 10) :



SUBROUTINE


Z = 0
N = 1
(dY_CO/dZ) = f(Z,Y_CO) Solute concentration profile
(dY_Tol/dZ) = f(Z,Y_Tol) Solvent concentration profile
(dT_g/dZ) = f(Z,T_g) Gas temperature profile
(dT_l/dZ) = f(Z,T_l) Liquid temperature profile
Material balance for liquid concentration profile
Material balance for flux profile
Z = Ze
NO
N = N + 1
Z = Z + ΔZ
YES
RETURN

10.4.2.4 Result and discussion

For the calculation of carbon monoxide complexing absorbed in the aluminum cuprous tetrachloride-toluene solution, the computer program COSORBER have been used, while the initial data of the COSORB® tower (table 10.4) have been put in, the results of computing conformed with the data obtained from the experimental of a pilot plant.

COMPOS. FEEDGAS	CO Flow	55.02 [kmol/h]	Temp. Gas	308.15 [K]
	H_2 Flow	129.3 [kmol/h]	Tol. Flow	0.000 [kmol/h]
	CO_2 Flow	29.35 [kmol/h]	Inrt. Flow	175.4 [kmol/h]
	N_2 Flow	12.33 [kmol/h]	Tot. Flow	230.5 [kmol/h]
	CH_4 Flow	4.412 [kmol/h]	Y_{CO} Flow	0.3136 [-]
	Ar Flow	0.000 [kmol/h]	Y_{Tol} Feed	0.0000 [-]
COSORB® SOLVENT	Tot. Flow	225.0 [kmol/h]	Temp. Liq.	313.15 [K]
	X_{CO} Feed	0.0028 [-]	Cu Flow	62.55 [Kmol/h]
	X_{Cu}	0.2774 [-]	CO Flow	0.631 [Kmol/h]
TOWER SPEC	Pressure	27.0 [bar]	Crit. Surf.	75 [Dyne/cm]
	Height	8.00 [m]	Packing	0.038 [m]
	Cross a.	0.70 [m]	Step h	0.04 [m]
	Spec. a.	130.0 [m]	Efficiency	0.90 [-]
ESTIMATIONS	Flow Top	175.0 [kmol/h]	# iteration	100 [-]
	Tg Top	314.15 [K]	Init. Flag	0 [-]
	Y_{CO} Top	0.00005 [-]	error	5E-6 [-]

Table 10.4 Input for COSORB® simulation with COSORBER (appendix 10)

For the gas feed we used the gas composition and gas flux of the calculated optimum from the reformer. For the COSORB® solvent we used the composition of the average analytical COSORB® data. For the packing of the tower we used metal pall rings (0.038 m). To get the required recovery the tower has to be 8 m high and a cross area of 0.7 m with a pressure of 28 bar.

Also the results of computing of the pressurized tower conformed with the theoretical regulations. The results of the input from table 10.4, have been shown in table 10.5 and the typical temperature profiles and concentration profiles along the packed height have been shown in Fig 10.9 and 10.10 .

It is visualized for the fact that the temperature of the liquid phase at the bottom (T_{L1}) decreases with the increasing of the liquid flux, and the required height of the packed tower also decreases. Meanwhile, the maximum temperature of the liquid has eliminated gradually, and similarly for the maximum temperature of the gas phase. At the same time, according to the different feed temperature of the gas phase at the bottom of the tower, the required height of the packings and the maximum gas temperature are different.

These results illustrated the reasonable accuracy of the mathematical model nd simulation of the simultaneous mass and heat transfer process in the chemical absorber.
The average value of the overall mass transfer coefficient $K_{o,g}$ approaches to the experimental data in pilot plant. Because of the situation of the solute in liquid phase of the column bottom, the liquid resistance induced and the enhancement factor reduced, so the mass transfer coefficient is rather small. And because of the solute is rather concentrated in the gas phase of the tower bottom, the solute gas flux is rather large, so the gas resistance is considerably small and the liquid resistance is obviously the dominant.

Height [m]	G Flow [kmol/h]	L Flow [kmol/h]	Y_{CO} [-]	Y_{Tol} [-]	T_{liquid}	T_{gas}
0.0	230.452	279.876	2.387514E-1	0.0000000	359.32	308.15
0.4	192.477	241.901	7.992858E-2	8.626694E-3	328.86	311.05
0.8	181.145	230.057	2.259267E-2	5.609578E-3	319.19	312.15
1.2	177.663	227.088	8.407853E-3	4.151519E-3	316.13	312.62
1.6	176.573	225.997	2.825435E-3	3.635643E-3	315.18	312.89
2.0	176.229	225.653	1.057301E-3	3.467124E-3	314.89	313.07
2.4	176.121	225.546	4.983931E-4	3.414167E-3	314.81	313.23
2.8	176.087	225.512	3.218511E-4	3.399694E-3	314.80	313.36
3.2	176.076	225.501	2.661109E-4	3.396578E-3	314.80	313.49
3.6	176.074	225.498	2.485232E-4	3.397110E-3	314.81	313.60
4.0	176.073	225.498	2.429829E-4	3.398684E-3	314.82	313.71
4.4	176.073	225.498	2.412457E-4	3.400480E-3	314.83	313.81
4.8	176.073	225.498	2.407085E-4	3.402246E-3	314.84	313.90
5.2	176.074	225.498	2.405493E-4	3.403912E-3	314.85	313.98
5.6	176.074	225.498	2.405086E-4	3.405461E-3	314.86	314.06
6.0	176.074	225.499	2.405046E-4	3.406895E-3	314.87	314.13
6.4	176.074	225.499	2.405115E-4	3.408220E-3	314.88	314.19
6.8	176.075	225.499	2.405213E-4	3.409443E-3	314.89	314.25
7.2	176.075	225.499	2.405313E-4	3.410573E-3	314.90	314.31
7.6	176.075	225.499	2.405409E-4	3.411616E-3	314.91	314.36
8.0	176.075	225.500	2.405498E-4	3.412579E-3	314.92	314.41

Table 10.5 Results of the COSORB® simulation output

Up in the packings, the gas resistance increased and the mass transfer coefficient decreased because of the higher efficiency of the absorption and the rapidly reducing solute concentration. However the gas solute concentration decreases while the height of the packings increases and the active concentration in absorbent increases, so the enhancement factor increases, and the liquid mass transfer coefficient at the top nearly doubles, but still smaller then the gas phase. This phenomenon becomes more appreciable when the liquid flux is smaller. This agree with the fact and also explores the mechanism of the process.

In the pressurized tower, if the same absorbent flux, temperature and feed composition are used, the required recovery for the same packings height would be higher then that of the conventional tower. This fact is caused by the increasing of the overall mass transfer coefficient. Further to analyze the mass transfer coefficient of the gas and liquid phase respectively, it would show that because the gas diffusivity reduces fifteen times (if 15 atm of pressure in the tower), the corresponding mass transfer coefficient decreases appreciably.

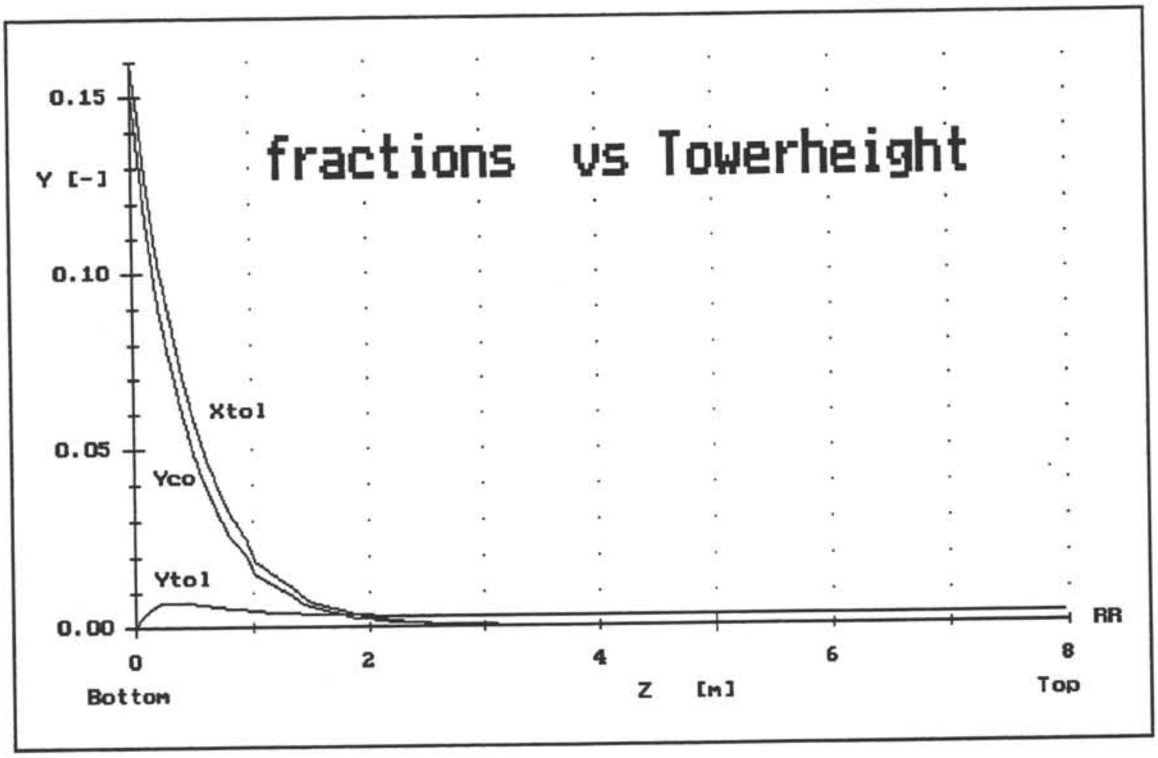


fig 10.9 The concentration profile of solvent and solute in the column

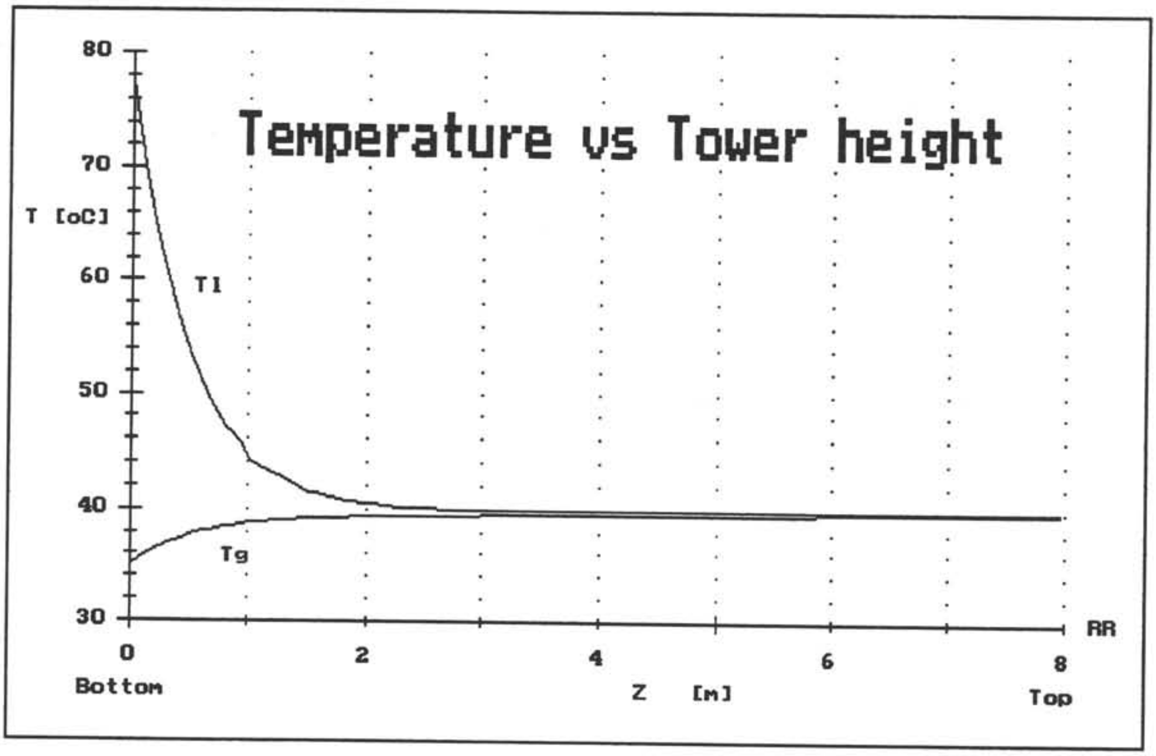


fig 10.10 Temperature profile of gas and liquid in absorber

However, the liquid phase in the pressurized tower reacts with the highly concentrated solute, the rate of complexing absorption increases while the surface tension on the wet packings increases, the convection effect and the surface renewal of the liquid phase increases, so that the enhancement factor and the rate of absorption increased. As a result, the liquid mass transfer coefficient at conventional absorber, the liquid mass transfer coefficient at the bottom of the pressurized absorber also increases several times compared with that in the conventional absorber. Obviously, the gas film resistance would be the dominant factor along the whole tower. From the result, it can be shown that the main factors for the change of gas and liquid film resistance in the chemical absorption process. Due to the different operating conditions, the result of simulating and computing, the mechanism and principles of the process can be explored clearly.

Since in this process the input gas is wet, the evaporation and condensation of the volatile solvent is limited therefore, the maximum temperature of the liquid is not appreciable, that means there would be no hot point along the absorber. (fig 10.10). The minimum driving force region is close to the bottom of the absorber, while the ratio of the liquid and gas is quite small, the minimum driving force region is still at the top of the tower. Because of the required high recovery, the concentration of the active component of the gas phase is so dilute that it is difficult to be absorbed.

10.4.2.5 Costs of COSORB®

The investment costs, feed gas and utility requirements for a reformer feed gas is presented in appendix 10 table A 10.10 . The investment requirements for the battery limits of COSORB® units include the initial charge of all expendable items, but do not include peripherical facilities such as buildings, flare systems and other equipment or process systems associated with supplying utilities, or administration of the unit. The utilities shown are based on operating the plant at design capacity.
The feed gas composition to the COSORB® unit is saturated with water in addition to the components shown in table 10.4 and contains particle matters and sulfur compounds. The gas stream require compression and cooling before particulates sulfur and water can be removed economically. The investment and operating costs presented herein include feed gas compression, water removal, sulfur removal and particulate removal facilities necessary to permit feeding the synthesis gas steam to COSORB® unit complexor.

The recovery costs consists the operating and investment cost for the COSORB® unit. The required sales price is the recovery cost plus net cost of the synthesis gas feed stream. The variable and fixed costs of recovering CO were calculated at design capacities of 1500 kg/h of CO. Fixed cost are based on 8,000 operating hours per year. Manpower includes one operator plus a fraction of direct supervision. Maintenance and taxes are calculated using industrial averages as shown, and depreciation is included based on ten year straight line rates. The annual cost of investment is taken as 30 percent of the installed cost of the battery limits COSORB® unit. This is equivalent to assuming a rate of return on investment of 30 percent before taxes. The recovery costs including investment costs are presented in appendix 10 table A 10.11 .

10.4.2.6 Conclusion

The mathematical model of adiabatic absorber with chemical reaction has been computed by the computer program COSORBER for the COSORB® system, and the results has conformed with the experimental data of a pilot plant. The enhancement factor, mass transfer coefficient and the profile of both temperature and concentration for both gas and liquid phase have all been described and visualized. By means of the forth order Rung-Kutta method, the differential equations of both heat and mass transfer have been solved, the results are reasonably accurate and less time consuming. Further more, the more precise of this model for scale up designing would be suggested as follows :
The effect of back mixing along the axis may be provided to modify the original one, also, the influence on the boundary and bulk conditions by simultaneous mass and heat transfer need to be further examined.

10.5 produced H_2 in a fuel cell system

Looking at the CO plant it is obvious that not only CO is produced but also a lot of H_2. In plant II for example the H_2 production is now some 150 kmol/h. Most of this quantity is used as fuel for the heating of the reformer. This is a rather expensive heating fuel. Having in mind that for selling the H_2 purifying is needed, another possible use of the hydrogen in the future could be a fuel cell system.

Fuel cell systems are electrochemical conversion systems, where the chemical energy escaping from the oxidation reaction, directly is transformed into electrical energy. For that purpose H_2 is the feed of the anode and O_2 out of the air is the feed to the cathode. The electrochemical reaction takes place at the electrodes, where an electric voltage is generated. As a result of ion-transport in the cell - using an electrolyte between the electrodes - a electron transport using an extern circuit exists, which can deliver electrical power.

In the past years a lot of different fuel cell systems are developed. Generally those systems are called after there electrolyte. The most important fuel cell are the alkaline fuel cell (AFC), the phosphoric acid fuel cell (PAFC), the molten carbonate fuel cell (MCFC), the solid oxide fuel cell (SOFC) and the polymer electrolyte fuel cell (PEFC). The temperature in those cells varies from 80 °C (PEFC) to 1000 °C (SOFC). For electricity production the most important are the PAFC-, the MCFC- and the SOFC-systems. These systems produce a DC-voltage combined with heat.

The classical natural gas systems for electricity production has a maximum efficiency of 40 - 45 %. The modern STEG-units (steam- and gas-turbines) have a maximum efficiency of 50 - 55 %. At this moment an efficiency of 50 % is the technical limit. The conversion of hydrogen and oxygen in a fuel cell is not a Carnot-cycle with its thermodynamic laws, but a electrochemical proces. That is why the efficiencies can be higher in a fuel cell. The results of a study of an MCFC-system show that the efficiency of such a system is about 52 -58 %. In fig.10.11 a comparison between efficiencies of different electrical power systems is made. The good environment characteristics are also a result of the fact that fuel cells are working with electrochemical conversion. Because of the fact that there is no direct combustion of fuel and oxygen the emission of SO_x, NO_x, CO and hydrocarbons can be very low.

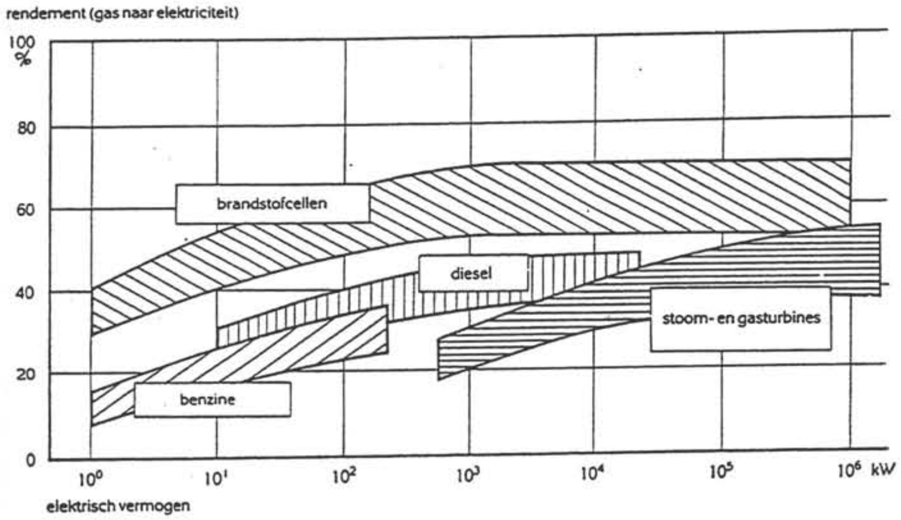


fig.10.11 : efficiencies of different systems.

The characteristics and advantages of fuel cell systems make a variety of applications possible. Fuel cells can be placed for generating a continue basic load, which is interesting for its high efficiency. The fact that the high electrical efficiency also remains by peak loads, makes fuel cells possible for so called loadfollowing uses, but in this case the use of gasturbines is preferred because of the lower installation costs and the fast characteristics of gasturbines. The most promising application in the near future is the cogeneration of electricity and heat. In first instance only PAFC-systems will be commercial available, but these systems have the disadvantage of producing heat at low temperature and have only an efficiency of 35-45 %. More useful, but only commercial in the second half of the nineties, are the MCFC- and the SOFC-systems. These systems produce high quality heat and have an efficiency of almost 60 %. This is the reason for choosing for the MCFC-system.

The hart of a fuel cell system is formed by the fuel cell itself. A fuel cell consists of a stack of basic-elements, such as a anode, cathode and in between the characteristic electrolyte. These cells, connected in series, are separated by a bipolar separationplate. which has not only a separation function but has also the function of distribution the fuel and the oxide-gasses correct. A schematic view of a fuel cell is given in fig. 10.12 .

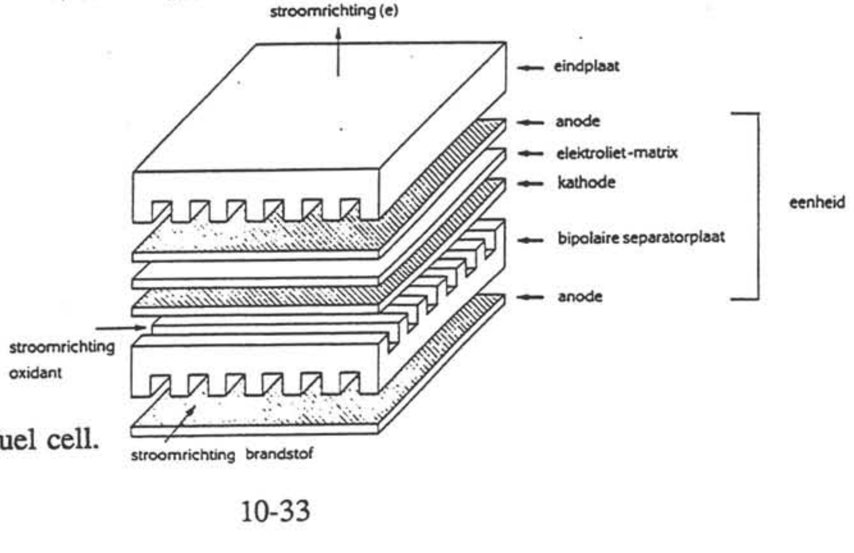


Fig.10.12: lay-out of a fuel cell.

The reactions that take place in the fuel cell (MCFC) are:

Anode: $H_2 + CO_3^{2-} \text{--->} H_2O + CO_2 + 2\,e^-$

Cathode: $CO_2 + 1/2\,O_2 + 2\,e^- \text{--->} CO_3^{2-}$

Nett: $H_2 + 1/2\,O_2 \text{--->} H_2O$

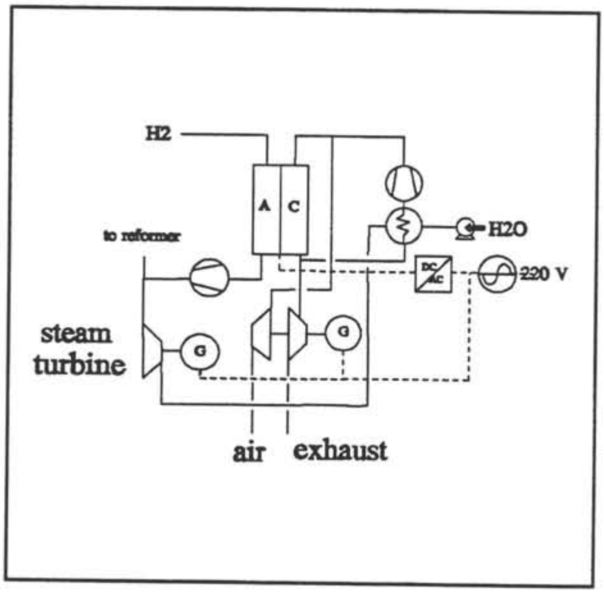


Fig 10.13 : MCFC-system

Fig.10.13 gives the circuit diagram of a MCFC-system with H_2 and air as feed. The feed reacts at the anode and produces steam, carbon dioxide and electricity. Some CO_2 is mixed with air and fed to the cathode after being compressed. The cathode off-gas comes free under pressure and can deliver power for compression air and electricity generation. The pressure is one of the most important operating parameter. At high pressure the fuel cell gives better results than at atmospheric pressure. This difference can be explained by the Nernst equation (10.47). This equation gives the correlation between the open cell voltage (OCV) and the gas composition:

$$OCV = E^0 + \frac{RT}{2F} * \ln \frac{[pH_2]}{[pCO_2] * [pH_2O]} + \frac{RT}{2F} * \ln [pCO_2] * [pO_2]^{1/2} \qquad (10.47)$$

With :
E_0 = the OCV by reference conditions
R = universal gas constant
T = absolute temperature
F = Faraday constant
p = partial pressure

Looking at the Nernst equation, it follows that the OCV is higher when the partial pressures from H_2 and O_2 are higher. The addition of inert components, such as N_2 from the air, will lower the partial pressure which will also lower the OCV. The best is to avoid inert components as much as possible. This is possible with recycle flows. A higher operating pressure gives not only a higher efficiency of the cell but also the volume of the gas decreases which results in smaller recycle compressors. On the other hand the performance of the steam turbine decreases with higher pressure. The optimum operation pressure is 7-8 bar.

The question of this system will be economical, has to be calculated later when such system is on the commercial market. At this moment several institutions around the world are working on the development of fuel cells. In the Netherlands there is "BCN' which means BrandstofCel Nederland (Fuel Cell Holland). This is a cooperation between "Verenigde Machine Fabrieken Stork NV, De Koninklijke Schelde Groep BV, ECN (Energy Centre Netherlands) and "Interduct clean technologie Delft".

The only economical system is the PAFC system. In lit [10.18] a study at the economics of a H_2 fuel cell is made. In Table 10.6 below are the results for the situation of a 20 % more CO producing plant with a H_2 separation unit which recovers 99% of the hydrogen at high purity.

Table 10.6 : cost estimation of H_2 fuel cell

Costs, in Dfl * 1000 (1990)	H_2-PAFC stack 4 MW
investment costs	8000
annual capital costs	1248
operation & maintenance	400
over-all efficiency (%)	52
fuel (1 Nm^3 H_2 = 0.34 Nm^3 NG)	1690
total annual costs	3338
kWh's produced	$32 * 10^6$
kWh-cost (ct/kWh_e)	10.4

The investment costs are based on data presented in lit.[10.19]. The investment cost of the fuel cell is the average of two figures mentioned : $ 1056 / kW (1980) and fl. 3960 for small units (1990). As the current system is not a small unit the price per kW is fl.2000.-. Capital charge is based on 15.6% (10 years, 9 % interest rate). Maintenance and

operational costs are assumed at annual 5% of the total investment costs, whereas the stack is supposed to run during 8000 hrs/a. The H_2 fuel price is the price of the amount natural gas with the same heat value. Also given in lit.[10.19] is the fact that 1 Nm^3/h of hydrogen corresponds to 1.23 kW electric power.

Looking at the price for one kWh electricity (10.4 ct/kWh) and comparing this with the price of the electricity on the plant (6.4 ct/kWh), the first conclusion is that the H_2 flow can not be used in a fuel cell system. However when you take into account that:

1) the calculations made in this paragraph are very rough.
2) the price of a fuel cell will decrease rapidly when large amounts are being produced.
3) because of the fact that this is a clean technology, maybe a subsidy will be given by the government.
4) the price of 10.4 ct/kWh is lower than the price of the common household user.

So there is a possibility of selling the electricity to the local power station, just as electricity from windmill generators is being sold.

10.6 EVALUATING THE NEW PLANT DESIGN

The new plant consists of various units. After the reformer there are several separation equipments. In this paragraph the influence of the different units and their conditions will be considered in order to understand the behavior of the total plant. The equipment that are involved in the plant are a reformer, a dryer, a COSORB® or a CO-vacuum swing adsorption unit (CO-VSA), and possibly a H_2-pressure swing adsorption (H_2-PSA) and a N_2-removal unit. The conditions of the several equipment are shown in fig.10.14

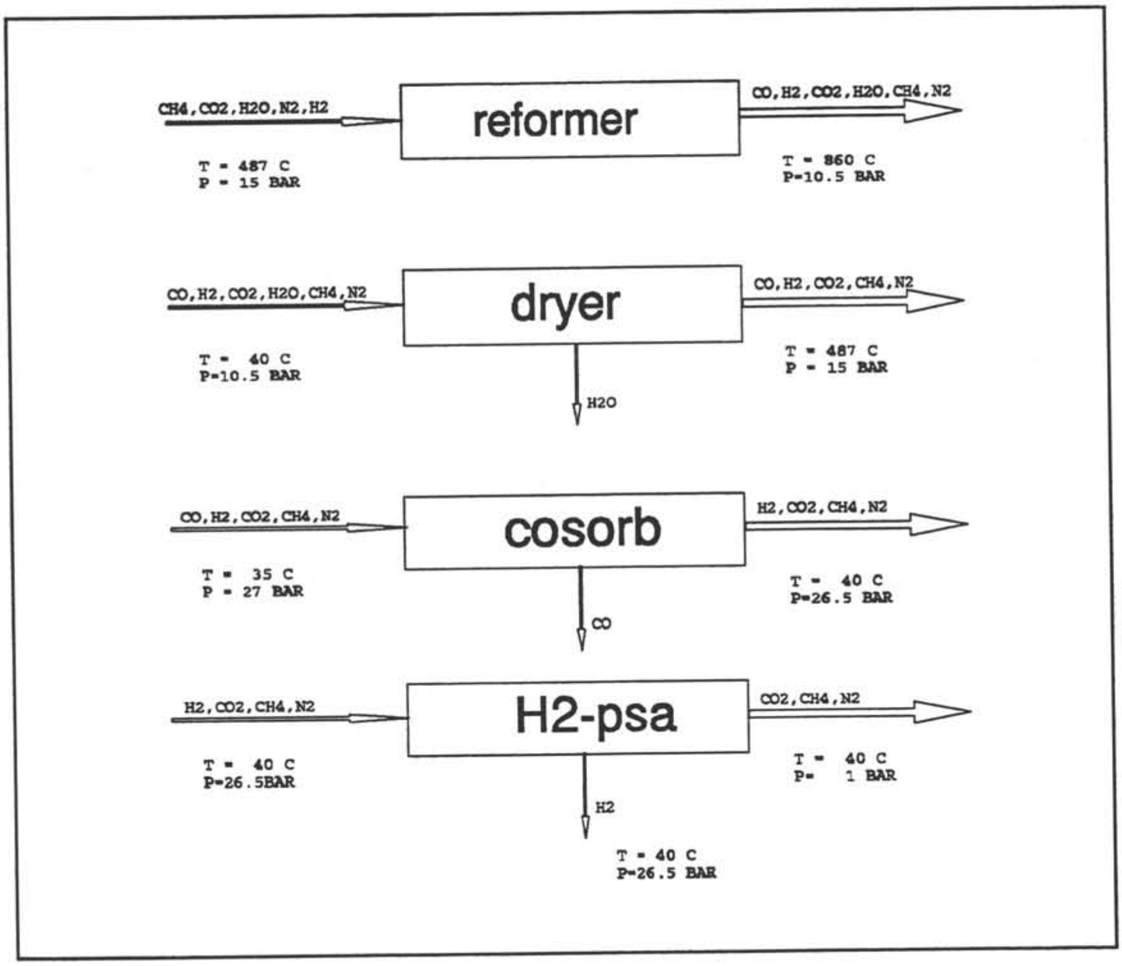


fig.10.14 : working conditions of equipment

After the reformer the gas stream consists mainly of CO, H_2, CO_2, CH_4, H_2O and N_2. In the dryer all the H_2O from the gas stream has to be removed before the gas is led to the COSORB® unit. In the COSORB® or CO-VSA unit almost all the CO (>99.9%) is removed with high purity (>99.9%). The other stream which leaves the unit consists mainly of CO_2, H_2 , CH_4 and N_2. With this stream it is possible to do several possibilities, which now will be discussed.

One option is to remove all H_2 in order to sell it. The H_2-PSA unit removes almost all the H_2 (99.9%) with high purity (99.9%) , which is necessary if the H_2 will be sold. The other gas stream which leaves the PSA unit contains CO_2, CH_4 and N_2, so a part of this stream could be recycled to the reformer. This stream has to be compressed from 1 to 14.2 bar and the temperature has to be brought from 40°C to 487°C. A part of the stream has to be purged in order to prevent accumulation of some substances. Because not all CO_2 reacts in the reformer, the little purge stream may consist of a high CO_2-percentage. A little MEA-stripper could be used to remove this CO_2, which will be recycled to the reformer, so that less CO_2 will be required in the feed and the feedcost will decrease.

Another possibility is to recycle a part of the H_2 from the H_2 -PSA unit to the reformer in order to increase the CO-production. This is achieved by the fact that H_2 will react with the CO_2, so that more CO_2 (and less CH_4) is converted to CO in the reformer. A little MEA stripper for removing the CO_2 from the purge gas can also be used in this case. It seems that if 60% of the produced H_2 is recycled to the reformer a maximum CO production can be achieved with a certain feed. Higher H_2 -recycles decrease the CO-production, because too much H_2 decreases the conversion of CH_4 to CO and H_2 .
If it is able to work with low purgestreams, the benefit of recycling H_2 becomes insignificant and the first option is recommended.
As the purge stream seems to have very little combustion value, it has no use burning this stream in the furnace.

The effect of a N_2-removal unit for the feedgas is that less N_2 is circulating in the recycleloop so that less purging is possible. If less purging is possible, less feed is required and the feedcost is lowered.

The amount of H_2 which is produced by the H_2 -PSA depends on the feedgas composition. If a certain feed is used, this amount does not seem to differ very much in the cases recycling H_2 to the reformer or not. When recycling H_2, the amount of H_2 which come out of the reformer increases also.

Another option is to work without a H_2 -PSA unit. The gas stream coming out from the COSORB® or CO-VSA unit contains H_2 , CO_2, CH_4 and N_2, so part of this stream is recycled to the reformer while the other part is purged in order to prevent accumulation. The recycle stream doesn't have to be compressed, but it has to be brought to a temperature of 487°C.
If the recycle is getting too much (so less is being purged), H_2 is piling up in the loop. This can decrease the conversion of CH_4 to CO and H_2 , which results in a lower CO production.
To solve this problem more CO_2 and less CH_4 (and so less steam) is fed to the reformer.
The use of a N_2-removal unit is only advantageous if high recycles are being applied. As no higher recycle than 60% is applied, this unit will not be necessary in this case.
The purge stream consists mainly of H_2 and also some CO_2, and the use of a MEA stripper to remove the CO_2 from the stream before burning it in the furnace have to be considered.

In the reformer mentioned in the earlier chapters, a gas stream of about 300 kmol/hr is going into the reformer (in the 20% capacity increased case). If the same reformer is being considered, the amount of gas going into the reformer at one of the new possibilities must be lower than this value. The gastemperature in the tubes will otherwise not be able to rise from 487°C to 860°C due to the decreased heat transfer, and the reaction will not be able to occur as required.

With recycling the different streams not only the amount of the stream that goes into the reformer should be considered, but also the composition of the stream should be analyzed. This is very important, because coke formation in the reformer has to be avoided. This can be done by adding steam. Also more CO_2 has also has a positive influence on avoiding coke formation. More steam is required when H_2 is recycled, because then more CO_2 reacts, which result in less CO_2 in the recycleloop. The problem that occur in this case, is that more steam has a negative effect on the CO-production. This can be solved by adding more CO_2 instead of steam and less CH_4.

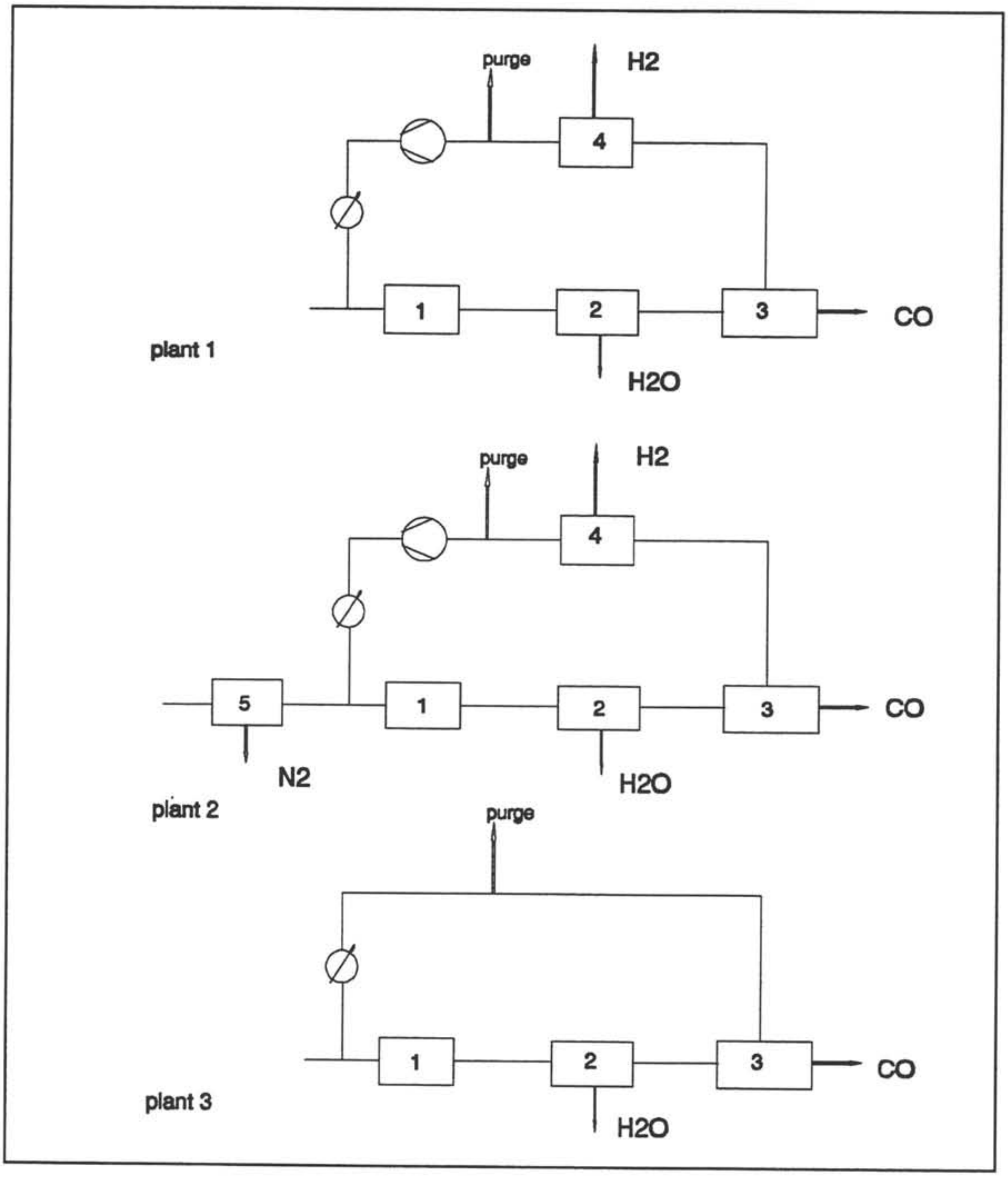


Fig 10.15: three options considered

index: 1 = CO_2-reformer
2 = dryer
3 = CO-VSA
4 = H_2-PSA
5 = N_2 removal unit

10.7 CONCLUSIONS FOR THE NEW PLANT

To come to a conclusion which plant is economically the best for producing 55 kmol CO/hr the original reformer with different feed is used. The cases that are considered here are :

PLANT 1: a plant with a H_2 -PSA and without a N_2-removal unit. No H_2 from the H_2-PSA unit is being applied as feed to the reformer. A recycle of 90% is applied.

PLANT 2: a plant with a H_2 -PSA and with a N_2-removal unit. No H_2 from the H_2-PSA unit is being applied as feed to the reformer. A recycle of 60% is applied.

PLANT 3: a plant without a H_2 -PSA and without a N_2-removal unit. As a recycle of 60% is applied, a N_2-removal unit is not necessary.

The three plants are shown in fig.10.15. The different streams that are involved in the three processes are shown in table 10.7 to 10.9. The feedgas compositions are calculated by trial and error with a computerprogram, Mercury, which simulated the plant mathematically. When searching for a feed for the plants, some aspects had to be taken into consideration. These where:

a. the plant has to produce 55 kmol CO/hr.
b. the amount of gas into the reformer had to be about 250 kmol/hr.
c. the coke formation criterium has to be applied:

$$\frac{1/2CO_2 + H_2O}{CH_4} > 3 \tag{10.46}$$

To work safe a value of 3.5 is applied.

d. the amount of all the gasses except for H_2 going into the H_2 -PSA may not exceed a value of 60 kmol/hr, otherwise this unit would become too expensive.
e. the amount of CO_2 in the feed has to brought to a minimum, because CO_2 is expensive

Table 10.7 : streams of plant 1

PLANT 1 (kmol/h)	H_2	CO	CO_2	CH_4	H_2O	N_2
feed			34	39	110	6.86
recycle			25.55	1.11		10.29
reformer in			59.55	40.11	110	17.15
reformer out	97.81	55.23	42.58	1.85	88.71	17.15
products	97.81	55.23				
purge			17.03	0.74		6.86

Table 10.8 : streams of plant 2

PLANT 2 (kmol/h)	H_2	CO	CO_2	CH_4	H_2O	N_2
feed			20.4	39	113	1.36
recycle			37.93	1.75		12.24
reformer in			58.33	40.75	113	13.60
reformer out	100.2	54.99	42.15	1.94	90.38	13.60
products	100.2	54.99				
purge			4.22	0.19		1.36

Table 10.9 : streams of plant 3

PLANT 3 (kmol/h)	H_2	CO	CO_2	CH_4	H_2O	N_2
feed			40	28.5	80	4.97
recycle	77.92		17.61	2.65		7.36
reformer in	77.92		57.61	31.15	80	12.33
reformer out	129	55.00	29.35	4.41	81.53	12.33
products		55.00				
purge	51.08		11.74	1.77		4.97

To make an estimation for the prices for producing CO, the method of chapter 9 is applied. However, the cost estimation of this chapter is not as accurate as in chapter 9, because in chapter 9 flowsheets of a consisting plant were available.
Chosen is for a CO-VSA unit, because the price of this unit seems to be lower than that for a COSORB® unit. The investment cost of the N_2-removal unit is estimated to be $ 3.000.000.

In order to calculate the costs of the utilities, the heat duties of the reformer, compressor work and the heat duties for the different recycles were calculated.

In table 10.10 the investment costs of the three plants are calculated. As expected the investment costs are the cheapest for plant 3 and most expensive for plant 2. Finally in table 10.11 the production cost of CO is calculated. It can be seen that although the price of raw materials and utilities of plant 3 is the highest, the production costs for this plant are the lowest.

Table 10.10 : investment costs for the three options

Costs in 10^3 $	plant 1	plant 2	plant 3
Furnace	885.5	885.5	885.5
Dryer system	75	75	75
Recycle compressor	39.4	48.5	
Compressor drivers	9.2	12.3	
CO-VSA			516
CO-VSA + H_2-PSA	1074	1074	
N_2-removal unit		570	
PCE	2083.1	2653.1	1476.5
Total PPC PPC=f_a*PCE	6770.1	8622.6	4798.6
Fixed Capital FC=f_b*PPC	9816.6	12502.8	6958.0
Working Capital (10%)	981.7	1250.3	695.8
Investment Cost	10798.3	13753.1	7653.8

Table 10.11 : CO-product cost calculation

A. Variable Costs in 10^3 \$	plant 1	plant 2	plant 3
1. Raw materials			
- Feed gas price	2769	2246	2619
- Net H_2 Credit	-640	-656	
2. Utilities			
- Electricity for recycle compressors	39	55	
- Natural Gas:			
- heat exchangers	8	11	48
- furnace	416	419	
Subtotal A	2592	2075	2667
B. Fixed Costs in 10^3 \$			
1. Maintenance	981.7	1250.3	695.8
2. Operating Labour	824	824	824
3. Supervision	165	165	165
4. Plant Overheads	412	412	412
5. Capital charges	1472.5	1875.4	1043.7
6. Insurance	98.5	125	69.6
7. Rates	196.4	250	139.2
8. Royalties	98.2	125	69.6
Subtotal B	4248	5026.7	3418.9
Direct Production Costs A+B	6840	7102	6086
C. Share of the Company's general operating expenses (25% of direct prod. costs)	1710	1776	1522
Annual Operating Costs (A + B + C) in 10^3 \$	8550	8878	7608
Production Cost (1540.6 kg CO/hr)	\$ 0.67/kg	\$ 0.70/kg	\$ 0.60/kg

When a new reformer should be designed, it could be designed for bigger gas streams so that it is possible to work with H_2 -recycles or with higher total recycles if no H_2 -PSA unit is used. This can cause a cheaper feed gas, because less feed is then required to produce the same amount of CO. But there are also some disadvantages when working under these conditions. The recycle streams have to be brought to reformer conditions (temperature, pressure) and more heat will be required in the reformer as the streams are bigger. All these factors should be considered when a new reformer will be designed, because a theoretical optimum does not have to be a practical optimum, just because of the economic aspects that are involved.

10.8 CONCLUSIONS AND RECOMMENDATIONS

Searching for an alternative CO-production process, several different options are found. For these options the costs for investment, feed, maintenance, operating and labour are calculated. After evaluation of costs, the most economical CO-production plant is chosen. The conclusions, based on the different options mentioned in this chapter, are:

1. For a CO production process is coal gasification only economical with a production higher than 6.5 ton/hr. Because the production in the existing plant is only 1.22 ton/hr., the choice is made to use the existing furnace fed with a different feed containing much CO_2.

2. After cost evaluation, the most economical way to produce CO is with a plant consisting of a CO_2-reformer and a CO-Vacuum Swing Adsorption system. The CO is produced for $ 0.60 /kg CO.

3. The COSORB® process is reliable process to recover CO from a mixed gas stream. However the investment cost are rather high the COSORB® process operating cost are low. The recovery cost of CO amount $ 0.70 /kg CO.

4. If there is a H_2 rich stream coming out of the plant, the H_2 can be put in a Phosphoric Acid Fuel Cell (PACF) to produce electricity for 10.4 dutch cents/ kWh. This is more than the electricity generated on the site, but less expensive than the normal electricity rate.

RECOMMENDATIONS

1. Because the equipment prices are coming from different sources, it is recommendable to evaluate the actual prices on the current market for the different equipment. This might change the price for producing CO.

2. Some further investigations can be made on the recent developments in the area of H_2 membrane separation systems. This is recommendable because the developments for such systems are going fast.

LITERATURE:

10.1 Lath E., Herbert P., 'make CO from coke, CO_2 and O_2', Hydrocarbon Processing, August 1986, pp. 55-56.

10.2 Kirk-Othmar, 'fuels,synthetic (gaseous)', volume 11, pp. 411-425.

10.3 US. patent : 5.073.356, 'Integrated process for the production of carbon monoxide', David E. Guro, Air Product and Chemicals Inc.

10.4 Farooque, Kush and Abens, 'Novel electrochemical hydrogen separation device using phosphoric acid membrane cell', Separation Science and Technology, **25** (13-15), 1990, pp. 1361-1373

10.5 White,D.M., Barkley,P., Chem. Engng. Prog., **85** (1989), pp 25-33.

10.6 Jasra R.V., Choudary N.V., Bhat S.G.T., Separation Science and Technology , **26** (7), (1991), pp 855-930.

10.7 Watson Allan M., Linde AG, 'Use pressure swing adsorption for lowest cost hydrogen',march (1983), pp.91-95.

10.8 US. patent : 4.914.076, Toshiaki Tsuji, 'method of producing an adsorbent for separation and recovery of CO', apr. 3 (1990).

10.9 Smits, J.M., H.C. Van Ness, 'Introduction to Chemical Engineering Thermodynamics', McGraw-Hill, New York, fourth edition (1987).

10.10 Onda, K., E. Sada, T. Kobayashi and M. Fujine, 'Gas Absorption Accompanied by Complex Chemical Reactions-I.Reversible Chemical Reactions', Chem.Eng.Sci. **25**, 753-760 (1970).

10.11 Gholap, R. V. and R. V. and Chaudhari, 'Absorption of Carbon Monoxide with Reversible Reaction in Cuprous Chloride Solutions', Ind. Eng. Chem. Res. **27**, 2105-2110 (1988).

10.12 Danckwerts, P. V. , 'Gas-Liquid Reactions', McGraw-Hill, New York (1970).

10.13 Gholap, R. V. and R. V. and Chaudhari, 'Absorption of Carbon Monoxide with Reversible Reaction in $CuAlCl_4$-Toluene-Complex Solutions', Can. J. Chem. Eng. **70**, 505-510 (1992)

10.14 Seidell, A., 'Solubilities of Inorganic and Metal Organic Compounds', D. Van Nostrand, New York (1940).

10.15 Coulson, J.M., J.F. Richardson, 'Chemical Engineering', vol. 6, R.K. Sinnott, (1983).

10.16 Changluo, Z., Z. Rongxian, J. Gengming, and W. Qingzi, 'A mathematic model and simulation for non isothermal gas absorption with chemical reaction', J. Chem. Ind. Eng., **2**, 115-129, (1987).

10.17 Perry, R.H., D. Green, 'Perry's Chemical Engineers' Handbook', McGraw-Hill, New York, sixth edition.

10.18 Laag, P.C. van der, Lugten P.E., 'systeemstudies voor brandstofcellen', Energiecentrum Oktober (1990) , pp. 264-268.

10.19 Seeters van J.E.A.M., Fortuin J.B., 'Utilization potential of secondary hydrogen gas in industry as fuel for fuel cell systems in the Netherlands', TEBODIN report for NOVEM B.V.

10.20 Klein, C.A.N. van der, 'De Brandstofcel: Ontwikkelingen en perspectieven', Energiespectrum Maart (1990) , pp. 77-82.

10.21 Teuner S.C., 'Make CO from CO_2', Hydrocarbon Processing, May (1985), pp. 106-107.

10.22 Esselink A.J., 'Low cost carbon monoxide', K.T.I.- report, The Hague, (1975).

10.23 Wang Shoou-I, 'careful design considerations can optimize H_2/CO production', Technology nov 1, (1982), Oil & Gas journal, pp. 55-62.

11 CONCLUSIONS AND RECOMMANDATIONS

11.1 Conclusions

- The capacity increase of 20% is possible in two ways:
  1. Adding more CO_2 in the feed stream.
  2. Adding more CO_2 in the feed stream in combination with a pre-reformer.

  Both solutions lead to the same CO price (\$ 0.88). This is less expensive than the actual CO price (\$ 1.03). Option 1 will make adaption of the MEA equipment necessary. Option 2 will not, but a pre-reformer has to be installed. The choice will depend on costs and ease of installation.

- Separate N_2 removal is economically not a better option for the current process, although it helps to increase purity.

- A completely different plant designed by group 4 could produce CO for \$0.60/kg. This is less expensive than the current CO production which has a CO price of \$0.78/kg.

- Coal gasification is not a good option because it is only economically by productions higher than 6.5 ton/hr.

- ASPEN is a very good aid designing new processes and process equipment. However working with ASPEN gave a lot of difficulties but most of them were problems with our computernetwork. The large memory use also gave some problems. The program itself has been very usefull to calculate the new streams and all physical properties of the stream but the enthalpy balances were unreliable.

- As alternative separation methods only cryogenic separation and PSA have to be taken into account. At this point membranes are commercially not available. For absorption is at this point no absorbent available. Cryogenic separation can be done by using a process designed by Linde or a process designed by Griesheim Gmbh. Linde's process is commercially available. Both methods remove approximately 80% N_2. PSA is too experimentally at this moment. If applied, it will only work in smaller plants like the one in use.

11.2 Recommendations

- The 20% capacity increase by adding CO_2 to the feed in combination with a pre-reformer is a good option and relatively inexpensive.

- The effect of the feed stream with a smaller amount of nitrogen on the Coldbox should be investigated.

12. EXPERIENCES WITH ASPEN PLUS.

12.1. Introduction to Aspen-Plus.

Aspen Plus (hereafter to be referred to as Aspen) is one of the many commercially available packages for the simulation of processes in the chemical industry. The use of Aspen is limited to static simulations, so no time-dependent processes can be modelled. The version used was release 8.5-4, in combination with ModelManager version 3-1.

12.2. How to create an Aspen input file.

Since the release of ModelManager, creating an Aspen input file has become very simple, especially when using ModelManager with graphics. In that case, the only thing to be done is drawing the flowsheet on the screen, selecting the various pieces of process-equipment from a menu and connecting these blocks by entering streams; most blocks have a number of icons to choose from. While building the flowsheet you must keep in mind what you want to have calculated; if you are not interested in an energy balance, most of the pumps are unnecessary, since Aspen does not take into account the pressure drop over a pipeline. It is also possible to give the desired outlet pressure after the pump as a specification on the previous block. Likewise, you can model a compressor as a heater with an increasing pressure over the apparatus, and a distillation column as a separation block with given composition and temperatures of the outgoing streams. When all blocks are placed, ModelManager asks for all required input, such as the equations of state to be used, the flows and compositions of the feed streams and the specifications for all blocks, e.g. the number of trays in a column, pressure drops over the various pieces of process-equipment and the reactions taking place in a reactor. When sufficient data is entered, ModelManager gives a prompt that the simulation can be executed and creates an input file to be used by the program itself; before the release of ModelManager these input files had to be writen directly, thus requiring a reasonable knowledge of the language used by Aspen. A more detailed description on the use of ModelManager and Aspen is given in appendix 12, as well as all models and an example of an Aspen input-file.

12.3. Aspen's special features.

Aspen is one of the more advanced simulation packages on the market and offers quite a lot of special features. For one, the choice of the model for the equation of state to be used is to be made out of over 25 options, varying from the ideal gas law to the Kent-Eisenberg model which is to be selected when using alkanolamines to remove CO_2 from a stream. It is possible to give every piece of process-equipment its own thermodynamic model.

An other impressive option is the amount of data which can be obtained about the operation of a distillation column; Aspen automatically gives data regarding the vapour/liquid equilibrium, but can also, on request, give properties of the mixture on each individual tray such as the surface tension, the viscosity, the density and the interaction parameters.

If enough expertise on the use of the computer language Fortran is present, one can write the routine to be used in a user-defined block; this can be necessary if the apparatus to be modelled is not present in the standard list used by Aspen (see appendix 12), or if the results of the standard routine are not satisfactory.

Aspen is a user-friendly program, providing an on-screen help facility on most of the topics; for more difficult and acute problems there is the Aspen-Plus-Hotline where a team of experts is ready to solve them.

12.4. Problems and possibilities for improvement.

The problems encountered while working with Aspen can be divided into three major groups: problems with the host-computer ("the network"), difficulties understanding and using the program itself and problems occurring while running the simulation.
The problems with the host-computer were the most time-consuming and often occurring; most of them can be described to lack of memory on the host-computer. In a case like that, Aspen gives a prompt that there is not enough memory left to generate the output files and the simulation is terminated. In the worst case the lack of memory does not occur until the simulation is completed; Aspen then tells you to delete a number of other files and tries again to read in the results. If however the the available memory is not enough, the entire program is terminated losing all data. When the network is used by someone else running more memory-consuming programs, Aspen will not run at all; there is no solution to this problem, however. Most of the other problems were solved when the amount of memory assigned to us was doubled. In this context I would like to point out the possibility of making a back-up file in which all relevant data is stored and which can be copied from the network to a floppy disk.
The inability to understand Aspen is caused by not having an up-to-date manual on how to use ModelManager. Most of the problems were solved eventually, but some remained. To name a few: it has not become clear how you can make a correction when you made a mistake in entering the name of a particular stream or block. Equally disturbing is the fact that numlock is inactive under ModelManager, even though you have got an enormous amount of data to enter. There is also no way of printing only a part of the entered flowsheet; when the simulated process is rather complicated this certainly is desirable.
Problems occurring when running or attempting to run a simulation are the following: sometimes, when using special routines for the equation of state, Aspen has to link with its library, which can take up to a quarter of an hour. There is, however, the possibility of saving these routines which we did not discover until recently. We already discussed the problems occurring when the network is used by others. Sometimes, Aspen refuses to read in the results, either by ignoring your command to do so or by pretending to be reading them in while doing nothing at all. Aspen would sometimes generate error messages nobody could understand, or present results which are physically impossible without giving as much as a warning. In this context I would like to point out the danger that a heat exchanger cools both streams (without change of phase), even though the enthalpy of one of them rises substantially. This has probably a lot to do with the unaccurateness of the enthalpy-calculating routines; this is the major reason for not being able to simulate processes with very complex heat recovery, such as the Coldbox.

APPENDIX 2

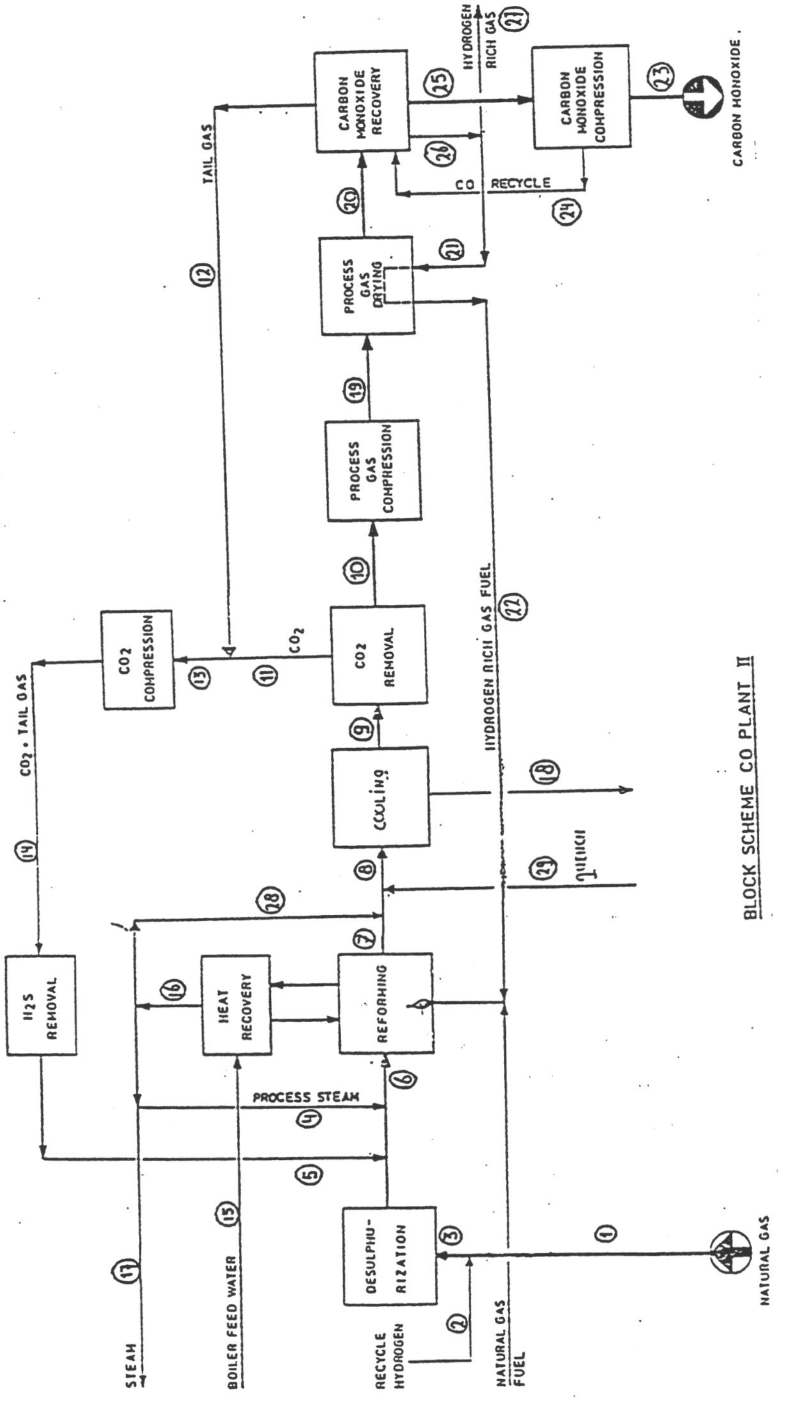


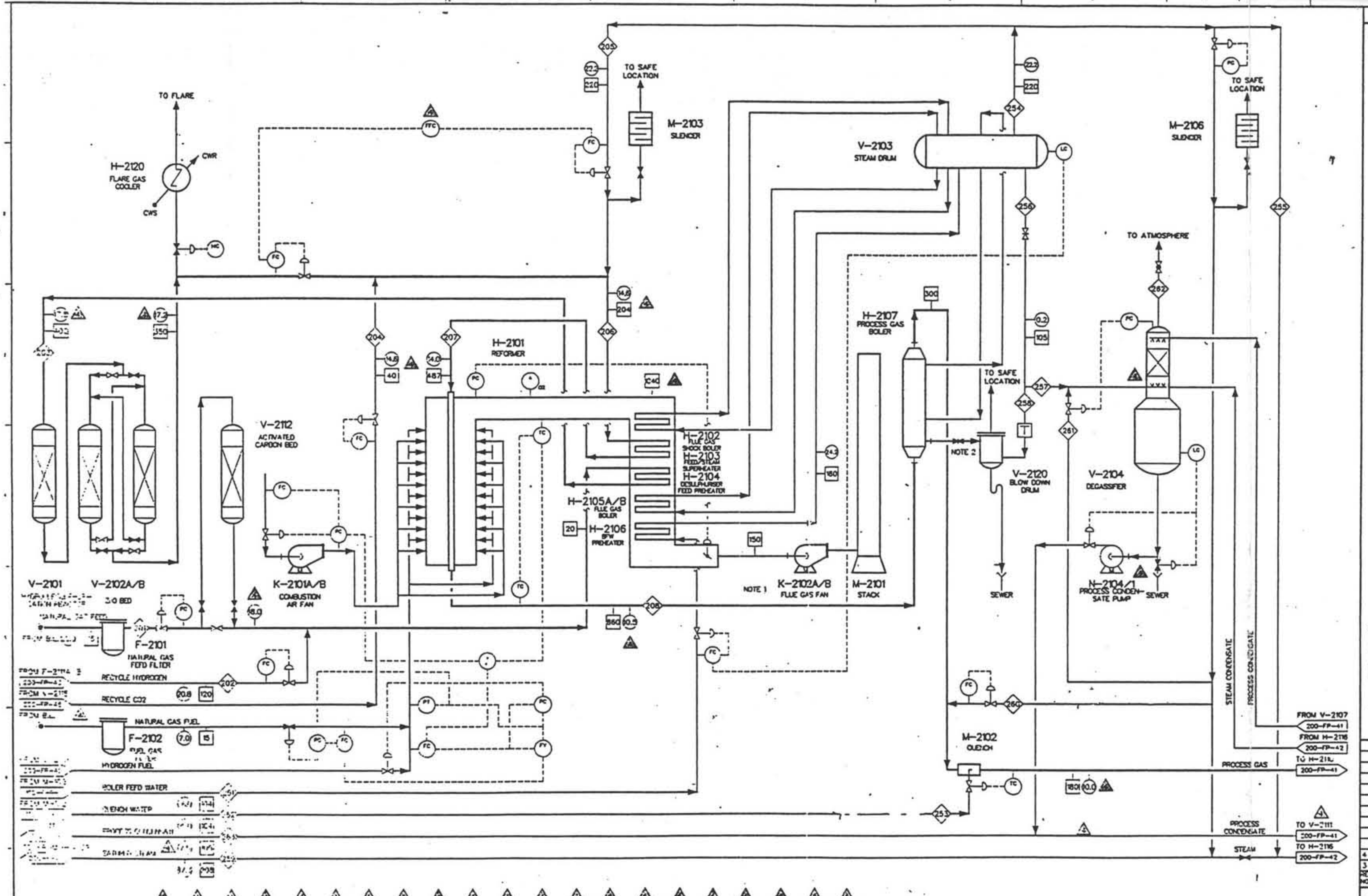
fig. A2.1 : block scheme of CO plant II

Table A2.1 : design streams of CO plant II

Block Scheme CO plant II

Stream number	Stream number	pressure [bar]	Temp [°C]	Components [kg/h] H_2	CO	CO_2	N_2	O_2	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_6H_{14}	MEA	H_2O	total
1	201	20	15	-	-	20,8	213,4	0,2	692,7	45.5	8.7	4.3	1.5	2,3	-	-	989.4
2	202	20.8	120	10,7	2,5	-	2.2	-	-	-	-	-	-	-	-	-	15.4
3	203	17,5	400	10,7	2.5	20,8	215,7	0,2	692,7	45.5	8,7	4.3	1,5	2.3	-	-	1004,8
4	205	22.2	220	-	-	-	-	-	-	-	-	-	-	-	-	2725,2	2725.2
5	204	14.6	40	6,2	199,4	13135	29.8	-	68.7	-	-	-	-	-	-	3.7	1621.3
6	207	14.0	487	16.9	201.9	13343	245.4	-	761.4	45.5	8.7	4.3	1.5	2,3	-	2729.1	5351,3
7	208	10.5	860	300.5	1498,1	1380,6	245.4	-	69.1	-	-	-	-	-	-	1858.0	5351,7
8	209	10.0	180	300.5	1498,1	1380,6	245,4	-	69.1	-	-	-	-	-	-	4292.6	7786.3
9	211	9.4	40	300.5	1498,1	1380,6	245,4	-	69.1	-	-	-	-	-	-	31,4	3525.1
10	212	9.3	40	300.1	1496.0	0.5	245,1	-	69.0	-	-	-	-	-	-	27.9	2138,6
11	215	0,5	40	0,4	2,0	1313,5	0,3		0,1	-	-	-	-	-	-	28	1344,3
12	227	1,0	31	5,8	197.3	-	29,4	-	68,6	-	-	-	-	-	-	-	301,1
13	216	0,5	40	6,2	199,4	1313,5	29,8	-	68,7	-	-	-	-	-	-	28	1645,6
14	217	15,2	40	6,2	199,4	1313,5	29,8	-	68,7	-	-	-	-	-	-	3,7	1621.3
15	251	26.0	104	-	-	-	-	-	-	-	-	-	-	-	-	6183,9	6183.9
16	254	22,2	220	-	-	-	-	-	-	-	-	-	-	-	-	5936,5	5936.5
17	255	22,2	220	-	-	-	-	-	-	-	-	-	-	-	-	347.9	347.9
18	266	2.5	98	-	-	-	-	-	-	-	-	-	-	-	-	4261,2	4261,2
19	219	27.7	35	300.1	1496,0	0,5	245,1	-	69.0	-	-	-	-	-	-	7.8	2118.5
20	223	27,2	35	298.3	1487.1	-	243,7	-	68,6	-	-	-	-	-	-	-	2097.8
21	222	2.7	27	241,4	56,7	-	50,1	-	-	-	-	-	-	-	-	-	348,2
22	222 [average flow]	2.0	40	243,2	65,6	0,5	51,5	-	0,4	-	-	-	-	-	-	7,8	369,0
23	226	8,6	35	-	1221,4	-	153,6	-	-	-	-	-	-	-	-	-	1375,0
24	225	8,6	35	-	238,6	-	39,0	-	-	-	-	-	-	-	-	-	268.7
25	224	1.0	31	-	1460,1	-	183,6	-	-		-						1643.7
26	228	3.3	25	292,5	68,3	-	60,7	-		-	-	-	-	-	-		421.5
27 [gaat ydalletjs van naar 2]	229	2,0	25	51.1	11.7	-	10,6	-	-	-		-	-	-	-		73 4
28	260	17.3	208	-	-	-	-	-	-	-	-	-	-	-	-	1046,7	1046,7
29	253	26.0	104	-	-	-	-	-	-	-	-	-	-	-	-	5811,8	5811.8

confidential



COMPONENTS	STREAM NUMBER Mw	201	202	203	204	205	206	207	208	251	252	253	254	255	256	257	258	259	260	261	262	263
		kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h
[illegible]	[illegible]		10.7	10.7	6.2		18.9	18.9	[illegible]													
[illegible]	28.01		[illegible]	[illegible]	199.4		[illegible]	201.9	[illegible]													
[illegible]	44.01	[illegible]		[illegible]	1313.5		[illegible]	1334.3	[illegible]													
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	29.9		[illegible]	245.4	[illegible]													
[illegible]	[illegible]	[illegible]							[illegible]													
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]		[illegible]	[illegible]														
[illegible]	[illegible]	45.5		45.5			[illegible]	45.5														
[illegible]	[illegible]	4.7		[illegible]			[illegible]	4.7														
[illegible]	58.124	4.3		4.3			4.3	4.3														
[illegible]	[illegible]	1.5		1.5				1.5														
[illegible]	[illegible]	[illegible]		[illegible]																		
[illegible]	61.084																					
[illegible]	18.015				3.7	[illegible]	[illegible]	[illegible]	[illegible]	6183.9	587.8	587.8	[illegible]	[illegible]	247.4	55.7	191.7	909.5	846.7	107.3	123.3	4647.0
[illegible]		489.4	15.4	2094.8	1617.5		[illegible]	[illegible]	2493.7													
[illegible]		489.4	15.4	1094.8	1621.3	[illegible]	[illegible]	5351.3	5351.7	6183.9	587.8	587.8	5235.5	147.9	247.4	55.7	191.7	909.5	846.7	107.3	123.3	4647.0
TEMPERATURE	[illegible]	35	170	400	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	104	104	104	220	220	220	105	105	208	208	208	105	105
PRESSURE	[illegible]	20.0	20.8	17.5	14.6	[illegible]	[illegible]	11.0	7.5	25.0	25.0	26.0	[illegible]	22.2	22.2	0.2	0.2	17.3	17.3	17.3	0.2	7.5
[illegible]		18.63	2.81	17.15	35.55	18.02	[illegible]	20.22	15.28	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02
[illegible]	kg/m³	17.02	[illegible]	5.65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	956.4	956.4	956.4	11.60	11.60	840.5	[illegible]	954.7	9.21	9.21	9.21	0.70	954.6
[illegible]	[illegible]	[illegible]	[illegible]	0.023	0.017	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.016	0.016	[illegible]	0.012	0.266	[illegible]	0.016	0.016	0.012	0.262
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.256	[illegible]	[illegible]	[illegible]	[illegible]	1.006	1.006	1.006	0.751	0.751	[illegible]	0.489	1.008	[illegible]	0.705	0.705	0.489	1.008
[illegible]	[illegible]	[illegible]	[illegible]	0.084	0.022	0.025	[illegible]	[illegible]	[illegible]	0.588	0.588	0.588	0.035	0.035	0.557	0.022	0.587	0.033	0.033	0.033	0.022	0.588
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	20.0	[illegible]	[illegible]	2.20	95.7	200.5	[illegible]	175.1	4.9

GENERAL NOTES

NOTE 1: BOTH FANS RUNNING

NOTE 2: INTERMITTENT BLOW DOWN

◇ STREAM NUMBER

○ PERMITTED PRESS. bar(g)

☐ PERMITTED TEMP. °C

REV NO.	PROJECT NO.	DESCRIPTION	DATE	DRWN	CHKD	APPR 1	APPR 2
4	[illegible]	AS BUILT	[illegible]	[illegible]	[illegible]		
3		REDRAWN	[illegible]	ZWT	[illegible]		[illegible]

REVISIONS

SCALE NONE

CAD NUMBER FP0204000004

STAMP

THIS DRAWING OR PRINT IS THE PROPERTY OF GE PLASTICS AND IS TO BE USED ONLY CONFIDENTIALLY BY AUTHORIZED PERSONNEL. IT SHALL NOT BE COPIED, REPRODUCED NOR EXHIBITED TO UNAUTHORIZED PERSONS AND IS TO BE RETURNED UPON REQUEST

TITLE

PROCESS FLOW DIAGRAM
CO PLANT II (1220kg/h)
REFORMING/STEAM GENERATION

GE Plastics

CONTRACTOR KTI

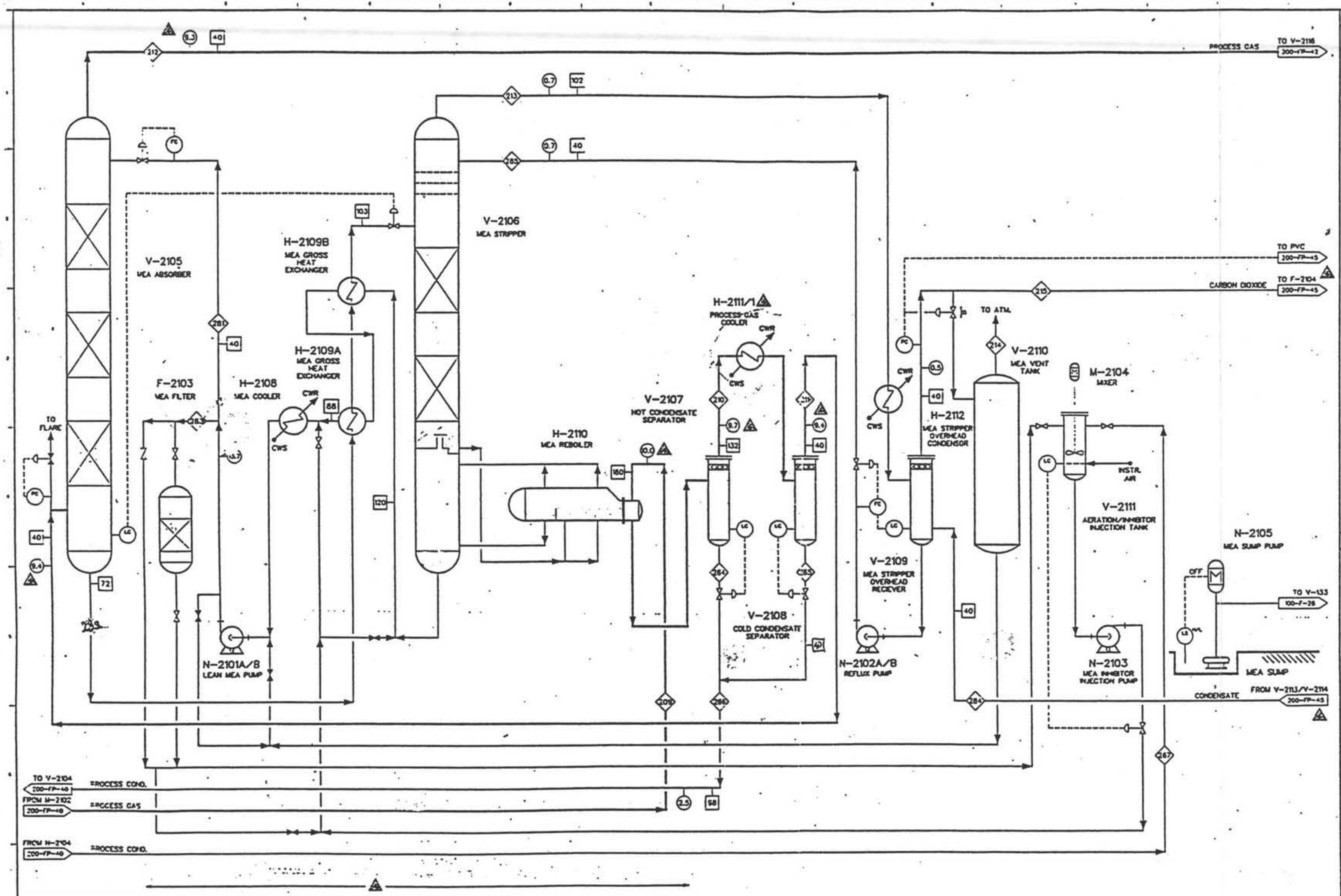
BY : ZWT

DATE : JULY'87

PROJECT NO. 31157

DRAWING NO. 200-FP-40

REV. 4



STREAM NUMBER / COMPONENTS	MW	209	210	211	212	213	214	215	264	265	266	267	281	282	283	284	285
		kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h	kg/h AVERFLOW	kg/h	kg/h	kg/h	kg/h	kg/h
HYDROGEN	2.016	300.5	300.5	300.5	300.1	0.4		0.4						0.4			
CARBON MONOXIDE	28.011	1498.1	1498.1	1498.1	1498.0	2.1	0.1	2.0						[illegible]			
CARBON DIOXIDE	44.010	1380.6	1380.6	1380.6	0.5	1380.1	68.7	1313.5					421.7	1801.9	48.4		
NITROGEN	28.013	245.4	245.4	245.4	245.1	0.3		0.3						0.3			
OXYGEN	31.999																
METHANE	16.043	69.1	69.1	69.1	69.0	0.1		0.1						0.1			
ETHANE	30.070																
PROPANE	44.097																
BUTANE	58.124																
PENTANE	72.151																
HEXANE	86.178																
MONO ETHANOL AMINE	61.084												5352.1	[illegible]			
STEAM/WATER	18.015	4292.8	1607.7	31.4	27.9	988.7	1.4	28.0	2584.9	1578.3	4281.2	17	13955.1	13268.5	609.9	23.7	983.0
TOTAL DRY		3493.7	3493.7	3493.7	2110.8	1383.1	66.8	1316.3									
TOTAL WET		7786.5	5101.4	3525.1	2138.7	2371.8	68.2	1344.3	2584.9	1578.3	4281.2	17	19707.9	22094.3	[illegible]	23.7	983.0
TEMPERATURE	°C	120	132	40	40	[illegible]	[illegible]	40	132	40	95	124	40	72	40	40	40
PRESSURE	barg	10.0	9.7	9.4	9.3	0.7	0.3	0.5	9.7	9.4	7.5	26.0	13.7	9.4	13.7	0.5	0.7
MOLECULAR WEIGHT		16.05	15.17	14.17	9.86	27.41	42.44	42.42	18.02	18.02	18.02	18.02		33.34	22.60	18.02	18.02
DENSITY ACTUAL	kg/m³	4.75	4.85	5.66	3.89	1.52	1.66	2.48	932.8	992.7	959.7	956.4	1022.9	1076.2	1022.9	992.3	992.3
VISCOSITY	cP	0.019	0.019	0.017	0.016	0.017	0.016	0.016	0.202	0.652	0.286	0.269	1.53	0.68	1.53	0.651	0.651
SPECIFIC HEAT	kcal/kg °C	0.510	0.514	0.516	0.715	0.317	0.213	0.214	1.016	0.997	4.209	1.016	0.879	0.866	0.879	0.997	0.997
THERMAL CONDUCTIVITY	kcal/hm °C	0.055	0.068	0.073	0.090	0.021	0.016	0.016	0.593	0.543	0.679	0.557	0.418	0.438	0.418	0.543	0.536
VOLUMETRIC FLOW	m³/h	[illegible]	[illegible]	[illegible]	549.1	1554.3	41.1	541.4	2.9	1.6	4.4	0.022	19.3	20.6	2.2	0.02	1.0

GENERAL NOTES

LEGENDS

◇ STREAM NUMBER
○ PERMITTED PRESS. bar(g)
☐ PERMITTED TEMP. °C

REV NO.	PROJECT NO.	DESCRIPTION	DATE	DRAWN	CHECKED		
4	CH00047	AS BUILT	JUL 89	HLV	HC		
3		CALMA REDRAWN	JUL 87	[illegible]			[illegible]

REVISIONS

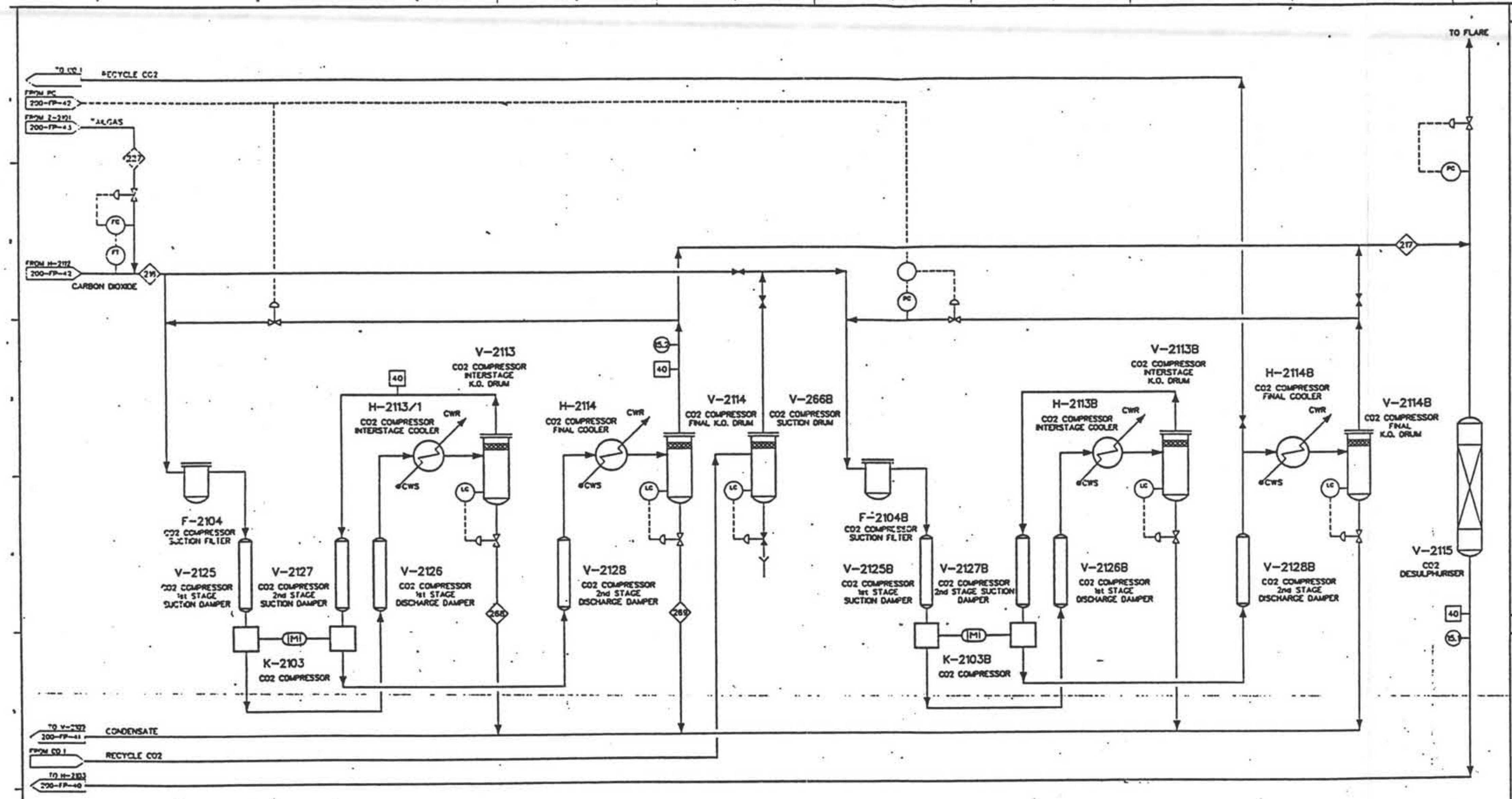
SCALE NONE
CAD NUMBER FP0204100004
STAMP

THIS DRAWING OR PRINT IS THE PROPERTY OF GE PLASTICS AND IS TO BE USED ONLY CONFIDENTIALLY BY AUTHORIZED PERSONNEL. IT SHALL NOT BE COPIED, REPPODUCED NOR EXHIBITED TO UNAUTHORIZED PERSONS AND IS TO BE RETURNED UPON REQUEST

TITLE
PROCESS FLOW DIAGRAM
CO-PLANT II (1220 kg/h)
CO2 REMOVAL

GE Plastics

CONTRACTOR KTI
BY: WvK
DATE: JUL 87
PROJECT NO. | ECO NO. | DRAWING NO. 200-FP-41 | REV. 4



STREAM NUMBER / COMPONENTS		[illegible]	217	227	268	289
	MW	kg/h	kg/h	kg/h	kg/h	kg/h
HYDROGEN	2.016	[illegible]	6.2	5.8		
CARBON MONOXIDE	28.011	[illegible]	199.4	197.3		
CARBON DIOXIDE	44.010	1313.5	1313.5			
NITROGEN	28.013	[illegible]	29.8	20.4		
OXYGEN	31.999					
METHANE	16.043	[illegible]	68.7	68.6		
ETHANE	30.070					
PROPANE	44.097					
BUTANE	58.124					
PENTANE	72.151					
HEXANE	86.178					
MONO ETHANOL AMINE	61.084					
STEAM/WATER	18.015	[illegible]	3.7		16.7	7.1
TOTAL DRY		1317.5	1617.5	301.2		
TOTAL WET		1345.6	1621.3	301.2	16.7	7.1
TEMPERATURE	°C	40	40	31	40	40
PRESSURE	bar(a)	[illegible]	[illegible]	10	15	[illegible]
MOLECULARE WEIGHT		35.55	35.55	19.74	18.02	[illegible]
DENSITY ACTUAL	kg/m³	[illegible]	22.97	1.57	992.3	[illegible]
VISCOSITY	cP	[illegible]	0.017	0.016	0.651	[illegible]
SPECIFIC HEAT	kcal/kg °C	0.744	0.757	0.380	0.997	[illegible]
THERMAL CONDUCTIVITY	kcal/hm °C	[illegible]	0.023	0.037	0.543	[illegible]
VOLUMETRIC FLOW	m³/h	[illegible]	[illegible]	191.5	0.017	[illegible]

GENERAL NOTES

[illegible]

LEGENDS

◇ STREAM NUMBER
○ PERMITTED PRESS. bar(g)
□ PERMITTED TEMP. °C

REV NO.	PROJECT NO.	DESCRIPTION	DATE	DRWN	CHKD	APPR 1	APPR 2
1	[illegible]	AS BUILT	[illegible]	[illegible]	[illegible]		

REVISIONS

SCALE NONE
CAD NUMBER FP0204500001

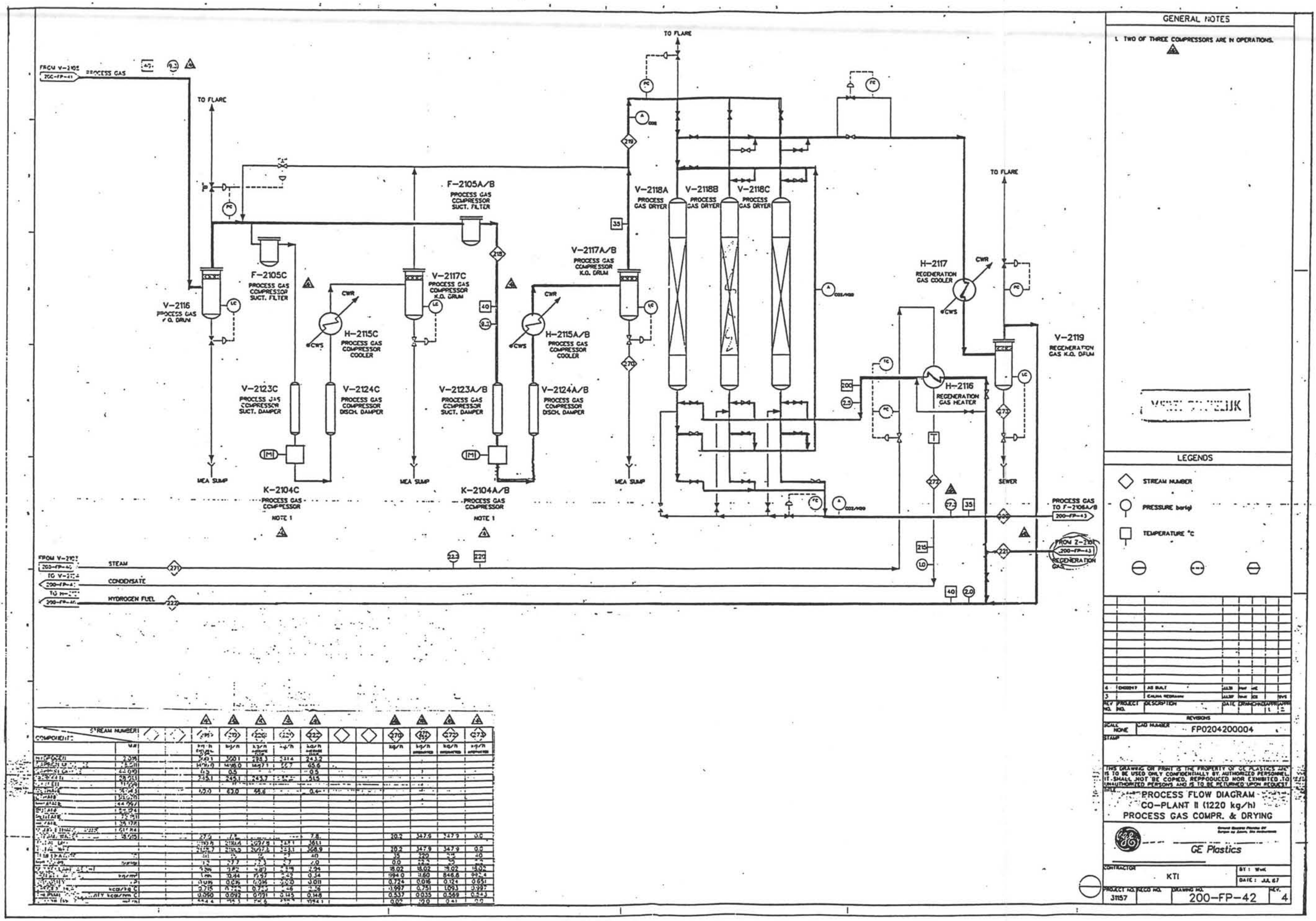
STAMP

THIS DRAWING OR PRINT IS THE PROPERTY OF GE PLASTICS AND IS TO BE USED ONLY CONFIDENTIALLY BY AUTHORIZED PERSONNEL. IT SHALL NOT BE COPIED, REPRODUCED NOR EXHIBITED TO UNAUTHORIZED PERSONS AND IS TO BE RETURNED UPON REQUEST.

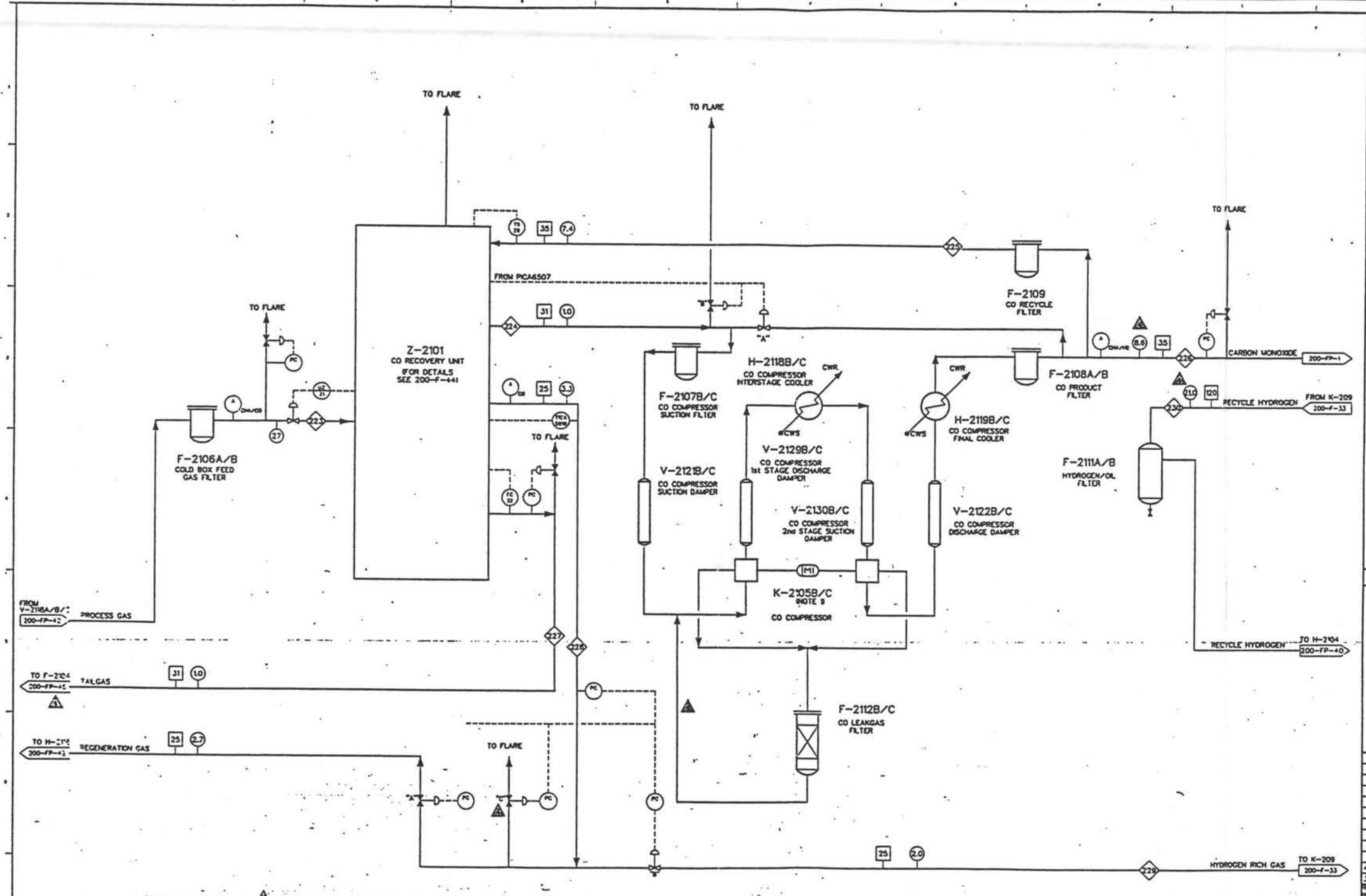
TITLE
PROCESS FLOW DIAGRAM
CO-PLANT II (1220 kg/h)
CARBON DIOXIDE & COMPRESSION

General Electric Plastics BV
Bergen op Zoom, the Netherlands
GE Plastics

CONTRACTOR KTI
BY: WH
DATE: FEB'91
PROJECT NO. 31157
RECO NO.
DRAWING NO. 200-FP-45
REV. 1



STREAM NUMBER / COMPONENTS	MW			[illegible]	219	220	221	222			270	271	272	273
				kg/h	kg/h	kg/h	kg/h	kg/h			kg/h	kg/h	kg/h	kg/h
HYDROGEN	2.016			[illegible]	300.1	298.3	[illegible]	243.2						
CARBON MONOXIDE	[illegible]			[illegible]	1498.0	1457.1	[illegible]	65.6						
CARBON DIOXIDE	44.010			0.5	0.5			0.5						
NITROGEN	[illegible]			245.1	245.1	243.7	[illegible]	51.5						
[illegible]	[illegible]													
METHANE	[illegible]			63.0	63.0	55.6		0.4						
[illegible]	[illegible]													
PROPANE	44.097													
BUTANE	[illegible]													
PENTANE	72.151													
[illegible]	[illegible]													
[illegible]	[illegible]													
WATER	18.015			27.9	7.8			7.8			20.2	347.9	347.9	0.0
TOTAL [illegible]				[illegible]	[illegible]	[illegible]	[illegible]	361.1						
TOTAL WT				[illegible]	[illegible]	[illegible]	[illegible]	368.9			20.2	347.9	347.9	0.0
TEMPERATURE	°C			[illegible]	[illegible]	[illegible]	[illegible]	40			35	220	[illegible]	40
PRESSURE	bar(g)			[illegible]	27.7	[illegible]	[illegible]	2.0			0.0	[illegible]	[illegible]	[illegible]
MOLECULAR WEIGHT				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			18.02	18.02	18.02	18.02
DENSITY	kg/m³			[illegible]	10.84	15.57	[illegible]	0.34			994.0	11.60	846.6	[illegible]
VISCOSITY	cP			[illegible]	[illegible]	[illegible]	[illegible]	0.011			0.724	0.016	0.124	0.651
SPECIFIC HEAT	kcal/kg °C			0.715	[illegible]	[illegible]	[illegible]	[illegible]			0.997	0.751	1.093	0.997
THERMAL CONDUCTIVITY	kcal/hm °C			0.090	0.092	0.091	0.145	0.148			0.537	0.035	0.569	0.543
[illegible]	m³/h			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			0.02	20.0	0.41	0.0



STREAM NUMBER / COMPONENTS	MW	223 kg/h	224 kg/h	225 kg/h	226 kg/h	227 kg/h	228 kg/h	229 kg/h	230 kg/h
HYDROGEN	2.016	298.3				5.8	292.5	51.1	10.7
CARBON MONOXIDE	28.011	1487.1	1460.1	238.6	1221.4	197.3	68.3	11.7	2.5
CARBON DIOXIDE	44.010								
NITROGEN	28.013	243.7	183.6	30.0	153.6	29.4	60.7	10.6	2.2
OXYGEN	31.999								
METHANE	16.043	68.6				68.6			
ETHANE	30.070								
PROPANE	44.097								
BUTANE	58.124								
PENTANE	72.151								
HEXANE	86.178								
MONO ETHANOLAMINE	61.084								
STEAM/WATER	18.015								
TOTAL DRY		2097.8	1643.7	268.7	1375.0	301.2	421.5	73.4	15.4
TOTAL WET		2097.8	1643.7	268.7	1375.0	301.2	421.5	73.4	15.4
TEMPERATURE	°C	35	31	35	35	31	25	25	120
PRESSURE	bar(g)	27.2	1.0	8.6	8.6	1.0	3.3	2.0	21.0
MOLECULAR WEIGHT		9.50	28.01	28.01	28.01	19.74	2.81	2.81	2.81
DENSITY ACTUAL	kg/m³	10.64	2.23	10.53	10.53	1.57	0.49	0.34	1.87
VISCOSITY	cP	0.016	0.018	0.018	0.018	0.016	0.010	0.010	0.012
SPECIFIC HEAT	kcal/kg°C	0.723	0.250	0.252	0.252	0.380	2.456	2.46	2.53
THERMAL CONDUCTIVITY	kcal/hm°C	0.091	0.022	0.023	0.023	0.037	0.144	0.144	0.180
	m³/h	197.3	736.3	25.5	130.6	191.5	863.5	215.5	8.2

GENERAL NOTES

1) K-2105 B WILL BE A COMMON SPARE FOR K-2105 C AND THE NEW CO COMPRESSOR FOR CO PLANT I(K-2105 A)

VERTROUWELIJK

LEGENDS

◇ STREAM NUMBER
○ PERMITTED PRESS. bar(g)
☐ PERMITTED TEMP. °C

REV NO.	PROJECT NO.	DESCRIPTION	DATE	DRWN	CHKD	APPR 1	APPR 2
4	CHO0347	AS BUILT	JUL 31	HLV	JC		
3		CALMA REDRAWN	JUL 27	WvK			3-8

REVISIONS

SCALE NONE
CAD NUMBER FP0204300004

STAMP

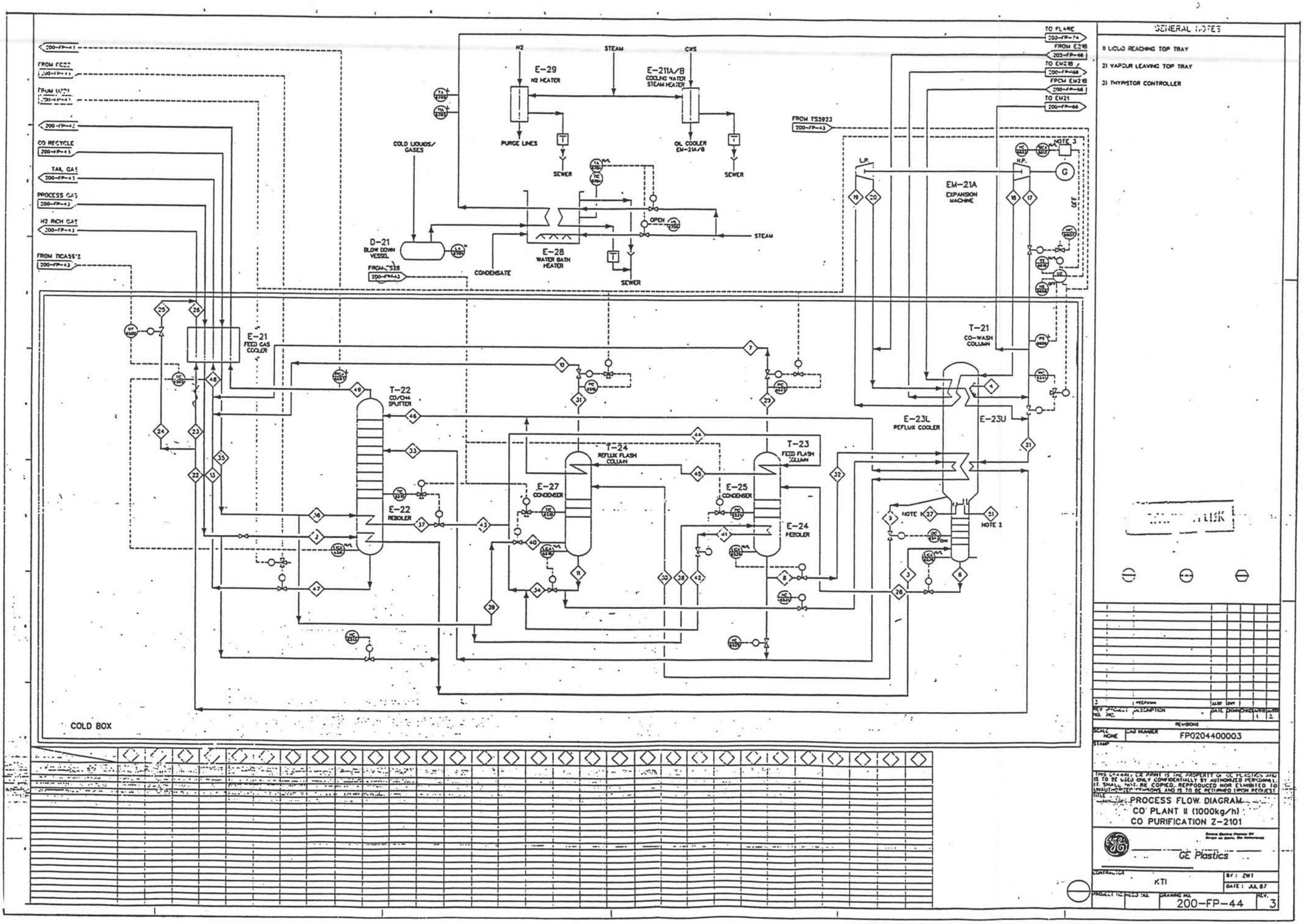
THIS DRAWING OR PRINT IS THE PROPERTY OF GE PLASTICS AND IS TO BE USED ONLY CONFIDENTIALLY BY AUTHORIZED PERSONNEL. IT SHALL NOT BE COPIED, REPPODUCED NOR EXHIBITED TO UNAUTHORIZED PERSONS AND IS TO BE RETURNED UPON REQUEST

TITLE
PROCESS FLOW DIAGRAM
CO-PLANT II (1220 kg/h)
CO RECOVERY & COMPRESSION

General Electric Plastics BV
Bergen op Zoom, the Netherlands
GE Plastics

CONTRACTOR KTI
BY : WvK
DATE : JUL '87

PROJECT NO. | RECD NO. | DRAWING NO. 200-FP-43 | REV. 4


200-FP-41
FROM FC22
200-FP-41
FROM UZ21
200-FP-41
200-FP-42
CO RECYCLE
200-FP-43
TAIL GAS
200-FP-43
PROCESS GAS
200-FP-43
H2 RICH GAS
200-FP-43
FROM TICA5512
200-FP-43
N2
STEAM
CWS
E-29
N2 HEATER
E-211A/B
COOLING WATER
STEAM HEATER
PURGE LINES
SEWER
OIL COOLER
EM-21A/B
SEWER
COLD LIQUIDS/
GASES
OPEN
STEAM
D-21
BLOW DOWN
VESSEL
FROM TS28
200-FP-43
CONDENSATE
E-28
WATER BATH
HEATER
SEWER
TO FLARE
200-FP-74
FROM E21B
200-FP-66
TO EM21B
200-FP-66
FROM EM21B
200-FP-66
TO EM21
200-FP-66
FROM TS5923
200-FP-43
NOTE 3
L.P.
H.P.
G
EM-21A
EXPANSION
MACHINE
OFF
E-21
FEED GAS
COOLER
T-22
CO/CH4
SPLITTER
E-22
REBOILER
T-24
REFLUX FLASH
COLUMN
E-27
CONDENSER
T-23
FEED FLASH
COLUMN
E-25
CONDENSER
E-24
REBOILER
T-21
CO-WASH
COLUMN
E-23L
REFLUX COOLER
E-23U
NOTE 2
NOTE
COLD BOX
GENERAL NOTES
1) LIQUID REACHING TOP TRAY
2) VAPOUR LEAVING TOP TRAY
3) THYRISTOR CONTROLLER
REV NO.
PROJECT INC.
DESCRIPTION
DATE
DRWN
CHKD
APPR 1
APPR 2
REVISIONS
SCALE NONE
CAD NUMBER
FP0204400003
STAMP
THIS DRAWING OR PRINT IS THE PROPERTY OF GE PLASTICS AND IS TO BE USED ONLY CONFIDENTIALLY BY AUTHORIZED PERSONNEL. IT SHALL NOT BE COPIED, REPRODUCED NOR EXHIBITED TO UNAUTHORIZED PERSONS AND IS TO BE RETURNED UPON REQUEST
TITLE
PROCESS FLOW DIAGRAM
CO PLANT II (1000kg/h)
CO PURIFICATION Z-2101
GE Plastics
CONTRACTOR
KTI
BY: ZWI
DATE: JUL 87
DRAWING NO.
200-FP-44
REV.
3

Appendix 3.1 Reformer heat duty calculations.

$T1 := 487 + 273.15$

$p1 := 15$

$R := 8.314$

$T2 := 860 + 273.15$

$p2 := 11$

$Tst := 25 + 273.15$

$$Tam := \frac{T1 + T2}{2}$$

$$M := \begin{bmatrix} 2.016 \\ 28.011 \\ 44.010 \\ 28.013 \\ 16.043 \\ 30.070 \\ 44.097 \\ 58.124 \\ 72.151 \\ 86.178 \\ 18.015 \end{bmatrix} \qquad yin := \begin{bmatrix} 8.38 \\ 7.21 \\ 30.32 \\ 8.76 \\ 47.46 \\ 1.51 \\ 0.20 \\ 0.07 \\ 0.02 \\ 0.03 \\ 151.49 \end{bmatrix} \qquad yuit := \begin{bmatrix} 149.06 \\ 53.48 \\ 31.37 \\ 8.76 \\ 4.31 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 103.13 \end{bmatrix}$$

$ytotin := \Sigma yin$

$ytotuit := \Sigma yuit$

$$y1 := \frac{yin}{ytotin} \qquad y2 := \frac{yuit}{ytotuit}$$

$$Tci := \begin{bmatrix} 33.2 \\ 132.9 \\ 304.2 \\ 126.2 \\ 190.6 \\ 305.4 \\ 369.8 \\ 425.2 \\ 469.6 \\ 507.4 \\ 647.3 \end{bmatrix} \qquad \omega i := \begin{bmatrix} -.22 \\ .049 \\ .225 \\ .040 \\ .008 \\ .098 \\ .152 \\ .193 \\ .251 \\ .296 \\ .344 \end{bmatrix} \qquad pci := \begin{bmatrix} 13.0 \\ 35.0 \\ 73.8 \\ 33.9 \\ 46.0 \\ 48.8 \\ 42.5 \\ 38.0 \\ 33.7 \\ 29.7 \\ 220.5 \end{bmatrix}$$

$$Cpcoef := \begin{bmatrix} 3.249 & 0.422\cdot10^{-3} & 0 & 0.083\cdot10^{5} \\ 3.376 & 0.557\cdot10^{-3} & 0 & -0.031\cdot10^{5} \\ 5.457 & 1.045\cdot10^{-3} & 0 & -1.157\cdot10^{5} \\ 3.280 & 0.593\cdot10^{-3} & 0 & 0.040\cdot10^{5} \\ 1.702 & 9.081\cdot10^{-3} & -2.164\cdot10^{-6} & 0 \\ 1.131 & 19.225\cdot10^{-3} & -5.561\cdot10^{-6} & 0 \\ 1.213 & 28.785\cdot10^{-3} & -8.824\cdot10^{-6} & 0 \\ 1.935 & 36.915\cdot10^{-3} & -11.402\cdot10^{-6} & 0 \\ 2.464 & 2.464\cdot10^{-3} & 45.351\cdot10^{-6} & 0 \\ 3.025 & 53.722\cdot10^{-3} & -16.791\cdot10^{-6} & 0 \\ 3.470 & 1.450\cdot10^{-3} & 0 & 0.212\cdot10^{5} \end{bmatrix}$$

$$E := \begin{bmatrix} 1 \\ Tam \\ \left[\dfrac{4\cdot Tam^{2} - T1\cdot T2}{3}\right] \\ \left[\dfrac{1}{T1\cdot T2}\right] \end{bmatrix} \qquad Cplos := R\cdot Cpcoef\cdot E$$

$$Cplos = \begin{bmatrix} 30.41362781 \\ 32.42198198 \\ 52.47736443 \\ 31.97570426 \\ 69.29036111 \\ 118.74389363 \\ 170.04141815 \\ 220.57482461 \\ 382.14034121 \\ 321.24517664 \\ 40.46635497 \end{bmatrix}$$

$cpin := y1\cdot Cplos$

$cpuit := y2\cdot Cplos$

Eerst ga ik ethaan en hoger (487gr C) laten reageren tot CH4

$$yeerst := \begin{bmatrix} yin_5 \\ yin_6 \\ yin_7 \\ yin_8 \\ yin_9 \end{bmatrix} \quad Tceerst := \begin{bmatrix} Tci_5 \\ Tci_6 \\ Tci_7 \\ Tci_8 \\ Tci_9 \end{bmatrix} \quad \omega eerst := \begin{bmatrix} \omega i_5 \\ \omega i_6 \\ \omega i_7 \\ \omega i_8 \\ \omega i_9 \end{bmatrix} \quad pceerst := \begin{bmatrix} pci_5 \\ pci_6 \\ pci_7 \\ pci_8 \\ pci_9 \end{bmatrix}$$

$$ytoteerst := \Sigma yeerst$$

$$yfrac := \frac{yeerst}{ytoteerst}$$

$$Tpc1 := yfrac^{T} \cdot Tceerst$$

$$ppc1 := yfrac^{T} \cdot pceerst \qquad ppr1 := \frac{p1}{ppc1_0}$$

$$\omega 1 := yfrac^{T} \cdot \omega eerst$$

$$Tpr1 := \frac{T1}{Tpc1_0}$$

$$B01 := 0.083 - \frac{0.422}{Tpr1^{1.6}} \qquad dB01 := \frac{0.675}{Tpr1^{2.6}}$$

$$B11 := 0.139 - \frac{0.172}{Tpr1^{4.2}} \qquad dB11 := \frac{0.722}{Tpr1^{5.2}}$$

$$Hr1 := ytoteerst \cdot R \cdot Tpc1 \cdot ppr1 \cdot (B01 - Tpr1 \cdot dB01 + \omega 1 \cdot (B11 - Tpr1 \cdot dB11))$$

id --> 25 gr C

$$\mathrm{cpeerst} := \begin{bmatrix} \mathrm{Cplos}_5 \\ \mathrm{Cplos}_6 \\ \mathrm{Cplos}_7 \\ \mathrm{Cplos}_8 \\ \mathrm{Cplos}_9 \end{bmatrix}$$

$$\mathrm{ytoteerst} := \Sigma \mathrm{yeerst}$$

$$\mathrm{yfrac} := \frac{\mathrm{yeerst}}{\mathrm{ytoteerst}}$$

$$\mathrm{cp} := \mathrm{yfrac} \cdot \mathrm{cpeerst} \qquad \mathrm{cp} = 134.44369555$$

$$\delta \mathrm{Hreact} := \mathrm{ytoteerst} \cdot \mathrm{cp} \cdot (298.15 - \mathrm{T1})$$

$$\mathrm{Hr} := \begin{bmatrix} -65.220 \\ -118.880 \\ -172.290 \\ -225.840 \\ -280.200 \end{bmatrix}$$

$$j := 0 \,..4$$

$$\mathrm{yCH4} := \sum_j (j + 2) \cdot \mathrm{yeerst}_j$$

$$\delta \mathrm{Hr} := \mathrm{yeerst} \cdot \mathrm{Hr}$$

Nu is er alleen CH4 dus deze weer opwarmen tot 487 gr C

$$\delta \mathrm{Hprod} := \mathrm{yCH4} \cdot \mathrm{Cplos}_4 \cdot (\mathrm{T1} - 298.15)$$

Even reeel gas van maken :

$$\mathrm{Tr} := \frac{\mathrm{T1}}{\mathrm{Tci}_4} \qquad \mathrm{pr} := \frac{\mathrm{p1}}{\mathrm{pci}_4}$$

$$\mathrm{B01} := 0.083 - \frac{0.422}{\mathrm{Tr}^{1.6}} \qquad \mathrm{B11} := 0.139 - \frac{0.172}{\mathrm{Tr}^{4.2}}$$

$$\mathrm{dB01} := \frac{0.675}{\mathrm{Tr}^{2.6}} \qquad \mathrm{dB11} := \frac{0.722}{\mathrm{Tr}^{5.2}}$$

$$Hr2 := yCH4 \cdot R \cdot Tci_4 \cdot pr \cdot \left[B01 - Tr \cdot dB01 + \omega i_4 \cdot (B11 - Tr \cdot dB11)\right]$$

$$\delta Hreactie1 := Hr1 + Hr2 + \delta Hr + \delta Hprod + \delta Hreact$$

==

Nu de hoofdreacties

$$y1 := \begin{bmatrix} yin_0 \\ yin_1 \\ yin_2 \\ yin_3 \\ \left[yin_4 + yCH4\right] \\ yin_{10} \end{bmatrix} \qquad Tci := \begin{bmatrix} Tci_0 \\ Tci_1 \\ Tci_2 \\ Tci_3 \\ Tci_4 \\ Tci_{10} \end{bmatrix} \qquad pci := \begin{bmatrix} pci_0 \\ pci_1 \\ pci_2 \\ pci_3 \\ pci_4 \\ pci_{10} \end{bmatrix} \qquad \omega i := \begin{bmatrix} \omega i_0 \\ \omega i_1 \\ \omega i_2 \\ \omega i_3 \\ \omega i_4 \\ \omega i_{10} \end{bmatrix}$$

$$ytot1 := \Sigma y1$$

$$yfract1 := \frac{y1}{ytot1}$$

$$Tpc1 := yfract1^{T} \cdot Tci$$

$$Tpr1 := \frac{T1}{Tpc1_0}$$

$$ppc1 := yfract1^{T} \cdot pci$$

$$\omega 1 := yfract1^{T} \cdot \omega i \qquad ppr1 := \frac{p1}{ppc1_0}$$

$$y2 := \begin{bmatrix} yuit_0 \\ yuit_1 \\ yuit_2 \\ yuit_3 \\ yuit_4 \\ yuit_{10} \end{bmatrix}$$

$$ytot2 := \Sigma y2$$

$$yfract2 := \frac{y2}{ytot2}$$

$$B01 := 0.083 - \frac{0.422}{Tpr1^{1.6}} \qquad dB01 := \frac{0.675}{Tpr1^{2.6}}$$

$$B11 := 0.139 - \frac{0.172}{Tpr1^{4.2}} \qquad dB11 := \frac{0.722}{Tpr1^{5.2}}$$

$$Hr1 := ytot1 \cdot R \cdot Tpc1 \cdot ppr1 \cdot (B01 - Tpr1 \cdot dB01 + \omega 1 \cdot (B11 - Tpr1 \cdot dB11))$$

$$Tpc2 := yfract2^{T} \cdot Tci$$

$$ppc2 := yfract2^{T} \cdot pci \qquad Tpr2 := \frac{T2}{Tpc2}$$

$$\underset{\sim}{\omega}2 := yfract2^{T} \cdot \underset{\sim}{\omega}i \qquad ppr2 := \frac{p2}{ppc2_{0}}$$

$$B02 := 0.083 - \frac{0.422}{Tpr2^{1.6}} \qquad dB02 := \frac{0.675}{Tpr2^{2.6}}$$

$$B12 := 0.139 - \frac{0.172}{Tpr2^{4.2}} \qquad dB12 := \frac{0.722}{Tpr2^{5.2}}$$

$$Hr2 := R \cdot ytot2 \cdot Tpc2 \cdot ppr2 \cdot (B02 - Tpr2 \cdot dB02 + \omega 2 \cdot (B12 - Tpr2 \cdot dB12))$$

nu voor ideaal mengsel van 487 naar 25 gr C

$$cplos := \begin{bmatrix} Cplos_{0} \\ Cplos_{1} \\ Cplos_{2} \\ Cplos_{3} \\ Cplos_{4} \\ Cplos_{5} \end{bmatrix} \qquad \begin{matrix} cp1 := yfract1^{T} \cdot cplos \\ cp2 := yfract2^{T} \cdot cplos \end{matrix}$$

$$\delta Hreactant := ytot1 \cdot cp1 \cdot (298.15 - T1)$$

$$\delta Hprod := ytot2 \cdot cp2 \cdot (T2 - 298.15)$$

$$X := 47.46$$

$$Y := 1.07$$

$$yout_{1} := yin_{1} + X - Y$$
$$yout_{2} := yin_{2} + Y$$
$$yout_{3} := yin_{3}$$
$$yout_{10} := yin_{10} - X - Y$$
$$yout_{0} := yin_{0} + 3 \cdot X + Y$$

$$yout_{4} := yCH4 - X$$

$$yout = \begin{bmatrix} 151.83 \\ 53.6 \\ 31.39 \\ 8.76 \\ -43.28 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 102.96 \end{bmatrix}$$

$CH_4 + H_2O \dashrightarrow CO + 3H_2$: $\delta Hst1 = 205813$ J/MOL CH_4
$CO + H_2O \dashrightarrow CO_2 + H_2$: $\delta Hst2 = -41166$ ''

$\delta Hst1 := 205813$ $\delta Hst2 := -41166$

$\delta Hreactie := X \cdot \delta Hst1 + Y \cdot \delta Hst2$

$\delta Hreactie = 9.72383736 \cdot 10^{6}$

$\delta Htotaal := \delta Hreactie + \delta Hprod + \delta Hreactant + Hr1 + Hr2$

$\delta Htotaal = 1.59444047 \cdot 10^{7}$ kJ/h

kWatt

$Q := \delta Htotaal + \delta Hreactie1$

$$Qtotaal := \frac{Q}{3600}$$

$Qtotaal = 4.43445582 \cdot 10^{3}$

Appendix 3.2. Prediction of the streams and calculation of the equilibrium constants.

To predict the composition of the flows, the following equations were solved with Mercury.
$T =$
$T_{app3} =$
$T_{app4} =$
$P =$

$m =$
$H_{2f} = m^*$
$CO_f = m^*$
$CO_{2f} = m^*$
$N_{2f} = m^*$
$CH_4 = m^*$
$H_2O_f = m^*$
$H_2O_s =$

$$K_3=\exp[-\frac{27464}{T-T_{app3}}+30.707]$$

$$K_4=\exp[\frac{4578}{T-T_{app4}}-4.33]$$

$$K_4=\exp[\frac{4084}{T}-3.765]$$

$$K_3=\frac{P_{CO}*P_{H_2}^3}{P_{CH_4}*P_{H_2O}}$$

$$K_4=\frac{P_{H2}*P_{CO2}}{P_{CO}*P_{H2O}}$$

$$P_i=\frac{n_i}{n_{tot}}*P$$

$$H_2r=0.0562*H_2$$

$$CO_r=0.1348*CO$$

$$CO_{2r}=0.951*CO_2$$

$$H_2O_r=0.002*H_2O$$

$$CH_{4r}=0.994*CH_4$$

$$N_{2r}=0.13*N_2$$

$$H_2=H_{2r}+H_{2f}+3*x-y$$

$$CO=CO_r+CO_f+x-y$$

$$H_2O=H_2O_r+H_2O_f-x-y$$

$$CH_4=CH_{4r}+CH_{4f}-x$$

$$CO_2=CO_{2r}+CO_{2f}+y$$

$$N_2=N_{2r}+N_{2f}$$

$$n = H_2 + CO + CO_2 + CH_4 + H_2O + N_2$$

with

T : temperature (K).

T_{appj} : temperature approach for reaction j (K).

P : pressure (atm).

m : multiplication factor for the natural gas (-).

H_2O_s: molar flow of steam, added to the feed (kmol/h).

i_f : molar flow of component i in feed (kmol/h).

i_r : molar flow of component i in recycle (kmol/h).

i : amount of component i in equilibrium with the other components (kmol/h).

K_j : equilibrium constant of reaction j.

x : conversion of CH_4 (kmol/h).

y : production of CO_2 (kmol/h).

n : total molar flow (kmol/h).

Furthermore, the flows of the components are assumed to be positive.
The recycle ratio is calculated by using the design streams.

Appendix 3.3. Calculation of the design (KTI) overall heat transfer coefficient.

For the calculation of the overall heat transfer coefficient the following data was required [A1]:

kst : Conductivity of tube metal (W/m/K)
Dti : Internal tube diameter (m)
Dte : External tube diameter (m)
aw : Wall heat transfer coefficient ($W/m^2/K$)
ker : Effective conductivity of the catalyst bed (W/m/K)
ker° : Static contribution of the effective conductivity of the catalyst bed (W/m/K)
kg : Process gas conductivity (W/m/K)
dp : equivalent particle diameter (m)
rhog : density of process gas (kg/m^3)
v : velocity of process gas (m/s)
μ : viscosity of process gas (Pa * s)
Cpg : Specific heat of process gas (J/kg/K)
Vcyl : volume of a cylinder with same external diameter and height as the annular catalyst particle (m^3)
Scyl : external surface area of a cylinder with same external diameter and height as the annular catalyst particle (m^2)
Sp : external surface area of the catalyst particle (m^2)
Vp : volume of the catalyst particle (m^3)
ε : void fraction of packing (-)
Dt : inner catalyst diameter (m)

<u>kst (Conductivity of the tube metal)</u>

The tubes are made of steel containing 30-35 % Ni, 19 - 23 % Cr and 1 - 1.5% Nb [A2].

kst = 23.2 W/m/K

<u>Dti (internal tube diameter)</u>

Information given by KTI [A2].

Dti = 0.10 m

Dte (external tube diameter)

Information given by KTI [A2].

Dte = 0.12 m

ker° (static contribution of the effective conductivity of the catalyst bed)

Relation found in literature [A3]. For (Raschig) Rings equation (A3.1) was found.

$$\frac{k^{\circ}_{er}}{k_g}=3 \qquad \text{(A3.1)}$$

kg (process gas conductivity)

The conductivities of the components and of the process gas, under the given conditions, are mentioned in table A3.1 [A4] (except for CO [A5]).

Table A3.1. Conductivities of the components and the process gas.

Comp.	Conductivity (W/m/K)	Percentage (weight%)	Contribution
H_2	42.91E-2	0.029	12.44E-3
CO_2	6.48E-2	0.344	22.29E-3
CO	6.67E-2	0.083	5.54E-3
H_2O	9.04E-2	0.403	36.43E-3
N_2	6.21E-2	0.046	2.86E-3
CH_4	15.65E-2	0.095	14.87E-3
gas			kg = 94.43E-3

Cpg (specific heat of process gas)

For the calculation of the specific heat of the components, equation (A3.2) is used [A3.6].

$$Cp_g^{ig}=R*(A+B*T+C*T^2+D*T^{-2}) \quad \text{(J/mol/K)} \qquad \text{(A3.2)}$$

The constants of the components, used in equation (A3.2) are mentioned in table A3.2.

Table A3.2. Constants for the calculation of the specific heats of the components.

component	A	B	C	D
CH_4	1.702	9.081E-3	-2.164E-6	---
N_2	3.280	0.593E-3	---	0.040E5
H_2	3.249	0.422E-3	---	0.083E5
CO	3.376	0.557E-3	---	-0.031E5
CO_2	5.457	1.045E-3	---	-1.157E5
H_2O	3.470	1.450E-3	---	0.121E5

With equation (A3.2), the specific heats of the components and of the process gas can be calculated. See for the results table A3.3.

Table 3.3. Specific heat of the components and of the process gas.

Comp.	Specific heat (J/kg/K)	Percentage (weight%)	Contribution
H_2	15205.0	0.029	441.0
CO_2	1193.6	0.344	410.6
CO	1157.9	0.083	96.1
H_2O	2247.8	0.403	905.9
N_2	1141.8	0.046	52.5
CH_4	4343.8	0.095	412.7
gas			Cpg = 2318.7

v (velocity of process gas)

Under the prevailing conditions the ideal gas law is valid (A3.3).

$$n=\frac{p*V}{R*T} \qquad \text{(A3.3)}$$

With the law, the process gas volume flow through the reformer can be calculated.

$$\frac{13.25*10^5*\Phi_v}{8.314*946.65}=296.1*\frac{1000}{3600}$$

$\Longrightarrow \Phi v = 0.4886\ m^3/s$

The reformer has 20 tubes, so the process gas volume flow per tube can be determined.

$\Longrightarrow \Phi v = 0.0244\ m^3/s/tube$

This means for the velocity of the process gas through the tubes

$$\phi_v = v * A = v * \pi * \frac{1}{4} * D_{ti}$$

$\Longrightarrow v = 3.11\ m/s$

dp (equivalent particle diameter)

The dimensions of the rings are shown in fig. A3.1.

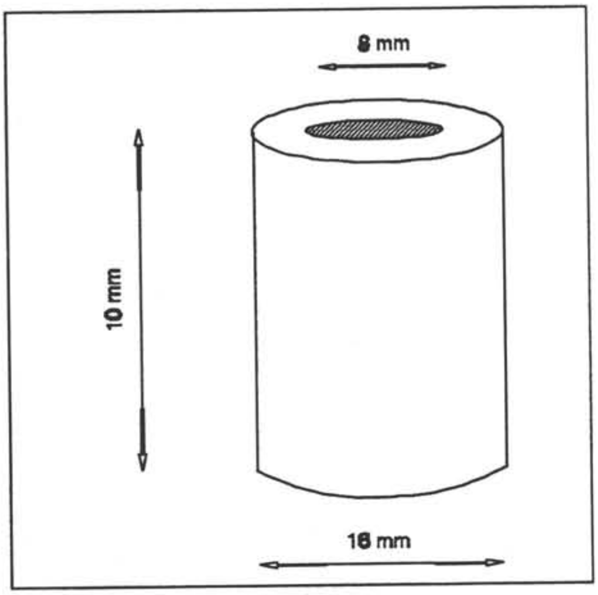


Figure A3.1. Dimensions of the catalyst rings.

The particle diameter dp is defined as follows, to account for the shape of the annular catalyst particle.

$$d_p = 6 * \frac{V_{cyl}}{S_{cyl}} * E^n$$

with

$$E=\frac{V_p*S_{cyl}}{S_p*V_{cyl}}$$

and

$$n=\frac{\dfrac{D_{ti}}{D_t}}{(\epsilon*\dfrac{D_{ti}^2}{D_t^2})^{0.4}+0.01*(\epsilon*\dfrac{D_{ti}^2}{D_t^2})^{0.75}}$$

⟹ dp = 5.0E-3 m

D_t (inner catalyst diameter)

Information given by KTI [A2]

D_t = 8E-3 m

µ (viscosity of process gas)

The viscosities of the components and the process gas under the given conditions are mentioned in table A3.4.

Table A3.4. Viscosity of the components and process gas.

Comp.	Viscosity (Pa*s)	Percentage (weight%)	Contribution
H_2	2.0E-5	0.029	0.6E-6
CO_2	4.2E-5	0.344	14.0E-6
CO	4.1E-5	0.083	3.4E-6
H_2O	3.3E-5	0.403	13.0E-6
N_2	4.1E-5	0.046	1.9E-6
CH_4	2.9E-5	0.095	2.7E-6
			μ = 36.4E-6

ε (void fraction of packing)

For the void fraction of the packing the following value is assumed.

$\varepsilon = 0.43$ (-)

rho (density of process gas)

The density of the process gas can be calculated with equation (A3.4).

$$rhog=\frac{\phi_m}{\phi_v}=\frac{5351.3}{1758.8}=3.04\frac{kg}{m^3} \tag{A3.4}$$

Calculation of the dimensionless constants:

$$Re_p=\frac{rhog*v*d_p}{\mu}=\frac{3.04*3.11*5.0E-3}{36.4E-6}=1301$$

$$Pr=\frac{\mu*Cp_g}{k_g}=\frac{36.4E-6*2318.7}{94.43E-3}=0.8931$$

Calculation of the overall heat transfer coefficient:

$$a_w = \frac{8.694*0.283}{(0.1)^{\frac{4}{3}}} + \frac{0.512*94.43E-3*0.1*1301*0.9630}{5.0E-3}$$

= 53.06 + 1211.61

= 1264.67

$$k_{er} = 0.283 + \frac{0.111*94.43E-3*1301*0.9630}{1+46*\frac{(5.0E-3)^2}{(0.1)^2}}$$

= 0.283 + 11.779

= 12.062

$$\frac{1}{U} = \frac{0.1}{2*23.2}*\ln(1.206) + \frac{1}{1264.67} + \frac{0.1}{8*12.062}$$

= 4.037E-4 + 7.907E-4 + 10.363E-4

$\Longrightarrow$ U = 448 W/m^2/K

Literature

A1. J.C. De Deken, E.F. Devos and G.F. Froment, Steam reforming of natural gas, Chem. React. Eng., 1982 281.

A2. Process data sheets for the reformer of CO plant II, KTI.

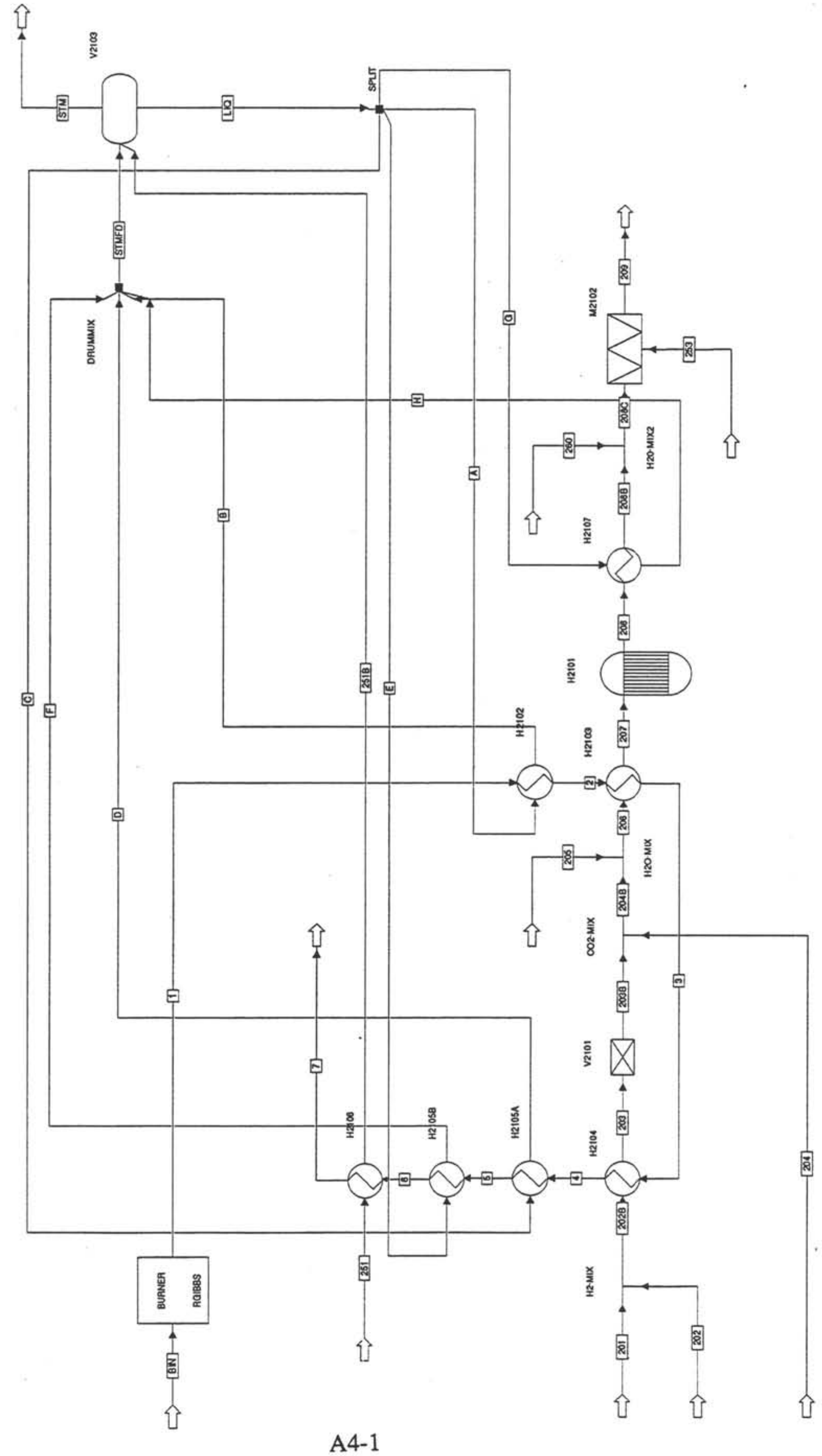
A3. S. Yagi and D. Kunii, Studies on effective thermal conductivities in packed beds, A.I.Ch.E.Jl, 1957 **3** 373.

A4. R.H. Perry and P.W. Green, Perry's Chemical Engineers' Handbook, 6th edition, McGraw-Hill, New York, 1991.

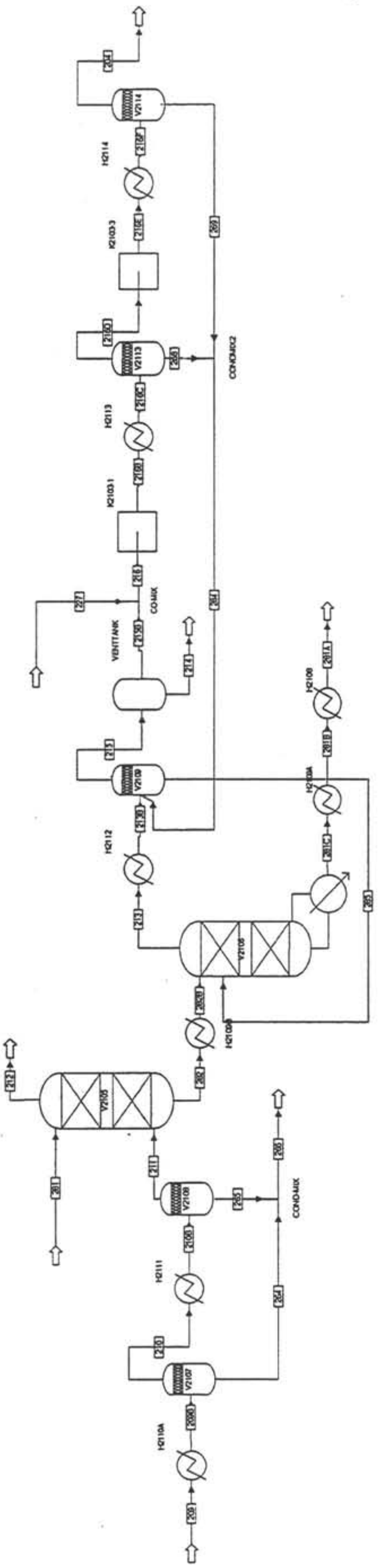
A5. J. Millat, Thermal conductivity of nitrogen and carbon dioxide, J. Phys. Chem. Ref. Data, 1989 **18** 575.

A6. J.M. Smith and H.C. van Ness, Introduction to chemical engineering thermodynamics, McGraw-Hill, New York, 1987.

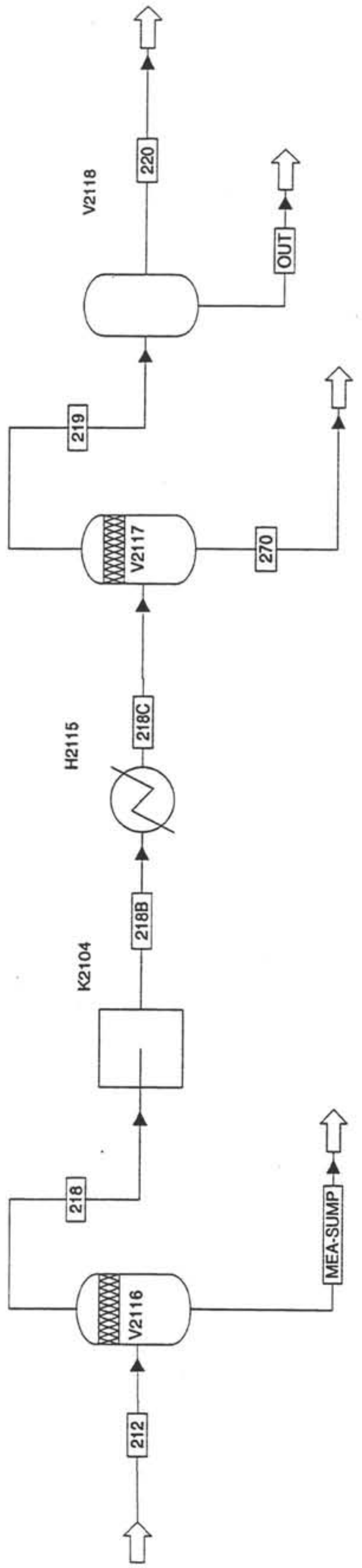
figuur A4.1 Aspen flowsheet reformer section



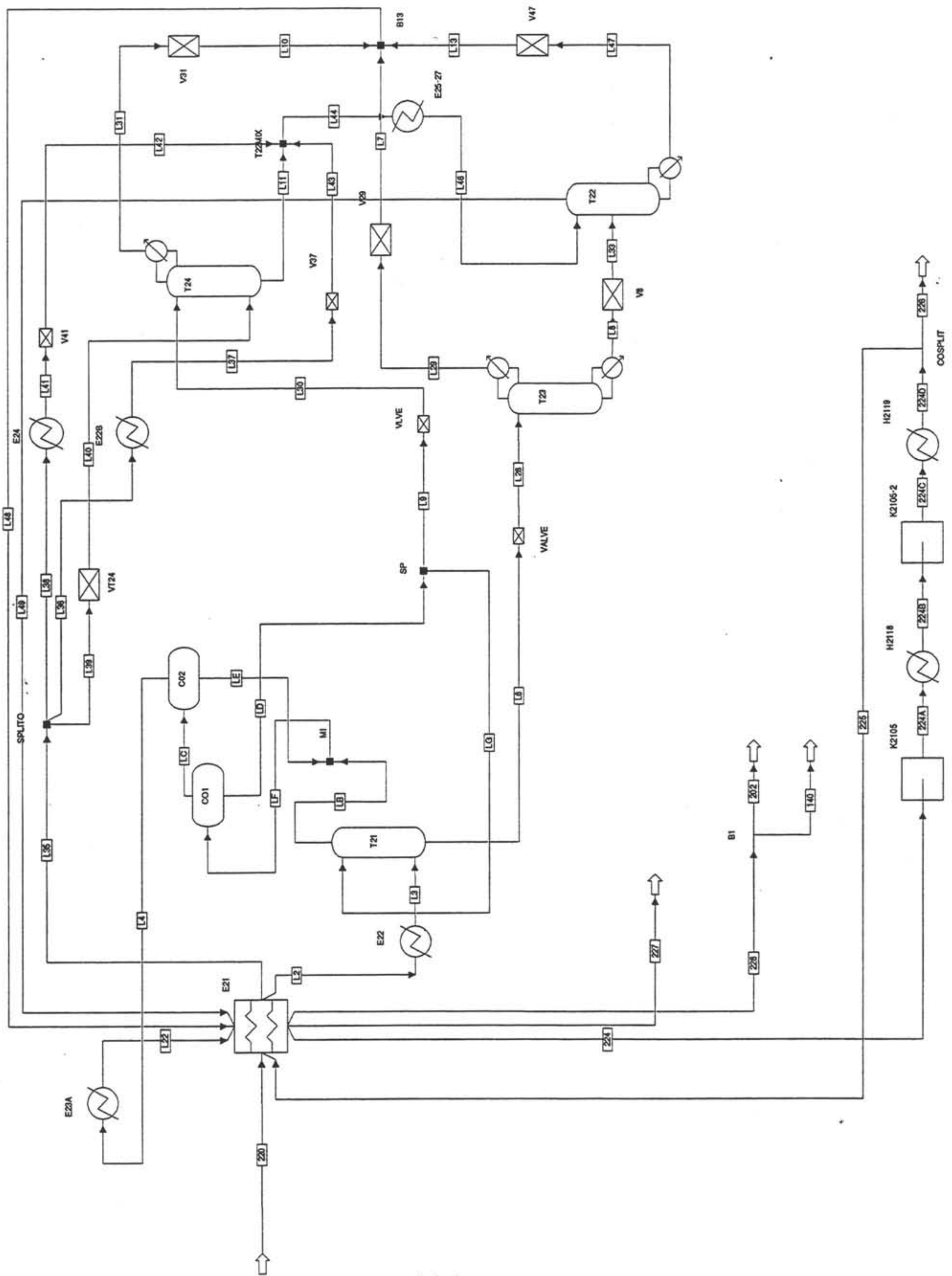
figuur A4.2 Aspen flowsheet CO_2 removal section



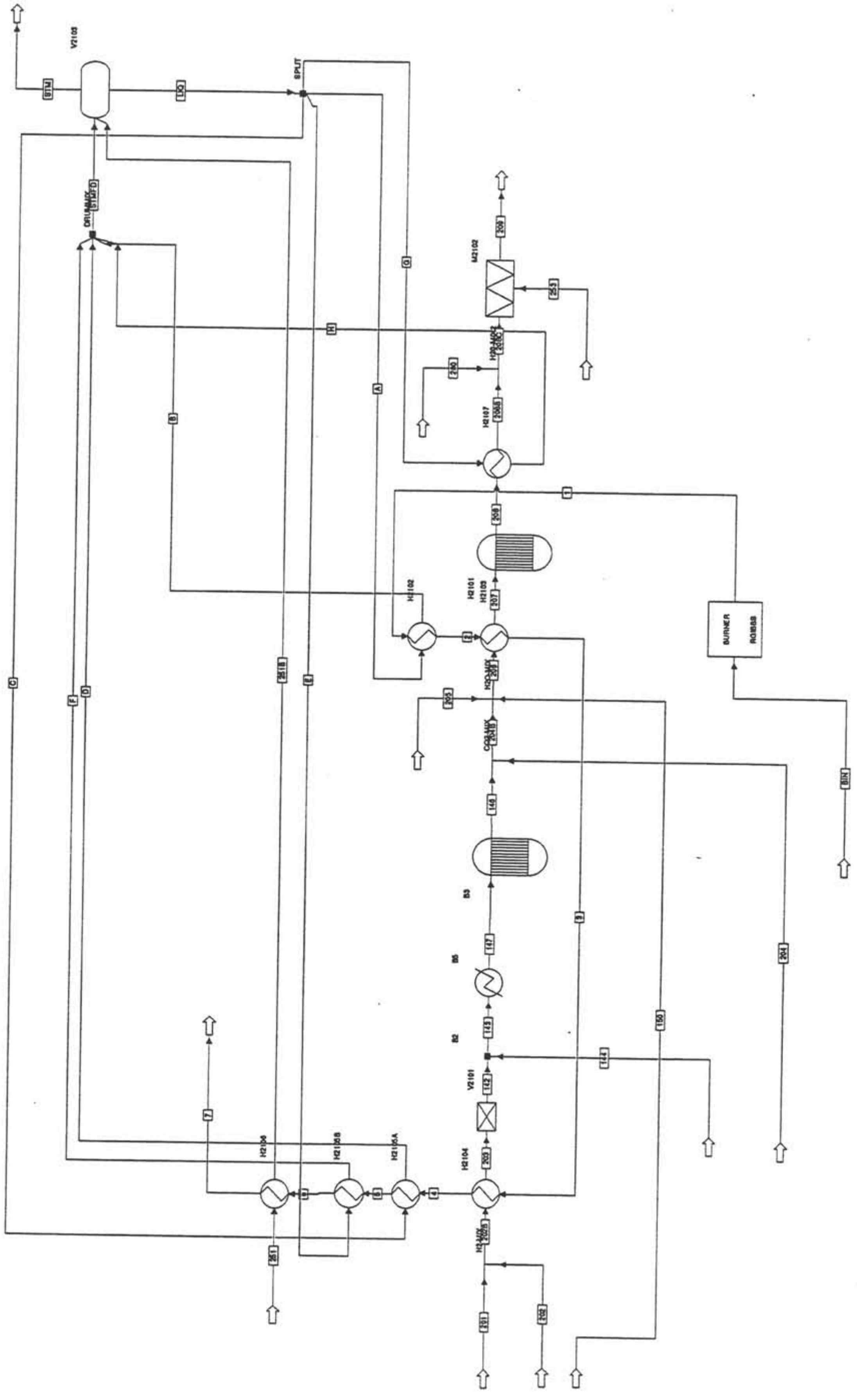
figuur A4.3 Aspen flowsheet drying section



figuur A4.4 Aspen flowsheet cryogenic separation section



figuur A4.5 reformer section with pre-reformer



APPENDIX 5

Block specifications of the reformer section used in Aspen

Table A5.1. The reactor (reformer).

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)
H2101	RGIBBS	207	208	860	11.5

The Gibbs reactor has nine reactions, three of them have a temperature approach (chapter 5).

Table A5.2. The burners.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	-Δp (bar)
BURNER	RGIBBS	Bin	Bout	1005.0	0.5

Table A5.3. The heat exchangers.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	-Δp (bar)	Vapour fraction
H2102	HEATX	1 (h)	2 (h)		0	
		A (c)	B (c)		0	0.048
H2103	HEATX	2 (h)	3 (h)		0	
		206 (c)	207 (c)	487	0.5	
H2104	HEATX	3 (h)	4 (h)		0	
		202B (c)	203 (c)	400	0.3	
H2105A	HEATX	4 (h)	5 (h)		0	
		C (c)	D (c)		0	0.048
H2105B	HEATX	5 (h)	6 (h)		0	
		E (c)	F (c)		0	0.048
H2106	HEATX	6 (h)	7 (h)		0	
		251 (c)	251B (c)	180	0.2	
H2107	HEATX	208 (h)	208B (h)		0	
		G (c)	H (c)		0	0.048

'h' and 'c' stand for hot and cold stream.

Table A5.4. The desulpherizer.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)
V2101	HEATER	203	203B	350.0	18.2

Table A5.5. The steamdrum.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	V_{frac}
V2103	FLASH2	STMFD 251B	STM (v) LIQ (l)	221	0.0421

'v' and 'l' stand for vapour and liquid.

Table A5.6. The mixing points.

Code	Block definition	Stream in	Stream out	P_{out} (bar)
M2102	MIXER	208C, 253	209	11.0
CO2-MIX	MIXER	203B, 204	204B	16.2
DRUMMIX	MIXER	B,D,F,H	STMFD	0
H2-MIX	MIXER	201, 202	202B	21.0
H2O-MIX	MIXER	204B, 205	206	15.6
H2O-MIX2	MIXER	208B, 260	208C	11.0

Table A5.7. The splitter.

Code	Block definition	Stream in	Stream out	Fraction of flow	-Δp (bar)
SPLIT	FSPLIT	LIQ	A		0
			C	0.13586	
			E	0.16845	
			G	0.56366	

Block specifications of the coldbox section used in Aspen

Table A5.8. The heat exchangers and valves.

Code	Block definition	Stream in	Stream out	ΔT (°C)	T_{out} (°C)	$-\Delta p$ (bar)	p (bar)	Heat duty
E21	MHEATX	220 (h)	L2 (h)	-192.6		0.2		
		225 (h)	L35 (h)	-190.1		0.2		
		L22 (c)	228 (c)					
		L49 (c)	224 (c)	205.5		0.2		
		L48 (c)	227 (c)	197.9		0.2		
E22	HEATER	L2	L3	- 7.2		0.1		
E22B	HEATER	L36	L37	- 5.7		0.1		
E23A	HEATER	L4	L22		-176.1		3.9	
E24	HEATER	L38	L41	- 2.5		0.1		
E25-27	HEATER	L44	L46		-184.5	0.18		
H2118	HEATER	224A	224B		30.0	0.2		
H2119	HEATER	224C	224D		35.0	0.2		
V29	HEATER	L29	L7			3.1		0
V31	HEATER	L31	L10			5.3		0
V37	HEATER	L37	L43			6.6		0
V39	HEATER	L39	L40			1.25		0
V41	HEATER	L41	L42			6.6		0
V47	HEATER	L47	L13			0.1		0
V6	HEATER	L6	L28			21.83		0
V8	HEATER	L8	L33			3.02		0
V9	HEATER	L9	L30			19.50		0

Table A5.9. The splitters.

Code	Block definition	Stream in	Stream out	Fraction of flow	Flow (kg/h)
B1	FSPLIT	228	140		
			202		H_2: 10.7
CO-SPLIT	FSPLIT	224D	226		
			225	0.16347	
SPLIT1	FSPLIT	L35	L38	0.546	
			L36	0.156	
			L39		
SPLIT2	FSPLIT	LD	L9	0.25640	
			LG		

Table A5.10. The mixing points.

Code	Block definition	Stream in	Stream out	-Δp (bar)
MIX1	MIXER	LB LE	LF	0
MIX2	MIXER	L13 L7 L10	L48	0
T22MIX	MIXER	L42 L43 L11	L44	0

Table A5.11. The flashers.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)
CO1	FLASH2	LF	LC (v) LD (l)	-171.5	27.347
CO2	FLASH2	LC	L4 (v) LE (l)	-201.5	27.3

Table A5.12. The columns.

Code	Block definition	Stream in	Stream out	T (°C)	p (bar)
T21	RADFRAC	L3 (st.20) LG (st.10	LB (st.1) L6 (st.20)	-173.6 (st.1) -172.0 (st.20)	27.3 (st.1)
T22	RADFRAC	L33 (st.9) L46 (st.1)	L46 (st.1) L47 (st.12)		2.25 (st.1)
T23	RADFRAC	L28 (st.1)	L29 (st.1) L8 (st.4)		5.4 (st.1)
T24	RADFRAC	L40 (st.5) L30 (st.1)	L31 (st.1) L11 (st.5)		7.6 (st.1)

Code	Condensor duty	Reboiler duty	Molar boilup ratio	Molar reflux ratio	Mass reflux ratio
T21	0	0			
T22	0		7.51333		
T23	-4962.0			6.55	
T24		0			10.355

Table A5.13. The compressors.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)	Mechanical efficiency
K2105-1	COMPR	224	224A	100.0	6.0	1.0
K2105-2	COMPR	224B	224C	90.0	9.6	1.0

The compressors are polytropic centrifugal compressors. 'st.' stands for stage, 'v' for vapour, 'l' for liquid, 'h' for hot streams and 'c' for cold streams.

Block specifications of the MEA section used in Aspen

Table A5.14. The heat exchangers.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)	-Δp (bar)
H2108	HEATER	281B	281A	40.0	14.7	
H2109A	HEATER	281C	281B	88.0		0
H2109B	HEATER	282	282B	104.0		0
H2110A	HEATER	209	209B	132.0	10.7	
H2111	HEATER	210	210B	40.0	10.4	
H2112	HEATER	213	213B	40.0	1.5	
H2113	HEATER	216B	216C	40.0		0.2
H2114	HEATER	216E	216F	40.0	16.2	

Table A5.15. The separators.

Code	Block definition	Stream in	Stream out	-Δp (bar)	Fraction of flow
VENTTANK	SEP	215	215B 214	0 0	214: CO_2 0.047619 N_2 0.048326 MEA 1.0 H_2O 0.047620

Table A5.16. The mixing points.

Code	Block definition	Stream in	Stream out	p_{out} (bar)
CO-MIX	MIXER	215B 227	216	1.5
COND-MIX	MIXER	264 265	266	3.5
CONDMIX2	MIXER	269 268	284	1.5

Table A5.17. The flashers.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)
V2107	FLASH2	209B	210 (v) 264 (l)	40.0	10.7
V2108	FLASH2	210B	211 (v) 265 (l)	40.0	10.4
V2109	FLASH2	213B 284	215 (v) 285 (l)	40.0	1.5
V2113	FLASH2	216C	216D (v) 268 (l)	40.0	9.6
V2114	FLASH2	216F	204 (v) 269 (l)	40.0	16.2

Table A5.18. The columns.

Code	Block definition	Stream in	Stream out	T_{spec} (°C)	p_{spec} (bar)
V2105	RADFRAC	281 (st.1) 211 (st.20)	212 (st.1) 282 (st.20)	40.0 (st.1) 72.0 (st.20)	10.3 (st.1) 10.4 (st.20)
V2106	RADFRAC	285 (st.1) 282B (st.5)	213 (st.1) 218C (st.18)	102.0 (st.1) 120.0 (st.16)	1.7 (st.1)

Code	Condensor duty	Reboiler duty
V2105	0	0
V2106	0	2,850,000

V2105 has for component CO_2 a Murphree efficiency of 0.2 at stage 10. The reboiler duty of the V2106 column is an estimation, it is manipulated by the specification that the mass flow of CO_2 at stage 1 must be 1380 kg/h.

Table A5.19. The compressors.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)	Mechanical efficiency
K2103-1	COMPR	216	216B	145.0	9.6	1.0
K2103-3	COMPR	216D	216E	145.0	15.4	1.0

'v' and 'l' stand for vapour and liquid, 'st.' stands for stage.

Block specifications process gas compression and drying section used in Aspen

Table A5.20. The heat exchanger.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	-Δp (bar)
H2115	HEATER	218B	218C	35.0	2 0.2

Table A5.21. The separator.

Code	Block definition	Stream in	Stream out	-Δp (bar)	Fractions of flow
V2118	SEP	219	220 OUT	0 0	220: H_2 0.994 CO 0.994 N_2 0.994 CH_4 0.994 rest 0

Table A5.22. The flashers.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)
V2116	FLASH2	212	218 (v) MEASUMP (l)	40.0	10.3
V2117	FLASH2	218C	270 (l) 219 (v)	35.0	28.3

Table A5.23. The compressor.

Code	Block definition	Stream in	Stream out	T_{out} (°C)	p_{out} (bar)	Mechanical efficiency
K2104	COMPR	218	218B	145.0	28.5	1.0

'v' and 'l' stand for vapour and liquid.

Simulated design streams

```
STREAM ID                 1           140          2           201         202
FROM :                    BURNER      B1           H2102       ----        B1
TO   :                    H2102       ----         H2103       H2-MIX      H2-MIX

SUBSTREAM: MIXED
PHASE:                    VAPOR       VAPOR        VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                     3.7117-05  139.4111   3.7117-05     0.0          5.3075
  CO                     1.2567-06    2.5668   1.2567-06     0.0        9.7723-02
  CO2                      2.3270     0.0        2.3270      0.4726       0.0
  N2                     260.6468     1.1188   260.6468      7.6178     4.2596-02
  O2                       9.2645     0.0        9.2645      0.0          0.0
  CH4                    7.8087-31    0.0      7.8087-31    43.1777       0.0
  C2H6                     0.0        0.0        0.0         1.5131       0.0
  C3H8                     0.0        0.0        0.0         0.1972       0.0
  C4H10                    0.0        0.0        0.0       7.3980-02      0.0
  C5H12                    0.0        0.0        0.0       2.0790-02      0.0
  C6H14                    0.0        0.0        0.0       2.6689-02      0.0
  MEA                      0.0        0.0        0.0         0.0          0.0
  H2O                    121.8739     0.0      121.8739      0.0          0.0
  AR                       3.1215     0.0        3.1215      0.0          0.0
TOTAL FLOW:
  KMOL/HR                397.2340   143.0969   397.2340     53.1001       5.4478
  KG/HR                  1.0021+04  384.2934   1.0021+04   989.2000      14.6304
  CUM/SEC                  7.8199     0.2718     7.0955    1.6236-02   1.0351-02
STATE VARIABLES:
  TEMP    C             1005.0000    14.1653   886.5673     15.0000      14.1653
  PRES    BAR              1.5000     3.5000     1.5000     21.0000       3.5000
  VFRAC                    1.0000     1.0000     1.0000      1.0000       1.0000
  LFRAC                    0.0        0.0        0.0         0.0          0.0
  SFRAC                    0.0        0.0        0.0         0.0          0.0
ENTHALPY:
  J/KMOL               -4.3561+07 -2.2895+06 -4.7900+07 -6.8254+07 -2.2895+06
  J/KG                 -1.7268+06 -8.5254+05 -1.8988+06 -3.6638+06 -8.5254+05
  WATT                 -4.8066+06 -9.1007+04 -5.2854+06 -1.0067+06 -3464.7506
ENTROPY:
  J/KMOL-K              3.7538+04 -8631.7295  3.3977+04 -9.4630+04 -8631.7295
  J/KG-K                1488.0866 -3214.1423  1346.8881 -5079.7284 -3214.1423
DENSITY:
  KMOL/CUM              1.4110-02     0.1461  1.5551-02     0.9084       0.1461
  KG/CUM                   0.3559     0.3926     0.3922    16.9236       0.3926
AVG MW                    25.2260     2.6855    25.2260    18.6289       2.6855
```

Simulated design streams

```
STREAM ID                    202B         203          203B         204          204B
FROM :                       H2-MIX       H2104        V2101        V2114        CO2-MIX
TO   :                       H2104        V2101        CO2-MIX      CO2-MIX      H2O-MIX

SUBSTREAM: MIXED
PHASE:                       VAPOR        VAPOR        VAPOR        VAPOR        VAPOR
COMPONENTS: KMOL/HR
  H2                          5.3075       5.3075       5.3075       3.5315       8.8390
  CO                       9.7723-02    9.7723-02    9.7723-02       6.7552       6.8529
  CO2                         0.4726       0.4726       0.4726      29.8423      30.3149
  N2                          7.6604       7.6604       7.6604       0.9805       8.6410
  O2                          0.0          0.0          0.0          0.0          0.0
  CH4                        43.1777      43.1777      43.1777       4.5586      47.7363
  C2H6                        1.5131       1.5131       1.5131    1.0273-10       1.5131
  C3H8                        0.1972       0.1972       0.1972       0.0          0.1972
  C4H10                    7.3980-02    7.3980-02    7.3980-02       0.0       7.3980-02
  C5H12                    2.0790-02    2.0790-02    2.0790-02       0.0       2.0790-02
  C6H14                    2.6689-02    2.6689-02    2.6689-02       0.0       2.6689-02
  MEA                         0.0          0.0          0.0          0.0          0.0
  H2O                         0.0          0.0          0.0          0.1952       0.1952
  AR                          0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR                    58.5479      58.5479      58.5479      45.8634     104.4113
  KG/HR                    1003.8304    1003.8304    1003.8304    1613.8120    2617.6425
  CUM/SEC                  1.7996-02    4.4333-02    4.6625-02    1.9687-02    7.4631-02
STATE VARIABLES:
  TEMP    C                  14.2592     400.0000     350.0000      40.0000     226.9639
  PRES    BAR                21.0000      20.7000      18.2000      16.2000      16.2000
  VFRAC                       1.0000       1.0000       1.0000       1.0000       1.0000
  LFRAC                       0.0          0.0          0.0          0.0          0.0
  SFRAC                       0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL                 -6.2116+07   -4.5105+07   -4.7665+07   -2.8085+08   -1.5009+08
  J/KG                   -3.6229+06   -2.6307+06   -2.7801+06   -7.9815+06   -5.9868+06
  WATT                   -1.0102+06   -7.3355+05   -7.7520+05   -3.5780+06   -4.3532+06
ENTROPY:
  J/KMOL-K               -8.5515+04   -4.8826+04   -5.1700+04   -6218.8838   -2.5305+04
  J/KG-K                 -4987.6213   -2847.7721   -3015.3746    -176.7363   -1009.3497
DENSITY:
  KMOL/CUM                    0.9037       0.3668       0.3488       0.6471       0.3886
  KG/CUM                     15.4942       6.2897       5.9805      22.7701       9.7429
AVG MW                       17.1454      17.1454      17.1454      35.1873      25.0704
```

Simulated design streams

```
STREAM ID                  205        206        207        208        208B
FROM :                     ----       H2O-MIX    H2103      H2101      H2107
TO   :                     H2O-MIX    H2103      H2101      H2107      H2O-MIX2

SUBSTREAM: MIXED
PHASE:                     VAPOR      VAPOR      VAPOR      VAPOR      VAPOR
COMPONENTS: KMOL/HR
  H2                        0.0         8.8390     8.8390   149.1467   149.1467
  CO                        0.0         6.8529     6.8529    53.5113    53.5113
  CO2                       0.0        30.3149    30.3149    30.9846    30.9846
  N2                        0.0         8.6410     8.6410     8.6410     8.6410
  O2                        0.0         0.0        0.0        0.0        0.0
  CH4                       0.0        47.7363    47.7363     4.5862     4.5862
  C2H6                      0.0         1.5131     1.5131  7.6396-05  7.6396-05
  C3H8                      0.0         0.1972     0.1972  3.1213-09  3.1213-09
  C4H10                     0.0      7.3980-02  7.3980-02  1.7555-13  1.7555-13
  C5H12                     0.0      2.0790-02  2.0790-02  6.6516-18  6.6516-18
  C6H14                     0.0      2.6689-02  2.6689-02  2.8846-22  2.8846-22
  MEA                       0.0         0.0        0.0     9.6476-31  9.6476-31
  H2O                     151.2739   151.4691   151.4691   103.4714   103.4714
  AR                        0.0         0.0        0.0        0.0        0.0
TOTAL FLOW:
  KMOL/HR                 151.2739   255.6853   255.6853   350.3414   350.3414
  KG/HR                  2725.2000  5342.8425  5342.8425  5342.8432  5342.8432
  CUM/SEC                6.7293-02     0.1795     0.2964     0.7991     0.3815
STATE VARIABLES:
  TEMP   C                220.0000   215.1403   487.0000   860.0000   269.2265
  PRES   BAR               23.2000    15.6000    15.1000    11.5000    11.5000
  VFRAC                     1.0000     1.0000     1.0000     1.0000     1.0000
  LFRAC                     0.0        0.0        0.0        0.0        0.0
  SFRAC                     0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL                -2.3647+08 -2.0120+08 -1.8980+08 -9.5417+07 -1.1642+08
  J/KG                  -1.3126+07 -9.6284+06 -9.0830+06 -6.2567+06 -7.6339+06
  WATT                  -9.9366+06 -1.4290+07 -1.3480+07 -9.2857+06 -1.1330+07
ENTROPY:
  J/KMOL-K              -5.4783+04 -3.5298+04 -1.6547+04  3.5999+04  1.0004+04
  J/KG-K                -3040.9421 -1689.2132  -791.8444  2360.5322   655.9938
DENSITY:
  KMOL/CUM                  0.6244     0.3955     0.2396     0.1217     0.2550
  KG/CUM                   11.2492     8.2662     5.0071     1.8571     3.8901
AVG MW                     18.0150    20.8961    20.8961    15.2503    15.2503
```

Simulated design streams

```
STREAM ID                  208C        209         209B        210         210B
FROM :                     H20-MIX2    M2102       H2110A      V2107       H2111
TO   :                     M2102       H2110A      V2107       H2111       V2108

SUBSTREAM: MIXED
PHASE:                     VAPOR       VAPOR       MIXED       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                      149.1467    149.1467    149.1467    149.1465    149.1465
  CO                       53.5113     53.5113     53.5113     53.5112     53.5112
  CO2                      30.9846     30.9846     30.9846     30.9640     30.9640
  N2                        8.6410      8.6410      8.6410      8.6410      8.6410
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                       4.5862      4.5862      4.5862      4.5862      4.5862
  C2H6                    7.6396-05   7.6396-05   7.6396-05   7.6396-05   7.6396-05
  C3H8                    3.1213-09   3.1213-09   3.1213-09   3.1213-09   3.1213-09
  C4H10                   1.7555-13   1.7555-13   1.7555-13     0.0         0.0
  C5H12                   6.6516-18   6.6516-18   6.6516-18     0.0         0.0
  C6H14                   2.8846-22   2.8846-22   2.8846-22     0.0         0.0
  MEA                     9.6476-31   9.6476-31   9.6476-31     0.0         0.0
  H2O                     205.9804    230.9596    230.9596      1.4203      1.4203
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                 452.8505    477.8296    477.8296    248.2695    248.2695
  KG/HR                  7189.5432   7639.5432   7639.5432   3503.4858   3503.4858
  CUM/SEC                   0.4951      0.4461      0.2928      0.1683      0.1731
STATE VARIABLES:
  TEMP    C               250.6157    177.3879    132.0000     40.0000     40.0000
  PRES    BAR              11.0000     11.0000     10.7000     10.7000     10.4000
  VFRAC                     1.0000      1.0000      0.7017      1.0000      1.0000
  LFRAC                     0.0         0.0         0.2982      0.0         0.0
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                 -1.4364+08  -1.5088+08  -1.6456+08  -7.5301+07  -7.5300+07
  J/KG                   -9.0475+06  -9.4369+06  -1.0293+07  -5.3361+06  -5.3360+06
  WATT                   -1.8069+07  -2.0026+07  -2.1842+07  -5.1930+06  -5.1930+06
ENTROPY:
  J/KMOL-K               -1294.8596  -8374.8101  -4.0828+04   9002.9636   9242.6793
  J/KG-K                   -81.5598   -523.8183  -2553.6608    637.9822    654.9693
DENSITY:
  KMOL/CUM                  0.2540      0.2975      0.4533      0.4097      0.3983
  KG/CUM                    4.0337      4.7569      7.2473      5.7822      5.6206
AVG MW                     15.8762     15.9880     15.9880     14.1116     14.1116
```

Simulated design streams

```
STREAM ID              211         212         213         213B        214
FROM :                 V2108       V2105       V2106       H2112       VENTTANK
TO   :                 V2105       V2116       H2112       V2109       ----

SUBSTREAM: MIXED
PHASE:                 VAPOR       MIXED       VAPOR       MIXED       MIXED
COMPONENTS: KMOL/HR
  H2                 149.1465    149.1453   1.2347-03   1.2347-03      0.0
  CO                  53.5112     53.5103   9.0080-04   9.0080-04      0.0
  CO2                 30.9640   1.1361-02     31.3565     31.3565     1.4921
  N2                   8.6410      8.6409   5.3417-05   5.3417-05   2.5822-06
  O2                   0.0         0.0         0.0         0.0         0.0
  CH4                  4.5862      4.5862   1.9257-05   1.9257-05      0.0
  C2H6               7.6396-05   7.6395-05  1.0253-10   1.0253-10      0.0
  C3H8               3.1213-09   3.1213-09     0.0         0.0         0.0
  C4H10                0.0         0.0         0.0         0.0         0.0
  C5H12                0.0         0.0         0.0         0.0         0.0
  C6H14                0.0         0.0         0.0         0.0         0.0
  MEA                  0.0       4.0481-03  5.2707-05   5.2707-05   3.9385-05
  H2O                  1.4203      1.4521    222.5219    222.5219   6.1036-02
  AR                   0.0         0.0         0.0         0.0         0.0
 TOTAL FLOW:
  KMOL/HR            248.2695    217.3506    253.8807    253.8807     1.5532
  KG/HR             3503.4858   2142.0500   5388.7656   5388.7656    66.7710
  CUM/SEC              0.1731      0.1532      1.3112      0.1576   7.4384-03
 STATE VARIABLES:
  TEMP   C            40.0000     40.0442    110.9117     40.0000    40.0000
  PRES   BAR          10.4000     10.3000      1.7000      1.5000     1.5000
  VFRAC                1.0000      0.9999      1.0000      0.1284     1.0000
  LFRAC                0.0       2.4896-05     0.0         0.8715   2.0877-06
  SFRAC                0.0         0.0         0.0         0.0         0.0
 ENTHALPY:
  J/KMOL            -7.5300+07 -3.0027+07 -2.5786+08 -3.0052+08 -3.8730+08
  J/KG              -5.3360+06 -3.0468+06 -1.2148+07 -1.4158+07 -9.0092+06
  WATT              -5.1930+06 -1.8129+06 -1.8185+07 -2.1193+07 -1.6710+05
 ENTROPY:
  J/KMOL-K          9242.6793   9210.8349 -3.1120+04 -1.4501+05   894.0483
  J/KG-K             654.9693    934.6095 -1466.1721 -6831.6594    20.7971
 DENSITY:
  KMOL/CUM             0.3983      0.3938   5.3781-02     0.4472   5.8003-02
  KG/CUM               5.6206      3.8819      1.1415      9.4922     2.4934
 AVG MW               14.1116      9.8552     21.2255     21.2255    42.9889
```

Simulated design streams

```
----------------------

STREAM ID                    215         215B        216         216B        216C
FROM :                       V2109       VENTTANK    CO-MIX      K2103-1     H2113
TO   :                       VENTTANK    CO-MIX      K2103-1     H2113       V2113

SUBSTREAM: MIXED
PHASE:                       VAPOR       VAPOR       VAPOR       VAPOR       MIXED
COMPONENTS: KMOL/HR
  H2                       1.2348-03   1.2348-03     3.5314      3.5314      3.5314
  CO                       9.0093-04   9.0093-04     6.7552      6.7552      6.7552
  CO2                        31.3349     29.8427    29.8427     29.8427     29.8427
  N2                       5.3433-05   5.0851-05     0.9805      0.9805      0.9805
  O2                         0.0         0.0         0.0         0.0         0.0
  CH4                      2.0125-05   2.0125-05     4.5587      4.5587      4.5587
  C2H6                     1.0253-10   1.0253-10   1.0253-10   1.0253-10   1.0253-10
  C3H8                       0.0         0.0         0.0         0.0         0.0
  C4H10                      0.0         0.0         0.0         0.0         0.0
  C5H12                      0.0         0.0         0.0         0.0         0.0
  C6H14                      0.0         0.0         0.0         0.0         0.0
  MEA                      3.9385-05     0.0         0.0         0.0         0.0
  H2O                         1.2817      1.2207      1.2207      1.2207      1.2207
  AR                         0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                    32.6188     31.0656     46.8894     46.8894     46.8894
  KG/HR                    1402.1713   1335.4003   1632.3086   1632.3086   1632.3086
  CUM/SEC                     0.1562      0.1487      0.2202   4.6881-02   3.4589-02
STATE VARIABLES:
  TEMP    C                  40.0000     40.0000     33.1462    145.0000     40.0000
  PRES    BAR                 1.5000      1.5000      1.5000      9.6000      9.4000
  VFRAC                       1.0000      1.0000      1.0000      1.0000      0.9806
  LFRAC                      0.0         0.0         0.0         0.0       1.9364-02
  SFRAC                      0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                  -3.8728+08  -3.8728+08  -2.7988+08  -2.7584+08  -2.8072+08
  J/KG                    -9.0093+06  -9.0093+06  -8.0399+06  -7.9238+06  -8.0639+06
  WATT                    -3.5091+06  -3.3420+06  -3.6455+06  -3.5928+06  -3.6563+06
ENTROPY:
  J/KMOL-K                  916.9114    917.9789   1.3082+04   8963.4490  -4538.7397
  J/KG-K                     21.3302     21.3551    375.7963    257.4827   -130.3791
DENSITY:
  KMOL/CUM                 5.8003-02   5.8003-02   5.9145-02      0.2778      0.3765
  KG/CUM                      2.4933      2.4933      2.0589      9.6716     13.1089
AVG MW                       42.9864     42.9863     34.8118     34.8118     34.8118
```

Simulated design streams

```
STREAM ID               216D        216E        216F        218         218B
FROM :                  V2113       K2103-3     H2114       V2116       K2104
TO   :                  K2103-3     H2114       V2114       K2104       H2115

SUBSTREAM: MIXED
PHASE:                  VAPOR       VAPOR       MIXED       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                     3.5315      3.5315      3.5315    149.1453    149.1453
  CO                     6.7552      6.7552      6.7552     53.5103     53.5103
  CO2                   29.8423     29.8423     29.8423   1.1361-02   1.1361-02
  N2                     0.9805      0.9805      0.9805      8.6409      8.6409
  O2                     0.0         0.0         0.0         0.0         0.0
  CH4                    4.5586      4.5586      4.5586      4.5862      4.5862
  C2H6                1.0273-10   1.0273-10   1.0273-10   7.6395-05   7.6395-05
  C3H8                   0.0         0.0         0.0      3.1213-09   3.1213-09
  C4H10                  0.0         0.0         0.0         0.0         0.0
  C5H12                  0.0         0.0         0.0         0.0         0.0
  C6H14                  0.0         0.0         0.0         0.0         0.0
  MEA                    0.0         0.0         0.0      4.0470-03   4.0470-03
  H2O                    0.3072      0.3072      0.3072      1.2700      1.2700
  AR                     0.0         0.0         0.0         0.0         0.0
 TOTAL FLOW:
  KMOL/HR               45.9755     45.9755     45.9755    217.1684    217.1684
  KG/HR               1615.8331   1615.8331   1615.8331   2138.7677   2138.7677
  CUM/SEC             3.3841-02   2.8583-02   1.9688-02     0.1533    7.4669-02
 STATE VARIABLES:
  TEMP   C              40.0000    145.0000     40.0000     40.0000    145.0000
  PRES   BAR             9.6000     15.4000     16.2000     10.3000     28.5000
  VFRAC                  1.0000      1.0000      0.9975      1.0000      1.0000
  LFRAC                  0.0         0.0      2.4378-03      0.0         0.0
  SFRAC                  0.0         0.0         0.0         0.0         0.0
 ENTHALPY:
  J/KMOL             -2.8059+08  -2.7666+08  -2.8086+08  -2.9851+07  -2.6764+07
  J/KG               -7.9837+06  -7.8719+06  -7.9915+06  -3.0310+06  -2.7176+06
  WATT               -3.5834+06  -3.5333+06  -3.5869+06  -1.8007+06  -1.6145+06
 ENTROPY:
  J/KMOL-K           -1525.2264   5401.2695  -6609.4827   9222.0813   9174.0573
  J/KG-K               -43.3974    153.6829   -188.0604    936.4012    931.5248
 DENSITY:
  KMOL/CUM               0.3773      0.4468      0.6486      0.3934      0.8078
  KG/CUM                13.2631     15.7029     22.7977      3.8752      7.9564
 AVG MW                 35.1455     35.1455     35.1455      9.8484      9.8484
```

Simulated design streams

```
            ------------

STREAM ID                 218C        219         220         224         224A
FROM :                    H2115       V2117       V2118       E21         K2105-1
TO   :                    V2117       V2118       E21         K2105-1     H2118

SUBSTREAM: MIXED
PHASE:                    MIXED       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                    149.1453    149.1453    148.2504   1.5812-03   1.5812-03
  CO                     53.5103     53.5103     53.1893     52.3228     52.3228
  CO2                  1.1361-02   1.1361-02     0.0         0.0         0.0
  N2                      8.6409      8.6409      8.5891      7.7067      7.7067
  O2                      0.0         0.0         0.0         0.0         0.0
  CH4                     4.5862      4.5862      4.5586   6.5505-08   6.5505-08
  C2H6                 7.6395-05   7.6395-05     0.0         0.0         0.0
  C3H8                 3.1213-09   3.1213-09     0.0         0.0         0.0
  C4H10                   0.0         0.0         0.0         0.0         0.0
  C5H12                   0.0         0.0         0.0         0.0         0.0
  C6H14                   0.0         0.0         0.0         0.0         0.0
  MEA                  4.0470-03   4.0328-03     0.0         0.0         0.0
  H2O                     1.2700      0.3701      0.0         0.0         0.0
  AR                      0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR               217.1684    216.2685    214.5876     60.0311     60.0311
  KG/HR                2138.7677   2122.5559   2102.4483   1681.4545   1681.4545
  CUM/SEC              5.5039-02   5.5224-02   5.4804-02      0.1991   8.6447-02
STATE VARIABLES:
  TEMP    C              35.0000     35.0000     35.0000     21.3379    100.0000
  PRES    BAR            28.4000     28.3000     28.3000      2.0500      6.0000
  VFRAC                   0.9958      1.0000      1.0000      1.0000      1.0000
  LFRAC                4.1490-03     0.0         0.0         0.0         0.0
  SFRAC                   0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL              -3.0196+07  -2.9122+07  -2.8734+07  -9.6533+07  -9.4239+07
  J/KG                -3.0660+06  -2.9673+06  -2.9328+06  -3.4464+06  -3.3645+06
  WATT                -1.8215+06  -1.7495+06  -1.7128+06  -1.6097+06  -1.5715+06
ENTROPY:
  J/KMOL-K              -380.6202    347.4828    375.6344   7.5131+04   7.3097+04
  J/KG-K                 -38.6478     35.4052     38.3393   2682.3135   2609.6987
DENSITY:
  KMOL/CUM                1.0960      1.0878      1.0876   8.3727-02      0.1929
  KG/CUM                 10.7942     10.6764     10.6563      2.3451      5.4029
AVG MW                    9.8484      9.8144      9.7976     28.0097     28.0097
```

Simulated design streams

```
STREAM ID                    224B          224C          224D          225           226
FROM :                       H2118         K2105-2       H2119         CO-SPLIT      CO-SPLIT
TO   :                       K2105-2       H2119         CO-SPLIT      E21           ----

SUBSTREAM: MIXED
PHASE:                       VAPOR         VAPOR         VAPOR         VAPOR         VAPOR
COMPONENTS: KMOL/HR
  H2                       1.5812-03     1.5812-03     1.5812-03     2.5847-04     1.3227-03
  CO                         52.3228       52.3228       52.3228        8.5532       43.7696
  CO2                         0.0           0.0           0.0           0.0           0.0
  N2                          7.7067        7.7067        7.7067        1.2598        6.4469
  O2                          0.0           0.0           0.0           0.0           0.0
  CH4                      6.5505-08     6.5505-08     6.5505-08     1.0708-08     5.4797-08
  C2H6                        0.0           0.0           0.0           0.0           0.0
  C3H8                        0.0           0.0           0.0           0.0           0.0
  C4H10                       0.0           0.0           0.0           0.0           0.0
  C5H12                       0.0           0.0           0.0           0.0           0.0
  C6H14                       0.0           0.0           0.0           0.0           0.0
  MEA                         0.0           0.0           0.0           0.0           0.0
  H2O                         0.0           0.0           0.0           0.0           0.0
  AR                          0.0           0.0           0.0           0.0           0.0
TOTAL FLOW:
  KMOL/HR                    60.0311       60.0311       60.0311        9.8132       50.2178
  KG/HR                    1681.4545     1681.4545     1681.4545      274.8673     1406.5871
  CUM/SEC                  7.2499-02     5.2650-02     4.5505-02     7.4387-03     3.8066-02
STATE VARIABLES:
  TEMP   C                   30.0000       90.0000       35.0000       35.0000       35.0000
  PRES   BAR                  5.8000        9.6000        9.4000        9.4000        9.4000
  VFRAC                       1.0000        1.0000        1.0000        1.0000        1.0000
  LFRAC                       0.0           0.0           0.0           0.0           0.0
  SFRAC                       0.0           0.0           0.0           0.0           0.0
ENTHALPY:
  J/KMOL                  -9.6303+07    -9.4546+07    -9.6178+07    -9.6178+07    -9.6178+07
  J/KG                    -3.4382+06    -3.3755+06    -3.4337+06    -3.4337+06    -3.4337+06
  WATT                    -1.6059+06    -1.5766+06    -1.6038+06    -2.6217+05    -1.3416+06
ENTROPY:
  J/KMOL-K                 6.7251+04     6.8342+04     6.3645+04     6.3645+04     6.3645+04
  J/KG-K                   2400.9940     2439.9395     2272.2448     2272.2448     2272.2448
DENSITY:
  KMOL/CUM                    0.2300        0.3167        0.3664        0.3664        0.3664
  KG/CUM                      6.4424        8.8711       10.2642       10.2642       10.2642
AVG MW                       28.0097       28.0097       28.0097       28.0097       28.0097
```

Simulated design streams

```
STREAM ID                227        228        251        251B       253
FROM :                   E21        E21        ----       H2106      ----
TO   :                   CO-MIX     B1         H2106      V2103      M2102

SUBSTREAM: MIXED
PHASE:                   VAPOR      VAPOR      LIQUID     LIQUID     LIQUID
COMPONENTS: KMOL/HR
  H2                      3.5302   144.7187     0.0        0.0        0.0
  CO                      6.7543     2.6645     0.0        0.0        0.0
  CO2                     0.0        0.0        0.0        0.0        0.0
  N2                      0.9805     1.1614     0.0        0.0        0.0
  O2                      0.0        0.0        0.0        0.0        0.0
  CH4                     4.5586     0.0        0.0        0.0        0.0
  C2H6                    0.0        0.0        0.0        0.0        0.0
  C3H8                    0.0        0.0        0.0        0.0        0.0
  C4H10                   0.0        0.0        0.0        0.0        0.0
  C5H12                   0.0        0.0        0.0        0.0        0.0
  C6H14                   0.0        0.0        0.0        0.0        0.0
  MEA                     0.0        0.0        0.0        0.0        0.0
  H2O                     0.0        0.0      343.2639   343.2639    24.9791
  AR                      0.0        0.0        0.0        0.0        0.0
TOTAL FLOW:
  KMOL/HR                15.8237   148.5447   343.2639   343.2639    24.9791
  KG/HR                 296.9083   398.9239  6183.9000  6183.9000   450.0000
  CUM/SEC              5.4401-02    0.2822  2.4282-03  2.6602-03  1.7670-04
STATE VARIABLES:
  TEMP   C               17.2162    14.1653   104.0000   180.0000   104.0000
  PRES   BAR              1.9500     3.5000    27.0000    26.8000    27.0000
  VFRAC                   1.0000     1.0000     0.0        0.0        0.0
  LFRAC                   0.0        0.0        1.0000     1.0000     1.0000
  SFRAC                   0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL              -6.9048+07 -2.2895+06 -2.8210+08 -2.7526+08 -2.8210+08
  J/KG                -3.6799+06 -8.5254+05 -1.5659+07 -1.5279+07 -1.5659+07
  WATT                -3.0350+05 -9.4472+04 -2.6899+07 -2.6246+07 -1.9574+06
ENTROPY:
  J/KMOL-K             1.8996+04 -8631.7295 -1.5042+05 -1.3390+05 -1.5042+05
  J/KG-K               1012.4158 -3214.1423 -8349.6409 -7432.5015 -8349.6409
DENSITY:
  KMOL/CUM             8.0798-02    0.1461    39.2685    35.8435    39.2685
  KG/CUM                  1.5160     0.3926   707.4237   645.7212   707.4237
AVG MW                   18.7634     2.6855    18.0150    18.0150    18.0150
```

Simulated design streams

```
STREAM ID                 260          264          265          266          268
FROM :                    ----         V2107        V2108        COND-MIX     V2113
TO   :                    H20-MIX2     COND-MIX     COND-MIX     ----         CONDMIX2

SUBSTREAM: MIXED
PHASE:                    VAPOR         LIQUID      MIXED         LIQUID       LIQUID
COMPONENTS: KMOL/HR
  H2                        0.0       1.9116-04      0.0       1.9116-04    8.9701-08
  CO                        0.0       4.1375-05      0.0       4.1375-05    1.0236-07
  CO2                       0.0       2.0550-02      0.0       2.0550-02    3.7708-04
  N2                        0.0       6.1456-06      0.0       6.1456-06    1.3683-08
  O2                        0.0          0.0         0.0          0.0          0.0
  CH4                       0.0       3.7444-05      0.0       3.7444-05    7.2032-07
  C2H6                      0.0       9.3157-10      0.0       9.3157-10       0.0
  C3H8                      0.0          0.0         0.0          0.0          0.0
  C4H10                     0.0          0.0         0.0          0.0          0.0
  C5H12                     0.0          0.0         0.0          0.0          0.0
  C6H14                     0.0          0.0         0.0          0.0          0.0
  MEA                       0.0          0.0         0.0          0.0          0.0
  H2O                     102.5090     229.5393      0.0        229.5393       0.9134
  AR                        0.0          0.0         0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR                 102.5090     229.5601      0.0        229.5601       0.9138
  KG/HR                  1846.7000    4136.0574      0.0       4136.0574      16.4728
  CUM/SEC                5.7348-02    1.5381-03      0.0       1.5384-03    6.1242-06
STATE VARIABLES:
  TEMP   C                208.0000      40.0000    MISSING       40.1538      40.0000
  PRES    BAR              18.3000      10.7000    10.4000        3.5000       9.6000
  VFRAC                     1.0000       0.0       MISSING      0.0          0.0
  LFRAC                    0.0           1.0000    MISSING       1.0000       1.0000
  SFRAC                    0.0          0.0        MISSING      0.0          0.0
ENTHALPY:
  J/KMOL               -2.3667+08  -2.8771+08    MISSING  -2.8771+08  -2.8774+08
  J/KG                 -1.3137+07  -1.5968+07    MISSING  -1.5968+07  -1.5963+07
  WATT                 -6.7391+06  -1.8346+07    MISSING  -1.8346+07  -7.3043+04
ENTROPY:
  J/KMOL-K             -5.3384+04  -1.6654+05    MISSING  -1.6648+05  -1.6648+05
  J/KG-K               -2963.3323  -9243.1010    MISSING  -9240.0219  -9235.5050
DENSITY:
  KMOL/CUM                  0.4965      41.4588    MISSING       41.4489      41.4502
  KG/CUM                    8.9449     746.9772    MISSING      746.7984     747.1707
AVG MW                     18.0150      18.0173    MISSING       18.0173      18.0257
```

Simulated design streams

```
STREAM ID                   269         270         281         281A        281B
FROM :                      V2114       V2117       ----        H2108       H2109A
TO   :                      CONDMIX2    ----        V2105       ----        H2108

SUBSTREAM: MIXED
PHASE:                      LIQUID      LIQUID      LIQUID      LIQUID      LIQUID
COMPONENTS: KMOL/HR
  H2                      1.8952-08   1.8243-06      0.0         0.0         0.0
  CO                      2.1299-08   3.9548-07      0.0         0.0         0.0
  CO2                     7.5729-05   8.3739-08      9.5819      9.2001      9.2001
  N2                      2.8517-09   5.8657-08      0.0         0.0         0.0
  O2                         0.0         0.0         0.0         0.0         0.0
  CH4                     1.4756-07   3.6903-07      0.0         0.0         0.0
  C2H6                       0.0      8.8102-12      0.0         0.0         0.0
  C3H8                       0.0         0.0         0.0         0.0         0.0
  C4H10                      0.0         0.0         0.0         0.0         0.0
  C5H12                      0.0         0.0         0.0         0.0         0.0
  C6H14                      0.0         0.0         0.0         0.0         0.0
  MEA                        0.0      1.4206-05     87.1169     87.1128     87.1128
  H2O                        0.1120      0.8998    775.1928    774.9113    774.9113
  AR                         0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                    0.1120      0.8998    871.8917    871.2243    871.2243
  KG/HR                      2.0210     16.2117   1.9708+04   1.9686+04   1.9686+04
  CUM/SEC                 7.5113-07   6.0054-06   6.0353-03   8.0918-03   8.4725-03
STATE VARIABLES:
  TEMP   C                  40.0000     35.0000     40.0000     40.0000     88.0000
  PRES     BAR              16.2000     28.3000     14.7000     14.7000      1.7000
  VFRAC                      0.0         0.0         0.0         0.0         0.0
  LFRAC                      1.0000      1.0000      1.0000      1.0000      1.0000
  SFRAC                      0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                 -2.8775+08  -2.8810+08  -2.8449+08  -2.8376+08  -2.7909+08
  J/KG                   -1.5958+07  -1.5991+07  -1.2586+07  -1.2558+07  -1.2351+07
  WATT                   -8958.7728  -7.2014+04  -6.8900+07  -6.8671+07  -6.7541+07
ENTROPY:
  J/KMOL-K               -1.6644+05  -1.6799+05  -2.4699+05  -2.2427+05  -2.1026+05
  J/KG-K                 -9230.1662  -9324.4646  -1.0927+04  -9925.2547  -9305.2783
DENSITY:
  KMOL/CUM                  41.4486     41.6232     40.1289     29.9076     28.5637
  KG/CUM                   747.4247    749.8700    907.0601    675.7787    645.4138
AVG MW                      18.0325     18.0156     22.6036     22.5955     22.5955
```

Simulated design streams

```
--------------------

STREAM ID              281C         282          282B         284          285
FROM :                 V2106        V2105        H2109B       CONDMIX2     V2109
TO   :                 H2109A       H2109B       V2106        V2109        V2106

SUBSTREAM: MIXED
PHASE:                 LIQUID       LIQUID       MIXED        LIQUID       LIQUID
COMPONENTS: KMOL/HR
  H2                    0.0         1.2347-03    1.2347-03    1.0865-07    1.6489-09
  CO                    0.0         9.0080-04    9.0080-04    1.2366-07    7.3046-10
  CO2                   9.2001       40.5346      40.5346     4.5281-04    2.2065-02
  N2                    0.0         5.3417-05    5.3417-05    1.6535-08    3.9826-11
  O2                    0.0           0.0          0.0          0.0          0.0
  CH4                   0.0         1.9257-05    1.9257-05    8.6788-07    1.7323-10
  C2H6                  0.0         1.0253-10    1.0253-10      0.0          0.0
  C3H8                  0.0         7.3884-16    7.3884-16      0.0          0.0
  C4H10                 0.0           0.0          0.0          0.0          0.0
  C5H12                 0.0           0.0          0.0          0.0          0.0
  C6H14                 0.0           0.0          0.0          0.0          0.0
  MEA                  87.1128       87.1128      87.1128       0.0        1.3322-05
  H2O                 774.9113      775.1610     775.1610       1.0254     222.2656
  AR                    0.0           0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR             871.2243      902.8106     902.8106       1.0259     222.2877
  KG/HR              1.9686+04    2.1069+04    2.1069+04     18.4939    4005.0882
  CUM/SEC            6.6315-03    6.5955-03    4.1647-02    6.8773-06    1.4896-03
STATE VARIABLES:
  TEMP   C            118.0213       68.9435     104.0000      40.1884      40.0000
  PRES   BAR            1.7000       10.4000      10.4000       1.5000       1.5000
  VFRAC                 0.0           0.0        4.5200-02      0.0          0.0
  LFRAC                 1.0000        1.0000       0.9548       1.0000       1.0000
  SFRAC                 0.0           0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL            -2.7789+08   -2.8822+08   -2.8116+08   -2.8774+08   -2.8772+08
  J/KG              -1.2298+07   -1.2350+07   -1.2047+07   -1.5962+07   -1.5969+07
  WATT              -6.7251+07   -7.2280+07   -7.0509+07   -8.2001+04   -1.7766+07
ENTROPY:
  J/KMOL-K          -2.0053+05   -2.2534+05   -1.9835+05   -1.6641+05   -1.6652+05
  J/KG-K            -8874.7396   -9655.7333   -8499.1980   -9231.1477   -9241.9675
DENSITY:
  KMOL/CUM             36.4936       38.0229       6.0215      41.4379      41.4520
  KG/CUM              824.5923      887.3604     140.5274     746.9790     746.8649
AVG MW                 22.5955       23.3374      23.3374      18.0264      18.0175
```

Simulated design streams

```
STREAM ID                  3          4          5          6          7
FROM :                     H2103      H2104      H2105A     H2105B     H2106
TO   :                     H2104      H2105A     H2105B     H2106      ----

SUBSTREAM: MIXED
PHASE:                     VAPOR      VAPOR      VAPOR      VAPOR      VAPOR
COMPONENTS: KMOL/HR
  H2                    3.7117-05  3.7117-05  3.7117-05  3.7117-05  3.7117-05
  CO                    1.2567-06  1.2567-06  1.2567-06  1.2567-06  1.2567-06
  CO2                      2.3270     2.3270     2.3270     2.3270     2.3270
  N2                     260.6468   260.6468   260.6468   260.6468   260.6468
  O2                       9.2645     9.2645     9.2645     9.2645     9.2645
  CH4                   7.8087-31  7.8087-31  7.8087-31  7.8087-31  7.8087-31
  C2H6                     0.0        0.0        0.0        0.0        0.0
  C3H8                     0.0        0.0        0.0        0.0        0.0
  C4H10                    0.0        0.0        0.0        0.0        0.0
  C5H12                    0.0        0.0        0.0        0.0        0.0
  C6H14                    0.0        0.0        0.0        0.0        0.0
  MEA                      0.0        0.0        0.0        0.0        0.0
  H2O                    121.8739   121.8739   121.8739   121.8739   121.8739
  AR                       3.1215     3.1215     3.1215     3.1215     3.1215
TOTAL FLOW:
  KMOL/HR                397.2340   397.2340   397.2340   397.2340   397.2340
  KG/HR                 1.0021+04  1.0021+04  1.0021+04  1.0021+04  1.0021+04
  CUM/SEC                  5.8412     5.4002     4.5950     3.5573     2.4016
STATE VARIABLES:
  TEMP    C              681.5454   609.4574   477.8817   308.3998   120.0029
  PRES    BAR              1.5000     1.5000     1.5000     1.5000     1.5000
  VFRAC                    1.0000     1.0000     1.0000     1.0000     1.0000
  LFRAC                    0.0        0.0        0.0        0.0        0.0
  SFRAC                    0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL               -5.5236+07 -5.7744+07 -6.2209+07 -6.7745+07 -7.3661+07
  J/KG                 -2.1897+06 -2.2891+06 -2.4661+06 -2.6855+06 -2.9201+06
  WATT                 -6.0949+06 -6.3716+06 -6.8643+06 -7.4751+06 -8.1280+06
ENTROPY:
  J/KMOL-K              2.7019+04  2.4288+04  1.8813+04  1.0467+04 -1814.9320
  J/KG-K                1071.0806   962.8275   745.7787   414.9155   -71.9468
DENSITY:
  KMOL/CUM              1.8890-02  2.0433-02  2.4013-02  3.1018-02  4.5946-02
  KG/CUM                   0.4765     0.5154     0.6057     0.7824     1.1590
AVG MW                    25.2260    25.2260    25.2260    25.2260    25.2260
```

Simulated design streams

```
STREAM ID                  A           B           BIN          C           D
FROM :                     SPLIT       H2102       ----         SPLIT       H2105A
TO   :                     H2102       DRUMMIX     BURNER       H2105A      DRUMMIX

SUBSTREAM: MIXED
PHASE:                     LIQUID      MIXED       VAPOR        LIQUID      MIXED
COMPONENTS: KMOL/HR
  H2                        0.0         0.0        121.8254     0.0          0.0
  CO                        0.0         0.0          2.3027     0.0          0.0
  CO2                       0.0         0.0          0.0        0.0          0.0
  N2                        0.0         0.0        260.6468     0.0          0.0
  O2                        0.0         0.0         71.3772     0.0          0.0
  CH4                       0.0         0.0        2.4310-02    0.0          0.0
  C2H6                      0.0         0.0          0.0        0.0          0.0
  C3H8                      0.0         0.0          0.0        0.0          0.0
  C4H10                     0.0         0.0          0.0        0.0          0.0
  C5H12                     0.0         0.0          0.0        0.0          0.0
  C6H14                     0.0         0.0          0.0        0.0          0.0
  MEA                       0.0         0.0          0.0        0.0          0.0
  H2O                    1031.1889   1031.1889       0.0     1061.1022    1061.1022
  AR                        0.0         0.0          3.1215     0.0          0.0
TOTAL FLOW:
  KMOL/HR                1031.1889   1031.1889    459.2980   1061.1022    1061.1022
  KG/HR                  1.8577+04   1.8577+04   1.0021+04   1.9116+04    1.9116+04
  CUM/SEC                8.5677-03   2.9407-02      1.6619   8.8163-03    3.0260-02
STATE VARIABLES:
  TEMP    C               221.0000    221.0000     40.0000    221.0000     221.0000
  PRES    BAR              24.0094     24.0094      2.0000     24.0094      24.0094
  VFRAC                     0.0      4.8000-02      1.0000      0.0      4.8000-02
  LFRAC                     1.0000      0.9520      0.0         1.0000       0.9520
  SFRAC                     0.0         0.0         0.0         0.0          0.0
ENTHALPY:
  J/KMOL                -2.7130+08 -2.6962+08 -1.3052+05 -2.7130+08 -2.6962+08
  J/KG                  -1.5059+07 -1.4967+07 -5982.4219 -1.5059+07 -1.4967+07
  WATT                  -7.7710+07 -7.7232+07 -1.6652+04 -7.9965+07 -7.9472+07
ENTROPY:
  J/KMOL-K              -1.2552+05 -1.2213+05  4700.2516 -1.2552+05 -1.2213+05
  J/KG-K                -6967.2642 -6779.5164   215.4359 -6967.2642 -6779.5164
DENSITY:
  KMOL/CUM                 33.4325      9.7406  7.6766-02     33.4325       9.7406
  KG/CUM                  602.2870    175.4783     1.6748    602.2870     175.4783
AVG MW                     18.0150     18.0150    21.8174     18.0150      18.0150
```

Simulated design streams

```
STREAM ID                E            F            G            H            L10
FROM :                   SPLIT        H2105B       SPLIT        H2107        V31
TO   :                   H2105B       DRUMMIX      H2107        DRUMMIX      MIX2

SUBSTREAM: MIXED
PHASE:                   LIQUID       MIXED        LIQUID       MIXED        VAPOR
COMPONENTS: KMOL/HR
  H2                      0.0          0.0          0.0          0.0           1.2259
  CO                      0.0          0.0          0.0          0.0           1.3294
  CO2                     0.0          0.0          0.0          0.0           0.0
  N2                      0.0          0.0          0.0          0.0           0.3848
  O2                      0.0          0.0          0.0          0.0           0.0
  CH4                     0.0          0.0          0.0          0.0        1.1418-18
  C2H6                    0.0          0.0          0.0          0.0           0.0
  C3H8                    0.0          0.0          0.0          0.0           0.0
  C4H10                   0.0          0.0          0.0          0.0           0.0
  C5H12                   0.0          0.0          0.0          0.0           0.0
  C6H14                   0.0          0.0          0.0          0.0           0.0
  MEA                     0.0          0.0          0.0          0.0           0.0
  H2O                  1315.6387    1315.6387    4402.3326    4402.3326        0.0
  AR                      0.0          0.0          0.0          0.0           0.0
TOTAL FLOW:
  KMOL/HR              1315.6387    1315.6387    4402.3326    4402.3326        2.9402
  KG/HR                2.3701+04    2.3701+04    7.9308+04    7.9308+04       50.4898
  CUM/SEC              1.0931-02    3.7518-02    3.6577-02       0.1255    2.5762-03
STATE VARIABLES:
  TEMP    C             221.0000     221.0000     221.0000     221.0000    -183.0864
  PRES    BAR            24.0094      24.0094      24.0094      24.0094       2.3000
  VFRAC                   0.0       4.8000-02       0.0       4.8000-02       1.0000
  LFRAC                   1.0000       0.9520       1.0000       0.9520       0.0
  SFRAC                   0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL              -2.7130+08  -2.6962+08  -2.7130+08  -2.6962+08  -5.5917+07
  J/KG                -1.5059+07  -1.4967+07  -1.5059+07  -1.4967+07  -3.2563+06
  WATT                -9.9147+07  -9.8536+07  -3.3176+08  -3.2972+08  -4.5669+04
ENTROPY:
  J/KMOL-K            -1.2552+05  -1.2213+05  -1.2552+05  -1.2213+05   8253.5354
  J/KG-K              -6967.2642  -6779.5164  -6967.2642  -6779.5158    480.6349
DENSITY:
  KMOL/CUM               33.4325       9.7406      33.4325       9.7406       0.3170
  KG/CUM                602.2870     175.4783     602.2870     175.4783       5.4440
AVG MW                   18.0150      18.0150      18.0150      18.0150      17.1721
```

Simulated design streams

```
          --------

STREAM ID                  L11         L13         L2          L22         L28
FROM :                     T24         V47         E21         E23A        V6
TO   :                     T22MIX      MIX2        E22         E21         T23

SUBSTREAM: MIXED
PHASE:                     LIQUID      MIXED       VAPOR       VAPOR       MIXED
COMPONENTS: KMOL/HR
  H2                     4.1183-04   1.6328-15    148.2504    144.7187      2.3053
  CO                       17.1293      2.0378     53.1893      2.6645     34.6148
  CO2                       0.0         0.0         0.0         0.0         0.0
  N2                        3.3475   4.0712-02      8.5891      1.1614      4.0705
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                    3.1910-09      4.5204      4.5586      0.0         4.5586
  C2H6                      0.0         0.0         0.0         0.0         0.0
  C3H8                      0.0         0.0         0.0         0.0         0.0
  C4H10                     0.0         0.0         0.0         0.0         0.0
  C5H12                     0.0         0.0         0.0         0.0         0.0
  C6H14                     0.0         0.0         0.0         0.0         0.0
  MEA                       0.0         0.0         0.0         0.0         0.0
  H2O                       0.0         0.0         0.0         0.0         0.0
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                  20.4772      6.5990    214.5876    148.5447     45.5493
  KG/HR                   573.5680    130.7428   2102.4483    398.9239   1161.3720
  CUM/SEC                2.4084-04   1.0299-04   1.8868-02   8.5078-02   3.0026-03
STATE VARIABLES:
  TEMP     C             -169.3914   -172.9837   -157.6000   -176.1000   -177.3833
  PRES     BAR              7.6000      2.1500     28.1000      3.9000      5.4700
  VFRAC                     0.0      5.2909-03      1.0000      1.0000      0.1535
  LFRAC                     1.0000      0.9947      0.0         0.0         0.8464
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                -1.0348+08  -9.9581+07  -3.4366+07  -7.3772+06  -1.0262+08
  J/KG                  -3.6945+06  -5.0262+06  -3.5076+06  -2.7470+06  -4.0247+06
  WATT                  -5.8862+05  -1.8254+05  -2.0485+06  -3.0440+05  -1.2984+06
ENTROPY:
  J/KMOL-K              -1.8338+04  -1.3264+05  -2.8241+04  -3.8018+04  -2.9782+04
  J/KG-K                 -654.6788  -6694.9005  -2882.4528  -1.4157+04  -1168.0410
DENSITY:
  KMOL/CUM                 23.6182     17.7987      3.1591      0.4849      4.2138
  KG/CUM                  661.5463    352.6361     30.9522      1.3024    107.4414
AVG MW                     28.0099     19.8124      9.7976      2.6855     25.4970
```

Simulated design streams

```
STREAM ID              L29          L3           L30          L31          L33
FROM :                 T23          E22          V9           T24          V8
TO   :                 V29          T21          T24          V31          T22

SUBSTREAM: MIXED
PHASE:                 VAPOR        VAPOR        MIXED        VAPOR        MIXED
COMPONENTS: KMOL/HR
  H2                    2.3043     148.2504       1.2262       1.2259   9.8799-04
  CO                    3.3870      53.1893      15.9099       1.3294     31.2277
  CO2                   0.0          0.0          0.0          0.0          0.0
  N2                    0.5549       8.5891       3.3569       0.3848      3.5156
  O2                    0.0          0.0          0.0          0.0          0.0
  CH4                3.8212-02       4.5586       0.0       1.1418-18      4.5204
  C2H6                  0.0          0.0          0.0          0.0          0.0
  C3H8                  0.0          0.0          0.0          0.0          0.0
  C4H10                 0.0          0.0          0.0          0.0          0.0
  C5H12                 0.0          0.0          0.0          0.0          0.0
  C6H14                 0.0          0.0          0.0          0.0          0.0
  MEA                   0.0          0.0          0.0          0.0          0.0
  H2O                   0.0          0.0          0.0          0.0          0.0
  AR                    0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR               6.2845     214.5876      20.4931       2.9402     39.2648
  KG/HR               115.6755    2102.4483     542.1473      50.4898   1045.6965
  CUM/SEC            2.3454-03    1.7354-02    8.9800-04    7.7472-04   3.9269-03
STATE VARIABLES:
  TEMP    C          -178.8131    -164.8000    -176.7005    -177.7584   -182.1491
  PRES    BAR           5.4000      28.0000       7.8500       7.6000      2.3830
  VFRAC                 1.0000       1.0000       0.1341       1.0000      0.1107
  LFRAC                 0.0          0.0          0.8659       0.0         0.8892
  SFRAC                 0.0          0.0          0.0          0.0         0.0
ENTHALPY:
  J/KMOL            -6.5993+07   -3.4585+07   -9.6519+07   -5.5918+07  -1.0828+08
  J/KG              -3.5853+06   -3.5299+06   -3.6484+06   -3.2563+06  -4.0657+06
  WATT              -1.1520+05   -2.0615+06   -5.4944+05   -4.5670+04  -1.1810+06
ENTROPY:
  J/KMOL-K           8440.6659   -3.0173+04   -2.0389+04   -1127.7300  -3.3430+04
  J/KG-K              458.5718   -3079.5921    -770.7210     -65.6720  -1255.2716
DENSITY:
  KMOL/CUM              0.7443       3.4349       6.3391       1.0542      2.7774
  KG/CUM               13.7003      33.6539     167.7024      18.1033     73.9687
AVG MW                 18.4064       9.7976      26.4550      17.1721     26.6318
```

Simulated design streams

```
STREAM ID                  L35         L36         L37         L38         L39
FROM :                     E21         SPLIT1      E22B        SPLIT1      SPLIT1
TO   :                     SPLIT1      E22B        V37         E24         V39

SUBSTREAM: MIXED
PHASE:                     VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                     2.5847-04   4.0322-05   4.0322-05   1.4113-04   7.7025-05
  CO                        8.5532      1.3343      1.3343      4.6700      2.5488
  CO2                       0.0         0.0         0.0         0.0         0.0
  N2                        1.2598      0.1965      0.1965      0.6878      0.3754
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                    1.0708-08   1.6705-09   1.6705-09   5.8466-09   3.1910-09
  C2H6                      0.0         0.0         0.0         0.0         0.0
  C3H8                      0.0         0.0         0.0         0.0         0.0
  C4H10                     0.0         0.0         0.0         0.0         0.0
  C5H12                     0.0         0.0         0.0         0.0         0.0
  C6H14                     0.0         0.0         0.0         0.0         0.0
  MEA                       0.0         0.0         0.0         0.0         0.0
  H2O                       0.0         0.0         0.0         0.0         0.0
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                   9.8132      1.5308      1.5308      5.3580      2.9243
  KG/HR                   274.8673     42.8793     42.8793    150.0775     81.9104
  CUM/SEC                2.5055-03   3.9086-04   3.6609-04   1.3680-03   7.4664-04
STATE VARIABLES:
  TEMP   C               -155.1000   -155.1000   -160.8000   -155.1000   -155.1000
  PRES   BAR                9.2000      9.2000      9.1000      9.2000      9.2000
  VFRAC                     1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                     0.0         0.0         0.0         0.0         0.0
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                -1.0205+08  -1.0205+08  -1.0225+08  -1.0205+08  -1.0205+08
  J/KG                  -3.6434+06  -3.6434+06  -3.6506+06  -3.6434+06  -3.6434+06
  WATT                  -2.7818+05  -4.3397+04  -4.3482+04  -1.5189+05  -8.2899+04
ENTROPY:
  J/KMOL-K               3.3838+04   3.3838+04   3.2169+04   3.3838+04   3.3838+04
  J/KG-K                 1208.0928   1208.0928   1148.4985   1208.0928   1208.0928
DENSITY:
  KMOL/CUM                  1.0879      1.0879      1.1615      1.0879      1.0879
  KG/CUM                   30.4738     30.4738     32.5353     30.4738     30.4738
AVG MW                     28.0097     28.0097     28.0097     28.0097     28.0097
```

Simulated design streams

```
STREAM ID                 L4         L40        L41        L42        L43
FROM :                    CO2        V39        E24        V41        V37
TO   :                    E23A       T24        V41        T22MIX     T22MIX

SUBSTREAM: MIXED
PHASE:                    VAPOR      VAPOR      VAPOR      VAPOR      VAPOR
COMPONENTS: KMOL/HR
  H2                   144.7187  7.7025-05  1.4113-04  1.4113-04  4.0322-05
  CO                     2.6645     2.5488     4.6700     4.6700     1.3343
  CO2                    0.0        0.0        0.0        0.0        0.0
  N2                     1.1614     0.3754     0.6878     0.6878     0.1965
  O2                     0.0        0.0        0.0        0.0        0.0
  CH4                    0.0     3.1910-09  5.8466-09  5.8466-09  1.6705-09
  C2H6                   0.0        0.0        0.0        0.0        0.0
  C3H8                   0.0        0.0        0.0        0.0        0.0
  C4H10                  0.0        0.0        0.0        0.0        0.0
  C5H12                  0.0        0.0        0.0        0.0        0.0
  C6H14                  0.0        0.0        0.0        0.0        0.0
  MEA                    0.0        0.0        0.0        0.0        0.0
  H2O                    0.0        0.0        0.0        0.0        0.0
  AR                     0.0        0.0        0.0        0.0        0.0
TOTAL FLOW:
  KMOL/HR              148.5447     2.9243     5.3580     5.3580     1.5308
  KG/HR                398.9239    81.9104   150.0775   150.0775    42.8793
  CUM/SEC             8.3025-03  8.6639-04  1.3406-03  4.9807-03  1.3647-03
STATE VARIABLES:
  TEMP    C            -201.5000  -156.8238  -157.6000  -167.4827  -171.2600
  PRES    BAR            27.3000     7.9500     9.1000     2.5000     2.5000
  VFRAC                   1.0000     1.0000     1.0000     1.0000     1.0000
  LFRAC                   0.0        0.0        0.0        0.0        0.0
  SFRAC                   0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL              -8.1343+06 -1.0205+08 -1.0214+08 -1.0214+08 -1.0225+08
  J/KG                -3.0289+06 -3.6434+06 -3.6464+06 -3.6464+06 -3.6506+06
  WATT                -3.3564+05 -8.2898+04 -1.5201+05 -1.5201+05 -4.3482+04
ENTROPY:
  J/KMOL-K            -6.2953+04  3.4897+04  3.3193+04  4.2971+04  4.1847+04
  J/KG-K              -2.3441+04  1245.8932  1185.0432  1534.1477  1494.0189
DENSITY:
  KMOL/CUM                4.9698     0.9375     1.1102     0.2988     0.3116
  KG/CUM                 13.3468    26.2616    31.0968     8.3699     8.7280
AVG MW                    2.6855    28.0097    28.0097    28.0097    28.0097
```

Simulated design streams

```
STREAM ID                  L44         L46         L47         L48         L49
FROM :                     T22MIX      E25-27      T22         MIX2        T22
TO   :                     E25-27      T22         V47         E21         E21

SUBSTREAM: MIXED
PHASE:                     MIXED       LIQUID      LIQUID      MIXED       VAPOR
COMPONENTS: KMOL/HR
  H2                     5.9328-04   5.9328-04   1.6328-15     3.5302    1.5812-03
  CO                       23.1337     23.1337      2.0378     6.7543      52.3228
  CO2                      0.0         0.0         0.0         0.0          0.0
  N2                        4.2319      4.2319   4.0712-02     0.9805       7.7067
  O2                       0.0         0.0         0.0         0.0          0.0
  CH4                    1.0708-08   1.0708-08      4.5204     4.5586    6.5505-08
  C2H6                     0.0         0.0         0.0         0.0          0.0
  C3H8                     0.0         0.0         0.0         0.0          0.0
  C4H10                    0.0         0.0         0.0         0.0          0.0
  C5H12                    0.0         0.0         0.0         0.0          0.0
  C6H14                    0.0         0.0         0.0         0.0          0.0
  MEA                      0.0         0.0         0.0         0.0          0.0
  H2O                      0.0         0.0         0.0         0.0          0.0
  AR                       0.0         0.0         0.0         0.0          0.0
TOTAL FLOW:
  KMOL/HR                  27.3662     27.3662      6.5990    15.8237      60.0311
  KG/HR                   766.5249    766.5249    130.7428   296.9083    1681.4545
  CUM/SEC                8.4820-03   2.8213-04   6.7915-05  9.1534-03    5.1031-02
STATE VARIABLES:
  TEMP   C               -183.2570   -184.5000   -172.4673  -180.6837    -184.1620
  PRES   BAR                2.5000      2.3250      2.2500     2.1500       2.2500
  VFRAC                     0.3952   0.0         0.0           0.5971       1.0000
  LFRAC                     0.6047      1.0000      1.0000     0.4028     0.0
  SFRAC                    0.0         0.0         0.0         0.0          0.0
ENTHALPY:
  J/KMOL                -1.0315+08  -1.0546+08  -9.9581+07 -7.8128+07  -1.0264+08
  J/KG                  -3.6826+06  -3.7649+06  -5.0262+06 -4.1638+06  -3.6645+06
  WATT                  -7.8411+05  -8.0165+05  -1.8254+05 -3.4341+05  -1.7116+06
ENTROPY:
  J/KMOL-K              -2121.9147  -2.7792+04  -1.3265+05 -4.7083+04   3.8596+04
  J/KG-K                  -75.7558   -992.2272  -6695.2605 -2509.2788    1377.9520
DENSITY:
  KMOL/CUM                  0.8962     26.9439     26.9907     0.4802       0.3267
  KG/CUM                   25.1029    754.6960    534.7511     9.0103       9.1527
AVG MW                     28.0099     28.0099     19.8124    18.7634      28.0097
```

Simulated design streams

```
STREAM ID                   L6          L7          L8          L9          LB
FROM :                      T21         V29         T23         SPLIT2      T21
TO   :                      V6          MIX2        V8          V9          MIX1

SUBSTREAM: MIXED
PHASE:                      LIQUID      VAPOR       LIQUID      LIQUID      VAPOR
COMPONENTS: KMOL/HR
  H2                          2.3053      2.3043  9.8799-04      1.2262    149.5015
  CO                         34.6148      3.3870     31.2277    15.9099     64.7157
  CO2                         0.0         0.0        0.0        0.0         0.0
  N2                          4.0705      0.5549     3.5156     3.3569     14.2542
  O2                          0.0         0.0        0.0        0.0         0.0
  CH4                         4.5586  3.8212-02      4.5204     0.0       5.2456-13
  C2H6                        0.0         0.0        0.0        0.0         0.0
  C3H8                        0.0         0.0        0.0        0.0         0.0
  C4H10                       0.0         0.0        0.0        0.0         0.0
  C5H12                       0.0         0.0        0.0        0.0         0.0
  C6H14                       0.0         0.0        0.0        0.0         0.0
  MEA                         0.0         0.0        0.0        0.0         0.0
  H2O                         0.0         0.0        0.0        0.0         0.0
  AR                          0.0         0.0        0.0        0.0         0.0
TOTAL FLOW:
  KMOL/HR                    45.5493      6.2845    39.2648     20.4931    228.4715
  KG/HR                    1161.3720    115.6755  1045.6965    542.1473   2513.3874
  CUM/SEC                  5.1430-04   5.5388-03  4.3456-04  2.3577-04   1.7132-02
STATE VARIABLES:
  TEMP    C                -169.6737   -182.2501  -172.1917  -171.5000   -171.2848
  PRES    BAR                27.3000      2.3000     5.4000    27.3470     27.3000
  VFRAC                       0.0         1.0000     0.0        0.0         1.0000
  LFRAC                       1.0000      0.0        1.0000     1.0000      0.0
  SFRAC                       0.0         0.0        0.0        0.0         0.0
ENTHALPY:
  J/KMOL                 -1.0262+08  -6.5992+07 -1.0828+08 -9.6519+07 -3.7133+07
  J/KG                   -4.0247+06  -3.5853+06 -4.0657+06 -3.6484+06 -3.3754+06
  WATT                   -1.2984+06  -1.1520+05 -1.1810+06 -5.4944+05 -2.3566+06
ENTROPY:
  J/KMOL-K               -3.1517+04   1.5173+04 -3.3914+04 -2.1784+04 -2.7210+04
  J/KG-K                 -1236.1190    824.3378 -1273.4399  -823.4156 -2473.4417
DENSITY:
  KMOL/CUM                  24.6015      0.3151    25.0988    24.1446      3.7044
  KG/CUM                   627.2653      5.8012   668.4296   638.7475     40.7524
AVG MW                      25.4970     18.4064    26.6318    26.4550     11.0008
```

Simulated design streams

```
STREAM ID               LC          LD          LE          LF          LG
FROM :                  CO1         CO1         CO2         MIX1        SPLIT2
TO   :                  CO2         SPLIT2      MIX1        CO1         T21

SUBSTREAM: MIXED
PHASE:                  VAPOR       LIQUID      LIQUID      MIXED       LIQUID
COMPONENTS: KMOL/HR
  H2                   148.3965      4.7826      3.6776    153.1792      3.5563
  CO                    61.1690     62.0511     58.5043    123.2201     46.1412
  CO2                    0.0         0.0         0.0         0.0         0.0
  N2                    16.7122     13.0926     15.5506     29.8049      9.7357
  O2                     0.0         0.0         0.0         0.0         0.0
  CH4                    0.0         0.0         0.0     5.2456-13       0.0
  C2H6                   0.0         0.0         0.0         0.0         0.0
  C3H8                   0.0         0.0         0.0         0.0         0.0
  C4H10                  0.0         0.0         0.0         0.0         0.0
  C5H12                  0.0         0.0         0.0         0.0         0.0
  C6H14                  0.0         0.0         0.0         0.0         0.0
  MEA                    0.0         0.0         0.0         0.0         0.0
  H2O                    0.0         0.0         0.0         0.0         0.0
  AR                     0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR              226.2778     79.9264     77.7327    306.2042     59.4333
  KG/HR               2480.6710   2114.4593   2081.7430   4595.1304   1572.3119
  CUM/SEC             1.6903-02   9.1953-04   7.1708-04   1.6170-02   6.8377-04
STATE VARIABLES:
  TEMP    C           -171.5000   -171.5000   -201.5000   -174.9585   -171.5000
  PRES    BAR           27.3470     27.3470     27.3000     27.3000     27.3470
  VFRAC                  1.0000      0.0         0.0         0.6639      0.0
  LFRAC                  0.0         1.0000      1.0000      0.3360      1.0000
  SFRAC                  0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL             -3.5707+07  -9.6519+07  -9.5757+07  -5.2015+07  -9.6519+07
  J/KG               -3.2571+06  -3.6484+06  -3.5756+06  -3.4661+06  -3.6484+06
  WATT               -2.2444+06  -2.1429+06  -2.0676+06  -4.4242+06  -1.5935+06
ENTROPY:
  J/KMOL-K           -2.8312+04  -2.1784+04  -4.4861+04  -3.0948+04  -2.1784+04
  J/KG-K             -2582.4909   -823.4156  -1675.1372  -2062.2539   -823.4156
DENSITY:
  KMOL/CUM               3.7186     24.1446     30.1117      5.2602     24.1446
  KG/CUM                40.7669    638.7475    806.4147     78.9395    638.7475
AVG MW                  10.9629     26.4550     26.7807     15.0067     26.4550
```

Simulated design streams

```
  - ------------

STREAM ID                    LIQ          MEASUMP       OUT          STM          STMFD
FROM :                       V2103        V2116         V2118        V2103        DRUMMIX
TO   :                       SPLIT        ----          ----         ----         V2103

SUBSTREAM: MIXED
PHASE:                       LIQUID       LIQUID        MIXED        VAPOR        MIXED
COMPONENTS: KMOL/HR
  H2                          0.0         1.6653-07     0.8948        0.0          0.0
  CO                          0.0         3.6150-08     0.3210        0.0          0.0
  CO2                         0.0         6.6366-09    1.1361-02      0.0          0.0
  N2                          0.0         5.3679-09    5.1846-02      0.0          0.0
  O2                          0.0           0.0          0.0          0.0          0.0
  CH4                         0.0         3.2820-08    2.7517-02      0.0          0.0
  C2H6                        0.0           0.0        7.6395-05      0.0          0.0
  C3H8                        0.0           0.0        3.1213-09      0.0          0.0
  C4H10                       0.0           0.0          0.0          0.0          0.0
  C5H12                       0.0           0.0          0.0          0.0          0.0
  C6H14                       0.0           0.0          0.0          0.0          0.0
  MEA                         0.0         1.1001-06    4.0328-03      0.0          0.0
  H2O                      7810.2630       0.1822       0.3701      343.2634    7810.2625
  AR                          0.0           0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR                  7810.2630       0.1822       1.6809      343.2634    7810.2625
  KG/HR                    1.4070+05       3.2823      20.1075     6183.8913    1.4070+05
  CUM/SEC                  6.4892-02     1.2207-06    3.3726-04      0.1473       0.2227
STATE VARIABLES:
  TEMP    C                 221.0000      40.0000      35.0000     221.0000     221.0000
  PRES    BAR                24.0094      10.3000      28.3000      24.0094      24.0094
  VFRAC                       0.0          0.0          0.7805       1.0000     4.8000-02
  LFRAC                       1.0000       1.0000       0.2194       0.0          0.9520
  SFRAC                       0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL                  -2.7130+08  -2.8770+08  -8.8685+07  -2.3648+08  -2.6962+08
  J/KG                    -1.5059+07  -1.5970+07  -7.4137+06  -1.3127+07  -1.4967+07
  WATT                    -5.8858+08  -1.4560+04  -4.1409+04  -2.2548+07  -5.8496+08
ENTROPY:
  J/KMOL-K                -1.2552+05  -1.6656+05  -3.7930+04  -5.5051+04  -1.2213+05
  J/KG-K                  -6967.2642  -9245.2471  -3170.7566  -3055.8504  -6779.5160
DENSITY:
  KMOL/CUM                   33.4325      41.4597       1.3844       0.6470       9.7406
  KG/CUM                    602.2870     746.9080      16.5613      11.6559     175.4781
AVG MW                       18.0150      18.0152      11.9623      18.0150      18.0150
```

APPENDIX 5. Most important simulated in and out going actual streams

Table A5.1 Most important streams entering the plant

STREAM Comp.	201	205	251	253	260	BIN	281
H_2	0.0	0.0	0.0	0.0	0.0	125.347	0.0
CO	0.0	0.0	0.0	0.0	0.0	2.371	0.0
CO_2	0.486	0.0	0.0	0.0	0.0	0.0	9.859
N_2	7.839	0.0	0.0	0.0	0.0	268.204	0.0
O_2	0.0	0.0	0.0	0.0	0.0	73.446	0.0
CH_4	44.431	0.0	0.0	0.0	0.0	0.025	0.0
C_2H_6	1.556	0.0	0.0	0.0	0.0	0.0	0.0
C_3H_8	0.204	0.0	0.0	0.0	0.0	0.0	0.0
C_4H_{10}	0.076	0.0	0.0	0.0	0.0	0.0	0.0
C_5H_{12}	0.021	0.0	0.0	0.0	0.0	0.0	0.0
C_6H_{14}	0.028	0.0	0.0	0.0	0.0	0.0	0.0
MEA	0.0	0.0	0.0	0.0	0.0	0.0	89.643
H_2O	0.0	155.659	343.264	25.762	105.484	0.0	797.674
AR	0.0	0.0	0.0	0.0	0.0	3.212	0.0
kmol/h	54.641	155.659	343.264	25.762	105.484	472.605	897.176
kg/h	1017.9	2804.2	6183.9	464.1	1900.3	10311.0	20279.0
T (°C)	15.0	220.0	104.0	104.0	208.0	40.0	40.0
P (bar)	19.0	23.2	27.0	27.0	18.3	2.0	14.7

APPENDIX 5. Most important simulated in and out going actual streams

Table A5.2 Most important streams going out the plant

STREAM Comp.	226	STM	266	7	140	281A
H_2	0.001	0.0	0.0	0.0	143.472	0.0
CO	45.024	0.0	0.0	0.0	2.6401	0.0
CO_2	0.0	0.0	0.021	2.396	0.0	9.450
N_2	6.632	0.0	0.0	268.204	1.154	0.0
O_2	0.0	0.0	0.0	9.537	0.0	0.0
CH_4	0.0	0.0	0.0	0.0	0.0	0.0
C_2H_6	0.0	0.0	0.0	0.0	0.0	0.0
C_3H_8	0.0	0.0	0.0	0.0	0.0	0.0
C_4H_{10}	0.0	0.0	0.0	0.0	0.0	0.0
C_5H_{12}	0.0	0.0	0.0	0.0	0.0	0.0
C_6H_{14}	0.0	0.0	0.0	0.0	0.0	0.0
MEA	0.0	0.0	0.0	0.0	0.0	89.631
H_2O	0.0	343.264	236.238	125.397	0.0	797.674
AR	0.0	0.0	0.0	3.2112	0.0	0.0
kmol/h	51.057	343.264	236.259	408.746	147.267	897.176
kg/h	1446.9	6183.9	4256.8	10311.0	395.5	20279.0
T (°C)	90.0	221.0	40.2	138.5	13.8	40.0
P (bar)	9.6	24.0	3.5	1.5	3.5	14.7

APPENDIX 5. Most important simulated in and out going streams with less N_2

Table A5.3 Most important entering streams (less N_2 simulation)

STREAM Comp.	201	205	251	253	260	BIN	281
H_2	0.0	0.0	0.0	0.0	0.0	125.347	0.0
CO	0.0	0.0	0.0	0.0	0.0	2.371	0.0
CO_2	0.486	0.0	0.0	0.0	0.0	0.0	9.859
N_2	1.556	0.0	0.0	0.0	0.0	268.204	0.0
O_2	0.0	0.0	0.0	0.0	0.0	73.446	0.0
CH_4	44.431	0.0	0.0	0.0	0.0	0.025	0.0
C_2H_6	1.556	0.0	0.0	0.0	0.0	0.0	0.0
C_3H_8	0.204	0.0	0.0	0.0	0.0	0.0	0.0
C_4H_{10}	0.076	0.0	0.0	0.0	0.0	0.0	0.0
C_5H_{12}	0.021	0.0	0.0	0.0	0.0	0.0	0.0
C_6H_{14}	0.028	0.0	0.0	0.0	0.0	0.0	0.0
MEA	0.0	0.0	0.0	0.0	0.0	0.0	89.643
H_2O	0.0	155.659	343.264	25.762	105.484	0.0	797.674
AR	0.0	0.0	0.0	0.0	0.0	3.212	0.0
kmol/h	54.641	155.659	343.264	25.762	105.484	472.605	897.176
kg/h	1017.9	2804.2	6183.9	464.1	1900.3	10311.0	20279.0
T (°C)	15.0	220.0	104.0	104.0	208.0	40.0	40.0
P (bar)	19.0	23.2	27.0	27.0	18.3	2.0	14.7

APPENDIX 5. Most important simulated in and out going streams with less N_2

Table A5.4 Most important out going streams (less N_2 simulation)

STREAM Comp.	226	STM	266	7	140	281A
H_2	0.001	0.0	0.0	0.0	143.227	0.0
CO	44.764	0.0	0.0	0.0	3.154	0.0
CO_2	0.0	0.0	0.022	2.396	0.0	9.205
N_2	1.279	0.0	0.0	268.204	0.267	0.0
O_2	0.0	0.0	0.0	9.537	0.0	0.0
CH_4	0.0	0.0	0.0	0.0	0.0	0.0
C_2H_6	0.0	0.0	0.0	0.0	0.0	0.0
C_3H_8	0.0	0.0	0.0	0.0	0.0	0.0
C_4H_{10}	0.0	0.0	0.0	0.0	0.0	0.0
C_5H_{12}	0.0	0.0	0.0	0.0	0.0	0.0
C_6H_{14}	0.0	0.0	0.0	0.0	0.0	0.0
MEA	0.0	0.0	0.0	0.0	0.0	89.643
H_2O	0.0	343.264	236.529	125.397	0.0	797.674
AR	0.0	0.0	0.0	3.2112	0.0	0.0
kmol/h	46.043	343.264	236.551	408.746	146.648	897.176
kg/h	1289.7	6183.9	4262.0	10311.0	384.6	20279.0
T (°C)	90.0	221.0	40.2	148.8	15.2	40.0
P (bar)	9.6	24.0	3.5	1.5	3.5	14.7

Simulated capacity increase by using CO_2.

```
STREAM ID                 1          140        2          201        202
FROM :                    BURNER     B1         H2102      ----       B1
TO   :                    H2102      ----       H2103      H2-MIX     H2-MIX

SUBSTREAM: MIXED
PHASE:                    VAPOR      VAPOR      VAPOR      VAPOR      VAPOR
COMPONENTS: KMOL/HR
  H2                    3.8182-05  117.1113  3.8182-05    0.0       48.1150
  CO                    1.2933-06    2.2539  1.2933-06    0.0        0.9260
  CO2                      2.3955  0.0          2.3955   14.6080     0.0
  N2                     268.2040  0.7733     268.2040    7.1788     0.3177
  O2                       9.5373  0.0          9.5373    0.0        0.0
  CH4                   8.0301-31  0.0       8.0301-31   40.7093     0.0
  C2H6                     0.0     0.0          0.0       1.4266     0.0
  C3H8                     0.0     0.0          0.0       0.1848     0.0
  C4H10                    0.0     0.0          0.0    6.9851-02     0.0
  C5H12                    0.0     0.0          0.0    1.9404-02     0.0
  C6H14                    0.0     0.0          0.0    2.4600-02     0.0
  MEA                      0.0     0.0          0.0       0.0        0.0
  H2O                    125.3970  0.0        125.3970    0.0        0.0
  AR                       3.2116  0.0          3.2116    0.0        0.0
TOTAL FLOW:
  KMOL/HR                408.7456  120.1386   408.7456   64.2215    49.3588
  KG/HR                 1.0311+04  320.8922  1.0311+04 1555.7300   131.8382
  CUM/SEC                  8.0465    0.2279     7.6872 2.1459-02  9.3644-02
STATE VARIABLES:
  TEMP   C              1005.0000   13.7301   947.9141   15.0000    13.7301
  PRES   BAR               1.5000    3.5000     1.5000   19.0000     3.5000
  VFRAC                    1.0000    1.0000     1.0000    1.0000     1.0000
  LFRAC                    0.0       0.0        0.0       0.0        0.0
  SFRAC                    0.0       0.0        0.0       0.0        0.0
ENTHALPY:
  J/KMOL               -4.3557+07 -2.3930+06 -4.5655+07 -1.4026+08 -2.3930+06
  J/KG                 -1.7266+06 -8.9590+05 -1.8098+06 -5.7901+06 -8.9590+05
  WATT                 -4.9455+06 -7.9858+04 -5.1837+06 -2.5022+06 -3.2809+04
ENTROPY:
  J/KMOL-K              3.7540+04 -8630.1778  3.5860+04 -7.4323+04 -8630.1778
  J/KG-K                1488.1121 -3231.0463  1421.5486 -3068.0872 -3231.0463
DENSITY:
  KMOL/CUM              1.4110-02    0.1464  1.4770-02    0.8313     0.1464
  KG/CUM                   0.3559    0.3910     0.3725   20.1380     0.3910
AVG MW                    25.2263    2.6710    25.2263   24.2244     2.6710
```

Simulated capacity increase by using CO_2.

```
STREAM ID                  202B        203         203B        204         204B
FROM :                     H2-MIX      H2104       V2101       V2114       CO2-MIX
TO   :                     H2104       V2101       CO2-MIX     CO2-MIX     H2O-MIX

SUBSTREAM: MIXED
PHASE:                     VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                        48.1150     48.1150     48.1150      4.2859     52.4010
  CO                         0.9260      0.9260      0.9260      8.0093      8.9353
  CO2                       14.6080     14.6080     14.6080     35.9402     50.5482
  N2                         7.4965      7.4965      7.4965      0.9671      8.4636
  O2                         0.0         0.0         0.0         0.0         0.0
  CH4                       40.7093     40.7093     40.7093      5.9294     46.6388
  C2H6                       1.4266      1.4266      1.4266   1.5236-10      1.4266
  C3H8                       0.1848      0.1848      0.1848      0.0         0.1848
  C4H10                   6.9851-02   6.9851-02   6.9851-02      0.0      6.9851-02
  C5H12                   1.9404-02   1.9404-02   1.9404-02      0.0      1.9404-02
  C6H14                   2.4600-02   2.4600-02   2.4600-02      0.0      2.4600-02
  MEA                        0.0         0.0         0.0         0.0         0.0
  H2O                        0.0         0.0         0.0         0.2357      0.2357
  AR                         0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                  113.5803    113.5803    113.5803     55.3678    168.9482
  KG/HR                   1687.5682   1687.5682   1687.5682   1941.1781   3628.7465
  CUM/SEC                 3.5311-02   8.5969-02   9.0440-02   2.3763-02      0.1263
STATE VARIABLES:
  TEMP   C                  12.5537    400.0000    350.0000     40.0000    249.0306
  PRES   BAR                21.0000     20.7000     18.2000     16.2000     16.2000
  VFRAC                      1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                      0.0         0.0         0.0         0.0         0.0
  SFRAC                      0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                 -8.0348+07  -6.5514+07  -6.7641+07  -2.8052+08  -1.3741+08
  J/KG                   -5.4077+06  -4.4094+06  -4.5525+06  -8.0012+06  -6.3974+06
  WATT                   -2.5350+06  -2.0670+06  -2.1341+06  -4.3144+06  -6.4485+06
ENTROPY:
  J/KMOL-K               -4.7244+04  -1.4902+04  -1.7106+04  -7101.7192  -9427.6211
  J/KG-K                 -3179.7127  -1002.9696  -1151.2780   -202.5611   -438.9339
DENSITY:
  KMOL/CUM                   0.8935      0.3670      0.3488      0.6472      0.3714
  KG/CUM                    13.2755      5.4528      5.1831     22.6910      7.9776
AVG MW                      14.8579     14.8579     14.8579     35.0596     21.4784
```

Simulated capacity increase by using CO_2.

```
STREAM ID                 205         206         207         208         208B
FROM :                    ----        H2O-MIX     H2103       H2101       H2107
TO   :                    H2O-MIX     H2103       H2101       H2107       H2O-MIX2

SUBSTREAM: MIXED
PHASE:                    VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                       0.0        52.4010     52.4010    170.5384    170.5384
  CO                       0.0         8.9353      8.9353     67.0124     67.0124
  CO2                      0.0        50.5482     50.5482     37.0764     37.0764
  N2                       0.0         8.4636      8.4636      8.4636      8.4636
  O2                       0.0         0.0         0.0         0.0         0.0
  CH4                      0.0        46.6388     46.6388      5.9652      5.9652
  C2H6                     0.0         1.4266      1.4266    1.1303-04   1.1303-04
  C3H8                     0.0         0.1848      0.1848    5.2530-09   5.2530-09
  C4H10                    0.0       6.9851-02   6.9851-02   3.3607-13   3.3607-13
  C5H12                    0.0       1.9404-02   1.9404-02   1.4485-17   1.4485-17
  C6H14                    0.0       2.4600-02   2.4600-02   7.1454-22   7.1454-22
  MEA                      0.0         0.0         0.0       1.2575-30   1.2575-30
  H2O                    143.9411    144.1768    144.1768    113.0435    113.0435
  AR                       0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                143.9411    312.8894    312.8894    402.0998    402.0998
  KG/HR                 2593.1000   6221.8465   6221.8465   6221.8331   6221.8331
  CUM/SEC               6.4031-02     0.2289      0.3636      0.9172      0.4518
STATE VARIABLES:
  TEMP    C              220.0000    228.9851    487.0000    860.0000    286.1904
  PRES    BAR             23.2000     15.6000     15.1000     11.5000     11.5000
  VFRAC                    1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                    0.0         0.0         0.0         0.0         0.0
  SFRAC                    0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL               -2.3647+08  -1.8298+08  -1.7251+08  -9.5110+07  -1.1556+08
  J/KG                 -1.3126+07  -9.2018+06  -8.6751+06  -6.1467+06  -7.4685+06
  WATT                 -9.4550+06  -1.5903+07  -1.4993+07  -1.0623+07  -1.2908+07
ENTROPY:
  J/KMOL-K             -5.4783+04  -2.3071+04  -6026.3997   3.7849+04   1.2863+04
  J/KG-K               -3040.9421  -1160.2344   -303.0606   2446.0770    831.3111
DENSITY:
  KMOL/CUM                 0.6244      0.3796      0.2389      0.1217      0.2471
  KG/CUM                  11.2492      7.5484      4.7522      1.8842      3.8246
AVG MW                    18.0150     19.8851     19.8851     15.4733     15.4733
```

Simulated capacity increase by using CO_2.

```
STREAM ID                   208C        209         209B        210         210B
FROM :                      H20-MIX2    M2102       H2110A      V2107       H2111
TO   :                      M2102       H2110A      V2107       H2111       V2108

SUBSTREAM: MIXED
PHASE:                      VAPOR       VAPOR       MIXED       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                      170.5384    170.5384    170.5384    170.5382    170.5382
  CO                       67.0124     67.0124     67.0124     67.0124     67.0124
  CO2                      37.0764     37.0764     37.0764     37.0518     37.0518
  N2                        8.4636      8.4636      8.4636      8.4636      8.4636
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                       5.9652      5.9652      5.9652      5.9651      5.9651
  C2H6                    1.1303-04   1.1303-04   1.1303-04   1.1303-04   1.1303-04
  C3H8                    5.2530-09   5.2530-09   5.2530-09   5.2530-09   5.2530-09
  C4H10                   3.3607-13   3.3607-13   3.3607-13     0.0         0.0
  C5H12                   1.4485-17   1.4485-17   1.4485-17     0.0         0.0
  C6H14                   7.1454-22   7.1454-22   7.1454-22     0.0         0.0
  MEA                     1.2575-30   1.2575-30   1.2575-30     0.0         0.0
  H2O                     231.8889    269.7185    269.7185      1.6645      1.6645
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                 520.9452    558.7748    558.7748    290.6959    290.6959
  KG/HR                  8362.8331   9044.3331   9044.3331   4214.2579   4214.2579
  CUM/SEC                   0.5839      0.5098      0.3428      0.1970      0.2027
STATE VARIABLES:
  TEMP    C               263.3128    167.7082    132.0000     40.0000     40.0000
  PRES    BAR              11.0000     11.0000     10.7000     10.7000     10.4000
  VFRAC                     1.0000      1.0000      0.7026      1.0000      1.0000
  LFRAC                     0.0         0.0         0.2973      0.0         0.0
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                -1.4319+08  -1.5260+08  -1.6591+08  -7.8193+07  -7.8193+07
  J/KG                  -8.9198+06  -9.4276+06  -1.0250+07  -5.3937+06  -5.3937+06
  WATT                  -2.0721+07  -2.3685+07  -2.5752+07  -6.3140+06  -6.3140+06
ENTROPY:
  J/KMOL-K                912.0006  -8393.1186  -4.0026+04   1.0266+04   1.0506+04
  J/KG-K                   56.8111   -518.5416  -2472.8814    708.1352    724.6790
DENSITY:
  KMOL/CUM                  0.2478      0.3044      0.4527      0.4098      0.3983
  KG/CUM                    3.9782      4.9276      7.3282      5.9412      5.7751
AVG MW                     16.0531     16.1860     16.1860     14.4971     14.4971
```

Simulated capacity increase by using CO_2.

```
STREAM ID                 211        212        213        213B       214
FROM :                    V2108      V2105      V2106      H2112      VENTTANK
TO   :                    V2105      V2116      H2112      V2109      ----

SUBSTREAM: MIXED
PHASE:                    VAPOR      MIXED      VAPOR      MIXED      MIXED
COMPONENTS: KMOL/HR
  H2                    170.5382   170.5367  1.4075-03  1.4075-03     0.0
  CO                     67.0124    67.0112  1.1254-03  1.1254-03     0.0
  CO2                    37.0518  1.1361-02    37.7641    37.7641    1.7970
  N2                      8.4636     8.4636  5.2169-05  5.2169-05  2.5219-06
  O2                      0.0        0.0        0.0        0.0        0.0
  CH4                     5.9651     5.9651  2.5065-05  2.5065-05     0.0
  C2H6                 1.1303-04  1.1303-04  1.5235-10  1.5235-10     0.0
  C3H8                 5.2530-09  5.2530-09     0.0        0.0        0.0
  C4H10                   0.0        0.0        0.0        0.0        0.0
  C5H12                   0.0        0.0        0.0        0.0        0.0
  C6H14                   0.0        0.0        0.0        0.0        0.0
  MEA                     0.0     4.7331-03  6.3647-05  6.3647-05  4.7432-05
  H2O                     1.6645     1.6962   270.8446   270.8446  7.3508-02
  AR                      0.0        0.0        0.0        0.0        0.0
TOTAL FLOW:
  KMOL/HR               290.6959   253.6892   308.6114   308.6114     1.8706
  KG/HR                4214.2579  2584.9283  6541.3056  6541.3056    80.4149
  CUM/SEC                 0.2027     0.1788     1.5941     0.1899  8.9584-03
STATE VARIABLES:
  TEMP   C               40.0000    40.0419   110.9508    40.0000    40.0000
  PRES   BAR             10.4000    10.3000     1.7000     1.5000     1.5000
  VFRAC                   1.0000     0.9999     1.0000     0.1272     1.0000
  LFRAC                   0.0     2.3858-05     0.0        0.8727  2.0498-06
  SFRAC                   0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL              -7.8193+07 -3.2192+07 -2.5768+08 -3.0040+08 -3.8730+08
  J/KG                -5.3937+06 -3.1594+06 -1.2157+07 -1.4172+07 -9.0092+06
  WATT                -6.3140+06 -2.2686+06 -2.2090+07 -2.5752+07 -2.0124+05
ENTROPY:
  J/KMOL-K             1.0506+04  1.0685+04 -3.1191+04 -1.4520+05   894.0208
  J/KG-K                724.6790  1048.6483 -1471.5545 -6850.6006    20.7965
DENSITY:
  KMOL/CUM                0.3983     0.3939  5.3776-02     0.4513  5.8003-02
  KG/CUM                  5.7751     4.0140     1.1398     9.5665     2.4934
AVG MW                   14.4971    10.1893    21.1959    21.1959    42.9889
```

Simulated capacity increase by using CO_2.

```
 STREAM ID               215          215B         216          216B         216C
 FROM :                  V2109        VENTTANK     CO-MIX       K2103-1      H2113
 TO   :                  VENTTANK     CO-MIX       K2103-1      H2113        V2113

 SUBSTREAM: MIXED
 PHASE:                  VAPOR        VAPOR        VAPOR        VAPOR        MIXED
 COMPONENTS: KMOL/HR
   H2                 1.4076-03    1.4076-03       4.2860       4.2860       4.2860
   CO                 1.1256-03    1.1256-03       8.0094       8.0094       8.0094
   CO2                  37.7378      35.9407      35.9407      35.9407      35.9407
   N2                 5.2185-05    4.9663-05       0.9671       0.9671       0.9671
   O2                   0.0          0.0          0.0          0.0          0.0
   CH4                2.6190-05    2.6190-05       5.9293       5.9293       5.9293
   C2H6               1.5235-10    1.5235-10    1.5235-10    1.5235-10    1.5235-10
   C3H8                 0.0          0.0          0.0          0.0          0.0
   C4H10                0.0          0.0          0.0          0.0          0.0
   C5H12                0.0          0.0          0.0          0.0          0.0
   C6H14                0.0          0.0          0.0          0.0          0.0
   MEA                4.7432-05      0.0          0.0          0.0          0.0
   H2O                   1.5436       1.4701       1.4701       1.4701       1.4701
   AR                   0.0          0.0          0.0          0.0          0.0
 TOTAL FLOW:
   KMOL/HR              39.2841      37.4135      56.6029      56.6029      56.6029
   KG/HR              1688.6899    1608.2749    1963.4422    1963.4422    1963.4422
   CUM/SEC               0.1881       0.1791       0.2660    5.6590-02    4.1753-02
 STATE VARIABLES:
   TEMP    C            40.0000      40.0000      33.4351     145.0000      40.0000
   PRES    BAR           1.5000       1.5000       1.5000       9.6000       9.4000
   VFRAC                 1.0000       1.0000       1.0000       1.0000       0.9807
   LFRAC                0.0          0.0          0.0          0.0        1.9302-02
   SFRAC                0.0          0.0          0.0          0.0          0.0
 ENTHALPY:
   J/KMOL            -3.8728+08   -3.8728+08   -2.7955+08   -2.7551+08   -2.8040+08
   J/KG              -9.0093+06   -9.0093+06   -8.0591+06   -7.9427+06   -8.0834+06
   WATT              -4.2261+06   -4.0249+06   -4.3955+06   -4.3319+06   -4.4087+06
 ENTROPY:
   J/KMOL-K            916.8939     917.9625    1.2255+04    8120.0928   -5391.0193
   J/KG-K               21.3297      21.3547     353.2864     234.0894    -155.4145
 DENSITY:
   KMOL/CUM           5.8003-02    5.8003-02    5.9089-02       0.2778       0.3765
   KG/CUM                2.4933       2.4933       2.0496       9.6376      13.0626
 AVG MW                 42.9865      42.9864      34.6879      34.6879      34.6879
```

Simulated capacity increase by using CO_2.

```
STREAM ID              216D         216E         216F         218          218B
FROM :                 V2113        K2103-3      H2114        V2116        K2104
TO   :                 K2103-3      H2114        V2114        K2104        H2115

SUBSTREAM: MIXED
PHASE:                 VAPOR        VAPOR        MIXED        VAPOR        VAPOR
COMPONENTS: KMOL/HR
  H2                     4.2859       4.2859       4.2859     170.5367     170.5367
  CO                     8.0093       8.0093       8.0093      67.0112      67.0112
  CO2                   35.9403      35.9403      35.9403   1.1361-02    1.1361-02
  N2                     0.9671       0.9671       0.9671       8.4636       8.4636
  O2                     0.0          0.0          0.0          0.0          0.0
  CH4                    5.9294       5.9294       5.9294       5.9651       5.9651
  C2H6                1.5236-10    1.5236-10    1.5236-10    1.1303-04    1.1303-04
  C3H8                   0.0          0.0          0.0       5.2530-09    5.2530-09
  C4H10                  0.0          0.0          0.0          0.0          0.0
  C5H12                  0.0          0.0          0.0          0.0          0.0
  C6H14                  0.0          0.0          0.0          0.0          0.0
  MEA                    0.0          0.0          0.0       4.7318-03    4.7318-03
  H2O                    0.3709       0.3709       0.3709       1.4833       1.4833
  AR                     0.0          0.0          0.0          0.0          0.0
 TOTAL FLOW:
  KMOL/HR               55.5031      55.5031      55.5031     253.4764     253.4764
  KG/HR               1943.6180    1943.6180    1943.6180    2581.0934    2581.0934
  CUM/SEC             4.0851-02    3.4504-02    2.3764-02       0.1789    8.7153-02
 STATE VARIABLES:
  TEMP   C              40.0000     145.0000      40.0000      40.0000     145.0000
  PRES   BAR             9.6000      15.4000      16.2000      10.3000      28.5000
  VFRAC                  1.0000       1.0000       0.9975       1.0000       1.0000
  LFRAC                  0.0          0.0       2.4377-03       0.0          0.0
  SFRAC                  0.0          0.0          0.0          0.0          0.0
 ENTHALPY:
  J/KMOL             -2.8026+08   -2.7633+08   -2.8054+08   -3.2018+07   -2.8928+07
  J/KG               -8.0034+06   -7.8910+06   -8.0112+06   -3.1443+06   -2.8409+06
  WATT               -4.3210+06   -4.2603+06   -4.3252+06   -2.2544+06   -2.0368+06
 ENTROPY:
  J/KMOL-K           -2405.2237    4538.4885   -7490.1506    1.0697+04    1.0658+04
  J/KG-K               -68.6850     129.6039    -213.8934    1050.5261    1046.6972
 DENSITY:
  KMOL/CUM               0.3774       0.4468       0.6487       0.3935       0.8078
  KG/CUM                13.2162      15.6471      22.7187       4.0070       8.2265
 AVG MW                 35.0181      35.0181      35.0181      10.1827      10.1827
```

Simulated capacity increase by using CO_2.

```
STREAM ID                  218C        219         220         224         224A
FROM :                     H2115       V2117       V2118       E21         K2105-1
TO   :                     V2117       V2118       E21         K2105-1     H2118

SUBSTREAM: MIXED
PHASE:                     MIXED       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                      170.5367    170.5367    169.5135   2.4996-03   2.4996-03
  CO                       67.0112     67.0112     66.6092     66.2501     66.2501
  CO2                    1.1361-02   1.1361-02     0.0         0.0         0.0
  N2                        8.4636      8.4636      8.4128      7.5964      7.5964
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                       5.9651      5.9651      5.9293   1.0916-07   1.0916-07
  C2H6                   1.1303-04   1.1303-04     0.0         0.0         0.0
  C3H8                   5.2530-09   5.2530-09     0.0         0.0         0.0
  C4H10                     0.0         0.0         0.0         0.0         0.0
  C5H12                     0.0         0.0         0.0         0.0         0.0
  C6H14                     0.0         0.0         0.0         0.0         0.0
  MEA                    4.7318-03   4.7153-03     0.0         0.0         0.0
  H2O                       1.4833      0.4329      0.0         0.0         0.0
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                 253.4764    252.4259    250.4649     73.8490     73.8490
  KG/HR                  2581.0934   2562.1681   2538.2566   2068.4694   2068.4694
  CUM/SEC                6.4229-02   6.4446-02   6.3956-02      0.2450      0.1063
STATE VARIABLES:
  TEMP    C                35.0000     35.0000     35.0000     21.4353    100.0000
  PRES    BAR              28.4000     28.3000     28.3000      2.0500      6.0000
  VFRAC                     0.9958      1.0000      1.0000      1.0000      1.0000
  LFRAC                  4.1497-03     0.0         0.0         0.0         0.0
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                -3.2365+07  -3.1300+07  -3.0918+07  -9.9352+07  -9.7060+07
  J/KG                  -3.1784+06  -3.0837+06  -3.0508+06  -3.5471+06  -3.4653+06
  WATT                  -2.2788+06  -2.1947+06  -2.1511+06  -2.0381+06  -1.9911+06
ENTROPY:
  J/KMOL-K               1089.6573   1824.0174   1855.3902   7.6998+04   7.4954+04
  J/KG-K                  107.0098    179.7029    183.0824   2748.9953   2676.0391
DENSITY:
  KMOL/CUM                  1.0962      1.0880      1.0878   8.3700-02      0.1929
  KG/CUM                   11.1627     11.0436     11.0243      2.3443      5.4029
AVG MW                     10.1827     10.1501     10.1341     28.0094     28.0094
```

Simulated capacity increase by using CO_2.

```
STREAM ID               224B        224C        224D        225         226
FROM :                  H2118       K2105-2     H2119       CO-SPLIT    CO-SPLIT
TO   :                  K2105-2     H2119       CO-SPLIT    E21         ----

SUBSTREAM: MIXED
PHASE:                  VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                  2.4996-03   2.4996-03   2.4996-03   4.0861-04   2.0910-03
  CO                    66.2501     66.2501     66.2501     10.8299     55.4202
  CO2                   0.0         0.0         0.0         0.0         0.0
  N2                     7.5964      7.5964      7.5964      1.2417      6.3546
  O2                    0.0         0.0         0.0         0.0         0.0
  CH4                 1.0916-07   1.0916-07   1.0916-07   1.7844-08   9.1314-08
  C2H6                  0.0         0.0         0.0         0.0         0.0
  C3H8                  0.0         0.0         0.0         0.0         0.0
  C4H10                 0.0         0.0         0.0         0.0         0.0
  C5H12                 0.0         0.0         0.0         0.0         0.0
  C6H14                 0.0         0.0         0.0         0.0         0.0
  MEA                   0.0         0.0         0.0         0.0         0.0
  H2O                   0.0         0.0         0.0         0.0         0.0
  AR                    0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR               73.8490     73.8490     73.8490     12.0721     61.7769
  KG/HR               2068.4694   2068.4694   2068.4694    338.1327   1730.3367
  CUM/SEC             8.9185-02   6.4769-02   5.5978-02   9.1507-03   4.6827-02
STATE VARIABLES:
  TEMP   C              30.0000     90.0000     35.0000     35.0000     35.0000
  PRES   BAR             5.8000      9.6000      9.4000      9.4000      9.4000
  VFRAC                  1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                 0.0         0.0         0.0         0.0         0.0
  SFRAC                 0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL             -9.9125+07  -9.7368+07  -9.8999+07  -9.8999+07  -9.8999+07
  J/KG               -3.5390+06  -3.4762+06  -3.5345+06  -3.5345+06  -3.5345+06
  WATT               -2.0334+06  -1.9974+06  -2.0308+06  -3.3198+05  -1.6989+06
ENTROPY:
  J/KMOL-K            6.9108+04   7.0199+04   6.5502+04   6.5502+04   6.5502+04
  J/KG-K              2467.3191   2506.2708   2338.5616   2338.5616   2338.5616
DENSITY:
  KMOL/CUM               0.2300      0.3167      0.3664      0.3664      0.3664
  KG/CUM                 6.4424      8.8711     10.2643     10.2643     10.2643
AVG MW                  28.0094     28.0094     28.0094     28.0094     28.0094
```

Simulated capacity increase by using CO_2.

```
STREAM ID                  227         228         251         251B        253
FROM :                     E21         E21         ----        H2106       ----
TO   :                     CO-MIX      B1          H2106       V2103       M2102

SUBSTREAM: MIXED
PHASE:                     VAPOR       VAPOR       LIQUID      LIQUID      LIQUID
COMPONENTS: KMOL/HR
  H2                        4.2846   165.2264     0.0         0.0         0.0
  CO                        8.0083     3.1799     0.0         0.0         0.0
  CO2                       0.0        0.0        0.0         0.0         0.0
  N2                        0.9671     1.0910     0.0         0.0         0.0
  O2                        0.0        0.0        0.0         0.0         0.0
  CH4                       5.9293     0.0        0.0         0.0         0.0
  C2H6                      0.0        0.0        0.0         0.0         0.0
  C3H8                      0.0        0.0        0.0         0.0         0.0
  C4H10                     0.0        0.0        0.0         0.0         0.0
  C5H12                     0.0        0.0        0.0         0.0         0.0
  C6H14                     0.0        0.0        0.0         0.0         0.0
  MEA                       0.0        0.0        0.0         0.0         0.0
  H2O                       0.0        0.0      343.2639    343.2639     37.8295
  AR                        0.0        0.0        0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                  19.1894   169.4974   343.2639    343.2639     37.8295
  KG/HR                   355.1672   452.7304  6183.9000   6183.9000    681.5000
  CUM/SEC                6.6232-02     0.3215  2.4282-03   2.6602-03   2.6760-04
STATE VARIABLES:
  TEMP   C                 18.3697    13.7301   104.0000    180.0000    104.0000
  PRES   BAR                1.9500     3.5000    27.0000     26.8000     27.0000
  VFRAC                     1.0000     1.0000     0.0         0.0         0.0
  LFRAC                     0.0        0.0        1.0000      1.0000      1.0000
  SFRAC                     0.0        0.0        0.0         0.0         0.0
ENTHALPY:
  J/KMOL               -6.9526+07 -2.3930+06 -2.8210+08 -2.7526+08 -2.8210+08
  J/KG                 -3.7564+06 -8.9590+05 -1.5659+07 -1.5279+07 -1.5659+07
  WATT                 -3.7060+05 -1.1267+05 -2.6899+07 -2.6246+07 -2.9644+06
ENTROPY:
  J/KMOL-K              1.6443+04 -8630.1778 -1.5042+05 -1.3390+05 -1.5042+05
  J/KG-K                 888.4260 -3231.0463 -8349.6409 -7432.5015 -8349.6409
DENSITY:
  KMOL/CUM              8.0481-02     0.1464    39.2685     35.8435     39.2685
  KG/CUM                   1.4895     0.3910   707.4237    645.7212    707.4237
AVG MW                    18.5085     2.6710    18.0150     18.0150     18.0150
```

Simulated capacity increase by using CO_2.

```
STREAM ID                    260        264        265        266        268
FROM :                       ----       V2107      V2108      COND-MIX   V2113
TO   :                       H20-MIX2   COND-MIX   COND-MIX   ----       CONDMIX2

SUBSTREAM: MIXED
PHASE:                       VAPOR       LIQUID    MIXED       LIQUID     LIQUID
COMPONENTS: KMOL/HR
  H2                          0.0      2.1804-04   0.0      2.1804-04  1.0852-07
  CO                          0.0      5.1676-05   0.0      5.1676-05  1.2097-07
  CO2                         0.0      2.4515-02   0.0      2.4515-02  4.5265-04
  N2                          0.0      6.0036-06   0.0      6.0036-06  1.3453-08
  O2                          0.0        0.0       0.0        0.0        0.0
  CH4                         0.0      4.8563-05   0.0      4.8563-05  9.3388-07
  C2H6                        0.0      1.3738-09   0.0      1.3738-09    0.0
  C3H8                        0.0        0.0       0.0        0.0        0.0
  C4H10                       0.0        0.0       0.0        0.0        0.0
  C5H12                       0.0        0.0       0.0        0.0        0.0
  C6H14                       0.0        0.0       0.0        0.0        0.0
  MEA                         0.0        0.0       0.0        0.0        0.0
  H2O                       118.8454   268.0540    0.0      268.0540     1.0992
  AR                          0.0        0.0       0.0        0.0        0.0
TOTAL FLOW:
  KMOL/HR                   118.8454   268.0788    0.0      268.0788     1.0996
  KG/HR                    2141.0000  4830.0751    0.0     4830.0751    19.8221
  CUM/SEC                  6.6487-02  1.7962-03    0.0     1.7966-03  7.3693-06
STATE VARIABLES:
  TEMP   C                  208.0000    40.0000   MISSING    40.1538    40.0000
  PRES   BAR                 18.3000    10.7000   10.4000     3.5000     9.6000
  VFRAC                       1.0000     0.0      MISSING     0.0        0.0
  LFRAC                       0.0        1.0000   MISSING     1.0000     1.0000
  SFRAC                       0.0        0.0      MISSING     0.0        0.0
ENTHALPY:
  J/KMOL                 -2.3667+08 -2.8771+08   MISSING -2.8771+08 -2.8774+08
  J/KG                   -1.3137+07 -1.5968+07   MISSING -1.5968+07 -1.5963+07
  WATT                   -7.8130+06 -2.1424+07   MISSING -2.1424+07 -8.7893+04
ENTROPY:
  J/KMOL-K               -5.3384+04 -1.6654+05   MISSING -1.6648+05 -1.6648+05
  J/KG-K                 -2963.3323 -9243.0553   MISSING -9239.9762 -9235.5276
DENSITY:
  KMOL/CUM                   0.4965    41.4588   MISSING    41.4488    41.4502
  KG/CUM                     8.9449   746.9784   MISSING   746.7996   747.1700
AVG MW                      18.0150    18.0173   MISSING    18.0173    18.0257
```

Simulated capacity increase by using CO_2.

```
STREAM ID                   269         270         281         281A        281B
FROM :                      V2114       V2117       ----        H2108       H2109A
TO   :                      CONDMIX2    ----        V2105       ----        H2108

SUBSTREAM: MIXED
PHASE:                      LIQUID      LIQUID      LIQUID      LIQUID      LIQUID
COMPONENTS: KMOL/HR
  H2                      2.3003-08   2.0866-06     0.0         0.0         0.0
  CO                      2.5254-08   4.9521-07     0.0         0.0         0.0
  CO2                     9.1194-05   8.3660-08    11.2110     10.5143     10.5143
  N2                      2.8128-09   5.7450-08     0.0         0.0         0.0
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                     1.9193-07   4.7975-07     0.0         0.0         0.0
  C2H6                      0.0       1.3018-11     0.0         0.0         0.0
  C3H8                      0.0         0.0         0.0         0.0         0.0
  C4H10                     0.0         0.0         0.0         0.0         0.0
  C5H12                     0.0         0.0         0.0         0.0         0.0
  C6H14                     0.0         0.0         0.0         0.0         0.0
  MEA                       0.0       1.6526-05   101.9269    101.9222    101.9222
  H2O                       0.1352      1.0504    906.9775    906.6546    906.6546
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                   0.1353      1.0504   1020.1155   1019.0911   1019.0911
  KG/HR                     2.4398     18.9252   2.3058+04   2.3022+04   2.3022+04
  CUM/SEC                 9.0675-07   7.0106-06   7.0614-03   9.4647-03   9.9099-03
STATE VARIABLES:
  TEMP   C                 40.0000     35.0000     40.0000     40.0000     88.0000
  PRES    BAR              16.2000     28.3000     14.7000     14.7000      1.7000
  VFRAC                     0.0         0.0         0.0         0.0         0.0
  LFRAC                     1.0000      1.0000      1.0000      1.0000      1.0000
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                 -2.8775+08  -2.8810+08  -2.8449+08  -2.8373+08  -2.7906+08
  J/KG                   -1.5958+07  -1.5991+07  -1.2586+07  -1.2560+07  -1.2353+07
  WATT                   -1.0815+04  -8.4067+04  -8.0614+07  -8.0318+07  -7.8996+07
ENTROPY:
  J/KMOL-K               -1.6644+05  -1.6799+05  -2.4699+05  -2.2431+05  -2.1030+05
  J/KG-K                 -9230.2033  -9324.4639  -1.0927+04  -9929.6771  -9309.5128
DENSITY:
  KMOL/CUM                 41.4486     41.6232     40.1289     29.9089     28.5655
  KG/CUM                  747.4236    749.8700    907.0602    675.6515    645.3032
AVG MW                     18.0325     18.0156     22.6036     22.5902     22.5902
```

Simulated capacity increase by using CO_2.

```
STREAM ID                 281C         282          282B         284          285
FROM :                    V2106        V2105        H2109B       CONDMIX2     V2109
TO   :                    H2109A       H2109B       V2106        V2109        V2106

SUBSTREAM: MIXED
PHASE:                    LIQUID       LIQUID       MIXED        LIQUID       LIQUID
COMPONENTS: KMOL/HR
  H2                       0.0         1.4075-03    1.4075-03    1.3152-07    1.8998-09
  CO                       0.0         1.1254-03    1.1254-03    1.4622-07    9.2232-10
  CO2                     10.5143       48.2516      48.2516     5.4384-04    2.6856-02
  N2                       0.0         5.2169-05    5.2169-05    1.6266-08    3.9310-11
  O2                       0.0           0.0          0.0          0.0          0.0
  CH4                      0.0         2.5065-05    2.5065-05    1.1258-06    2.2784-10
  C2H6                     0.0         1.5235-10    1.5235-10      0.0          0.0
  C3H8                     0.0         1.2490-15    1.2490-15      0.0          0.0
  C4H10                    0.0           0.0          0.0          0.0          0.0
  C5H12                    0.0           0.0          0.0          0.0          0.0
  C6H14                    0.0           0.0          0.0          0.0          0.0
  MEA                    101.9222     101.9222     101.9222        0.0        1.6215-05
  H2O                    906.6546     906.9458     906.9458       1.2344      270.5353
  AR                       0.0           0.0          0.0          0.0          0.0
 TOTAL FLOW:
  KMOL/HR               1019.0911    1057.1222    1057.1222       1.2349      270.5622
  KG/HR                 2.3022+04    2.4688+04    2.4688+04      22.2619     4874.8776
  CUM/SEC               7.7557-03    7.7228-03    4.9501-02    8.2785-06    1.8131-03
 STATE VARIABLES:
  TEMP   C               118.0284      68.5646     104.0000      40.1884      40.0000
  PRES   BAR               1.7000      10.4000      10.4000       1.5000       1.5000
  VFRAC                    0.0          0.0       4.6068-02      0.0          0.0
  LFRAC                    1.0000       1.0000       0.9539       1.0000       1.0000
  SFRAC                    0.0          0.0          0.0          0.0          0.0
 ENTHALPY:
  J/KMOL               -2.7784+08   -2.8830+08   -2.8124+08   -2.8774+08   -2.8772+08
  J/KG                 -1.2299+07   -1.2345+07   -1.2043+07   -1.5962+07   -1.5969+07
  WATT                 -7.8651+07   -8.4659+07   -8.2584+07   -9.8708+04   -2.1624+07
 ENTROPY:
  J/KMOL-K             -2.0053+05   -2.2528+05   -1.9819+05   -1.6641+05   -1.6652+05
  J/KG-K               -8876.6332   -9646.6502   -8486.3451   -9231.1693   -9241.9675
 DENSITY:
  KMOL/CUM                36.4995      38.0232       5.9320      41.4379      41.4520
  KG/CUM                 824.5345     887.9808     138.5349     746.9783     746.8649
 AVG MW                   22.5902      23.3536      23.3536      18.0264      18.0175
```

Simulated capacity increase by using CO_2.

```
STREAM ID                  3          4          5          6          7
FROM :                     H2103      H2104      H2105A     H2105B     H2106
TO   :                     H2104      H2105A     H2105B     H2106      ----

SUBSTREAM: MIXED
PHASE:                     VAPOR      VAPOR      VAPOR      VAPOR      VAPOR
COMPONENTS: KMOL/HR
  H2                    3.8182-05  3.8182-05  3.8182-05  3.8182-05  3.8182-05
  CO                    1.2933-06  1.2933-06  1.2933-06  1.2933-06  1.2933-06
  CO2                      2.3955     2.3955     2.3955     2.3955     2.3955
  N2                     268.2040   268.2040   268.2040   268.2040   268.2040
  O2                       9.5373     9.5373     9.5373     9.5373     9.5373
  CH4                   8.0301-31  8.0301-31  8.0301-31  8.0301-31  8.0301-31
  C2H6                    0.0        0.0        0.0        0.0        0.0
  C3H8                    0.0        0.0        0.0        0.0        0.0
  C4H10                   0.0        0.0        0.0        0.0        0.0
  C5H12                   0.0        0.0        0.0        0.0        0.0
  C6H14                   0.0        0.0        0.0        0.0        0.0
  MEA                     0.0        0.0        0.0        0.0        0.0
  H2O                    125.3970   125.3970   125.3970   125.3970   125.3970
  AR                       3.2116     3.2116     3.2116     3.2116     3.2116
TOTAL FLOW:
  KMOL/HR                408.7456   408.7456   408.7456   408.7456   408.7456
  KG/HR                 1.0311+04  1.0311+04  1.0311+04  1.0311+04  1.0311+04
  CUM/SEC                  6.2891     5.5467     4.7415     3.7050     2.5517
STATE VARIABLES:
  TEMP    C              725.7996   607.8656   480.0039   315.4778   132.7314
  PRES    BAR              1.5000     1.5000     1.5000     1.5000     1.5000
  VFRAC                    1.0000     1.0000     1.0000     1.0000     1.0000
  LFRAC                   0.0        0.0        0.0        0.0        0.0
  SFRAC                   0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL               -5.3673+07 -5.7795+07 -6.2134+07 -6.7514+07 -7.3263+07
  J/KG                 -2.1276+06 -2.2911+06 -2.4631+06 -2.6763+06 -2.9042+06
  WATT                 -6.0940+06 -6.5621+06 -7.0547+06 -7.6656+06 -8.3183+06
ENTROPY:
  J/KMOL-K              2.8617+04  2.4227+04  1.8908+04  1.0855+04  -827.4121
  J/KG-K                1134.4139   960.3928   749.5480   430.3124   -32.7995
DENSITY:
  KMOL/CUM              1.8053-02  2.0470-02  2.3946-02  3.0645-02  4.4496-02
  KG/CUM                   0.4554     0.5163     0.6040     0.7730     1.1224
AVG MW                    25.2263    25.2263    25.2263    25.2263    25.2263
```

Simulated capacity increase by using CO_2.

```
STREAM ID               A           B           BIN         C           D
FROM :                  SPLIT       H2102       ----        SPLIT       H2105A
TO   :                  H2102       DRUMMIX     BURNER      H2105A      DRUMMIX

SUBSTREAM: MIXED
PHASE:                  LIQUID      MIXED       VAPOR       LIQUID      MIXED
COMPONENTS: KMOL/HR
  H2                     0.0         0.0        125.3472     0.0         0.0
  CO                     0.0         0.0          2.3705     0.0         0.0
  CO2                    0.0         0.0          0.0        0.0         0.0
  N2                     0.0         0.0        268.2040     0.0         0.0
  O2                     0.0         0.0         73.4460     0.0         0.0
  CH4                    0.0         0.0        2.4933-02    0.0         0.0
  C2H6                   0.0         0.0          0.0        0.0         0.0
  C3H8                   0.0         0.0          0.0        0.0         0.0
  C4H10                  0.0         0.0          0.0        0.0         0.0
  C5H12                  0.0         0.0          0.0        0.0         0.0
  C6H14                  0.0         0.0          0.0        0.0         0.0
  MEA                    0.0         0.0          0.0        0.0         0.0
  H2O                  513.0561    513.0561       0.0     1061.1022   1061.1022
  AR                     0.0         0.0          3.2116     0.0         0.0
TOTAL FLOW:
  KMOL/HR              513.0561    513.0561     472.6045  1061.1022   1061.1022
  KG/HR               9242.7065   9242.7065    1.0311+04  1.9116+04   1.9116+04
  CUM/SEC             4.2628-03   1.4631-02      1.7101   8.8163-03   3.0260-02
STATE VARIABLES:
  TEMP    C            221.0000    221.0000      40.0000   221.0000    221.0000
  PRES    BAR           24.0094     24.0094       2.0000    24.0094     24.0094
  VFRAC                  0.0      4.8000-02       1.0000     0.0      4.8000-02
  LFRAC                  1.0000      0.9520       0.0        1.0000      0.9520
  SFRAC                  0.0         0.0          0.0        0.0         0.0
ENTHALPY:
  J/KMOL           -2.7130+08 -2.6962+08 -1.3077+05 -2.7130+08 -2.6962+08
  J/KG             -1.5059+07 -1.4967+07 -5993.7285 -1.5059+07 -1.4967+07
  WATT             -3.8664+07 -3.8426+07 -1.7167+04 -7.9965+07 -7.9472+07
ENTROPY:
  J/KMOL-K         -1.2552+05 -1.2213+05  4700.4527 -1.2552+05 -1.2213+05
  J/KG-K           -6967.2642 -6779.5164   215.4409 -6967.2642 -6779.5164
DENSITY:
  KMOL/CUM              33.4325      9.7406   7.6766-02    33.4325      9.7406
  KG/CUM               602.2870    175.4783      1.6748   602.2870    175.4783
AVG MW                  18.0150     18.0150     21.8178    18.0150     18.0150
```

Simulated capacity increase by using CO_2.

```
STREAM ID                E            F            G            H            L10
FROM :                   SPLIT        H2105B       SPLIT        H2107        V31
TO   :                   H2105B       DRUMMIX      H2107        DRUMMIX      MIX2

SUBSTREAM: MIXED
PHASE:                   LIQUID       MIXED        LIQUID       MIXED        VAPOR
COMPONENTS: KMOL/HR
  H2                     0.0          0.0          0.0          0.0          1.4513
  CO                     0.0          0.0          0.0          0.0          1.6665
  CO2                    0.0          0.0          0.0          0.0          0.0
  N2                     0.0          0.0          0.0          0.0          0.3796
  O2                     0.0          0.0          0.0          0.0          0.0
  CH4                    0.0          0.0          0.0          0.0          2.5452-18
  C2H6                   0.0          0.0          0.0          0.0          0.0
  C3H8                   0.0          0.0          0.0          0.0          0.0
  C4H10                  0.0          0.0          0.0          0.0          0.0
  C5H12                  0.0          0.0          0.0          0.0          0.0
  C6H14                  0.0          0.0          0.0          0.0          0.0
  MEA                    0.0          0.0          0.0          0.0          0.0
  H2O                 1315.6387    1315.6387    4920.4654    4920.4654       0.0
  AR                     0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR             1315.6387    1315.6387    4920.4654    4920.4654       3.4975
  KG/HR               2.3701+04    2.3701+04    8.8642+04    8.8642+04      60.2423
  CUM/SEC             1.0931-02    3.7518-02    4.0882-02       0.1403    3.0713-03
STATE VARIABLES:
  TEMP    C            221.0000     221.0000     221.0000     221.0000    -182.8828
  PRES    BAR           24.0094      24.0094      24.0094      24.0094       2.3000
  VFRAC                  0.0       4.8000-02       0.0       4.8000-02      1.0000
  LFRAC                  1.0000       0.9520       1.0000       0.9520       0.0
  SFRAC                  0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL             -2.7130+08   -2.6962+08   -2.7130+08   -2.6962+08   -5.8607+07
  J/KG               -1.5059+07   -1.4967+07   -1.5059+07   -1.4967+07   -3.4026+06
  WATT               -9.9147+07   -9.8536+07   -3.7081+08   -3.6852+08   -5.6940+04
ENTROPY:
  J/KMOL-K           -1.2552+05   -1.2213+05   -1.2552+05   -1.2213+05    1.0236+04
  J/KG-K             -6967.2642   -6779.5164   -6967.2642   -6779.5158     594.2923
DENSITY:
  KMOL/CUM              33.4325       9.7406      33.4325       9.7406       0.3163
  KG/CUM               602.2870     175.4783     602.2870     175.4783       5.4485
AVG MW                  18.0150      18.0150      18.0150      18.0150      17.2240
```

Simulated capacity increase by using CO_2.

```
STREAM ID               L11          L13          L2           L22          L28
FROM :                  T24          V47          E21          E23A         V6
TO   :                  T22MIX       MIX2         E22          E21          T23

SUBSTREAM: MIXED
PHASE:                  LIQUID       MIXED        VAPOR        VAPOR        MIXED
COMPONENTS: KMOL/HR
  H2                 4.0934-04    2.5451-15     169.5135     165.2264       2.8351
  CO                   21.1709       2.0282      66.6092       3.1799      43.8190
  CO2                  0.0          0.0          0.0          0.0          0.0
  N2                    3.2435    3.1783-02       8.4128       1.0910       4.0686
  O2                   0.0          0.0          0.0          0.0          0.0
  CH4                5.3175-09       5.8788       5.9293       0.0          5.9293
  C2H6                 0.0          0.0          0.0          0.0          0.0
  C3H8                 0.0          0.0          0.0          0.0          0.0
  C4H10                0.0          0.0          0.0          0.0          0.0
  C5H12                0.0          0.0          0.0          0.0          0.0
  C6H14                0.0          0.0          0.0          0.0          0.0
  MEA                  0.0          0.0          0.0          0.0          0.0
  H2O                  0.0          0.0          0.0          0.0          0.0
  AR                   0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR              24.4149       7.9388     250.4649     169.4974      56.6521
  KG/HR               683.8605     152.0155    2538.2566     452.7304    1442.1882
  CUM/SEC            2.8736-04    1.2453-04    2.1890-02    9.7081-02    3.8080-03
STATE VARIABLES:
  TEMP    C          -169.2201    -170.9661    -157.6000    -176.1000    -177.0264
  PRES    BAR           7.6000       2.1500      28.1000       3.9000       5.4700
  VFRAC                0.0        5.2010-03       1.0000       1.0000       0.1566
  LFRAC                 1.0000       0.9948      0.0          0.0           0.8433
  SFRAC                0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL            -1.0687+08   -9.7950+07   -3.6570+07   -7.4679+06   -1.0445+08
  J/KG              -3.8156+06   -5.1153+06   -3.6085+06   -2.7959+06   -4.1029+06
  WATT              -7.2481+05   -2.1600+05   -2.5443+06   -3.5161+05   -1.6437+06
ENTROPY:
  J/KMOL-K          -1.6003+04   -1.4198+05   -2.6884+04   -3.7971+04   -2.8932+04
  J/KG-K             -571.3501   -7414.9639   -2652.8225   -1.4216+04   -1136.5184
DENSITY:
  KMOL/CUM             23.6009      17.7077       3.1782       0.4849       4.1325
  KG/CUM              661.0611     339.0736      32.2092       1.2954     105.2017
AVG MW                 28.0099      19.1482      10.1341       2.6710      25.4568
```

Simulated capacity increase by using CO_2.

```
STREAM ID                 L29          L3           L30          L31          L33
FROM :                    T23          E22          V9           T24          V8
TO   :                    V29          T21          T24          V31          T22

SUBSTREAM: MIXED
PHASE:                    VAPOR        MIXED        MIXED        VAPOR        MIXED
COMPONENTS: KMOL/HR
  H2                        2.8332     169.5135       1.4516       1.4513   1.8036-03
  CO                        4.3134      66.6092      19.6102       1.6665      39.5056
  CO2                       0.0          0.0          0.0          0.0          0.0
  N2                        0.5556       8.4128       3.2531       0.3796       3.5129
  O2                        0.0          0.0          0.0          0.0          0.0
  CH4                     5.0512-02      5.9293       0.0        2.5452-18      5.8788
  C2H6                      0.0          0.0          0.0          0.0          0.0
  C3H8                      0.0          0.0          0.0          0.0          0.0
  C4H10                     0.0          0.0          0.0          0.0          0.0
  C5H12                     0.0          0.0          0.0          0.0          0.0
  C6H14                     0.0          0.0          0.0          0.0          0.0
  MEA                       0.0          0.0          0.0          0.0          0.0
  H2O                       0.0          0.0          0.0          0.0          0.0
  AR                        0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR                   7.7529     250.4649      24.3149       3.4975      48.8992
  KG/HR                   142.9094    2538.2566     643.3393      60.2423    1299.2787
  CUM/SEC                 2.8999-03    2.0072-02    1.0574-03    9.2342-04    4.8931-03
STATE VARIABLES:
  TEMP   C               -178.6051    -164.8000    -176.6117    -177.5456    -181.9861
  PRES   BAR                5.4000      28.0000       7.8500       7.6000       2.3830
  VFRAC                     1.0000       0.9967       0.1325       1.0000       0.1106
  LFRAC                     0.0        3.2713-03      0.8674       0.0          0.8894
  SFRAC                     0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL                -6.7947+07   -3.6808+07   -9.9871+07   -5.8608+07   -1.1007+08
  J/KG                  -3.6862+06   -3.6320+06   -3.7746+06   -3.4027+06   -4.1426+06
  WATT                  -1.4633+05   -2.5608+06   -6.7455+05   -5.6940+04   -1.4951+06
ENTROPY:
  J/KMOL-K               9766.8538   -2.8989+04   -1.8197+04     852.7922   -3.2996+04
  J/KG-K                  529.8614   -2860.4830    -687.7553      49.5117   -1241.8411
DENSITY:
  KMOL/CUM                  0.7426       3.4662       6.3874       1.0521       2.7759
  KG/CUM                   13.6892      35.1278     169.0016      18.1217      73.7585
AVG MW                     18.4328      10.1341      26.4585      17.2240      26.5705
```

Simulated capacity increase by using CO_2.

```
STREAM ID                 L35          L36          L37          L38          L39
FROM :                    E21          SPLIT1       E22B         SPLIT1       SPLIT1
TO   :                    SPLIT1       E22B         V37          E24          V39

SUBSTREAM: MIXED
PHASE:                    VAPOR        VAPOR        VAPOR        VAPOR        VAPOR
COMPONENTS: KMOL/HR
  H2                    4.0861-04    6.3744-05    6.3744-05    2.2310-04    1.2177-04
  CO                      10.8299       1.6894       1.6894       5.9131       3.2273
  CO2                     0.0          0.0          0.0          0.0          0.0
  N2                      1.2417       0.1937       0.1937       0.6780       0.3700
  O2                      0.0          0.0          0.0          0.0          0.0
  CH4                   1.7844-08    2.7837-09    2.7837-09    9.7428-09    5.3175-09
  C2H6                    0.0          0.0          0.0          0.0          0.0
  C3H8                    0.0          0.0          0.0          0.0          0.0
  C4H10                   0.0          0.0          0.0          0.0          0.0
  C5H12                   0.0          0.0          0.0          0.0          0.0
  C6H14                   0.0          0.0          0.0          0.0          0.0
  MEA                     0.0          0.0          0.0          0.0          0.0
  H2O                     0.0          0.0          0.0          0.0          0.0
  AR                      0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR                 12.0721       1.8832       1.8832       6.5913       3.5974
  KG/HR                  338.1327      52.7487      52.7487     184.6204     100.7635
  CUM/SEC               3.0805-03    4.8055-04    4.5005-04    1.6819-03    9.1798-04
STATE VARIABLES:
  TEMP   C             -155.1000    -155.1000    -160.8000    -155.1000    -155.1000
  PRES   BAR                9.2000       9.2000       9.1000       9.2000       9.2000
  VFRAC                     1.0000       1.0000       1.0000       1.0000       1.0000
  LFRAC                     0.0          0.0          0.0          0.0          0.0
  SFRAC                     0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL               -1.0487+08   -1.0487+08   -1.0508+08   -1.0487+08   -1.0487+08
  J/KG                 -3.7442+06   -3.7442+06   -3.7514+06   -3.7442+06   -3.7442+06
  WATT                 -3.5168+05   -5.4862+04   -5.4967+04   -1.9202+05   -1.0480+05
ENTROPY:
  J/KMOL-K              3.5689+04    3.5689+04    3.4018+04    3.5689+04    3.5689+04
  J/KG-K                1274.1718    1274.1718    1214.5273    1274.1718    1274.1718
DENSITY:
  KMOL/CUM                  1.0885       1.0885       1.1623       1.0885       1.0885
  KG/CUM                   30.4907      30.4907      32.5573      30.4907      30.4907
AVG MW                     28.0094      28.0094      28.0094      28.0094      28.0094
```

Simulated capacity increase by using CO_2.

```
STREAM ID                 L4          L40         L41         L42         L43
FROM :                    CO2         V39         E24         V41         V37
TO   :                    E23A        T24         V41         T22MIX      T22MIX

SUBSTREAM: MIXED
PHASE:                    VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                    165.2264   1.2177-04   2.2310-04   2.2310-04   6.3744-05
  CO                      3.1799      3.2273      5.9131      5.9131      1.6894
  CO2                     0.0         0.0         0.0         0.0         0.0
  N2                      1.0910      0.3700      0.6780      0.6780      0.1937
  O2                      0.0         0.0         0.0         0.0         0.0
  CH4                     0.0      5.3175-09   9.7428-09   9.7428-09   2.7837-09
  C2H6                    0.0         0.0         0.0         0.0         0.0
  C3H8                    0.0         0.0         0.0         0.0         0.0
  C4H10                   0.0         0.0         0.0         0.0         0.0
  C5H12                   0.0         0.0         0.0         0.0         0.0
  C6H14                   0.0         0.0         0.0         0.0         0.0
  MEA                     0.0         0.0         0.0         0.0         0.0
  H2O                     0.0         0.0         0.0         0.0         0.0
  AR                      0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR               169.4974      3.5974      6.5913      6.5913      1.8832
  KG/HR                 452.7304    100.7635    184.6204    184.6204     52.7487
  CUM/SEC              9.4768-03   1.0652-03   1.6482-03   6.1241-03   1.6779-03
STATE VARIABLES:
  TEMP    C            -201.5000   -156.8294   -157.6000   -167.5142   -171.2942
  PRES    BAR            27.3000      7.9500      9.1000      2.5000      2.5000
  VFRAC                   1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                   0.0         0.0         0.0         0.0         0.0
  SFRAC                   0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL              -8.2245+06 -1.0487+08 -1.0496+08 -1.0496+08 -1.0508+08
  J/KG                -3.0792+06 -3.7442+06 -3.7473+06 -3.7473+06 -3.7514+06
  WATT                -3.8723+05 -1.0480+05 -1.9217+05 -1.9217+05 -5.4967+04
ENTROPY:
  J/KMOL-K            -6.2901+04  3.6747+04   3.5043+04   4.4817+04   4.3692+04
  J/KG-K              -2.3549+04  1311.9515   1251.1048   1600.0856   1559.9079
DENSITY:
  KMOL/CUM                4.9682      0.9381      1.1108      0.2989      0.3117
  KG/CUM                 13.2701     26.2757     31.1154      8.3739      8.7328
AVG MW                    2.6710     28.0094     28.0094     28.0094     28.0094
```

Simulated capacity increase by using CO_2.

```
STREAM ID                L44        L46        L47        L48        L49
FROM :                   T22MIX     E25-27     T22        MIX2       T22
TO   :                   E25-27     T22        V47        E21        E21

SUBSTREAM: MIXED
PHASE:                   MIXED      LIQUID     LIQUID     MIXED      VAPOR
COMPONENTS: KMOL/HR
  H2                  6.9619-04  6.9619-04  2.5451-15     4.2846  2.4996-03
  CO                    28.7735    28.7735     2.0282     8.0083    66.2501
  CO2                    0.0        0.0        0.0        0.0        0.0
  N2                     4.1152     4.1152  3.1783-02     0.9671     7.5964
  O2                     0.0        0.0        0.0        0.0        0.0
  CH4                 1.7844-08  1.7844-08     5.8788     5.9293  1.0916-07
  C2H6                   0.0        0.0        0.0        0.0        0.0
  C3H8                   0.0        0.0        0.0        0.0        0.0
  C4H10                  0.0        0.0        0.0        0.0        0.0
  C5H12                  0.0        0.0        0.0        0.0        0.0
  C6H14                  0.0        0.0        0.0        0.0        0.0
  MEA                    0.0        0.0        0.0        0.0        0.0
  H2O                    0.0        0.0        0.0        0.0        0.0
  AR                     0.0        0.0        0.0        0.0        0.0
TOTAL FLOW:
  KMOL/HR               32.8895    32.8895     7.9388    19.1894    73.8490
  KG/HR                921.2297   921.2297   152.0155   355.1672  2068.4694
  CUM/SEC             1.0336-02  3.3895-04  8.2147-05  1.1266-02  6.2846-02
STATE VARIABLES:
  TEMP   C             -183.1202  -184.5000  -170.4541  -179.5302  -184.0646
  PRES   BAR              2.5000     2.3250     2.2500     2.1500     2.2500
  VFRAC                   0.4003     0.0        0.0        0.5982     1.0000
  LFRAC                   0.5996     1.0000     1.0000     0.4017     0.0
  SFRAC                   0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL             -1.0639+08 -1.0874+08 -9.7950+07 -7.8657+07 -1.0546+08
  J/KG               -3.7982+06 -3.8821+06 -5.1154+06 -4.2498+06 -3.7651+06
  WATT               -9.7195+05 -9.9341+05 -2.1600+05 -4.1927+05 -2.1634+06
ENTROPY:
  J/KMOL-K             438.0986 -2.5661+04 -1.4199+05 -4.9479+04  4.0485+04
  J/KG-K                15.6408  -916.1387 -7415.3313 -2673.3087  1445.4213
DENSITY:
  KMOL/CUM               0.8839    26.9535    26.8451     0.4731     0.3264
  KG/CUM                24.7581   754.9654   514.0389     8.7567     9.1425
AVG MW                  28.0098    28.0098    19.1482    18.5085    28.0094
```

Simulated capacity increase by using CO_2.

```
STREAM ID               L6          L7          L8          L9          LB
FROM :                  T21         V29         T23         SPLIT2      T21
TO   :                  V6          MIX2        V8          V9          MIX1

SUBSTREAM: MIXED
PHASE:                  LIQUID      VAPOR       LIQUID      LIQUID      VAPOR
COMPONENTS: KMOL/HR
  H2                      2.8351      2.8332  1.8036-03     1.4516    170.8884
  CO                     43.8190      4.3134    39.5056    19.6102     79.6631
  CO2                     0.0         0.0        0.0        0.0         0.0
  N2                      4.0686      0.5556     3.5129     3.2531     13.7788
  O2                      0.0         0.0        0.0        0.0         0.0
  CH4                     5.9293  5.0512-02      5.8788     0.0     6.0613-13
  C2H6                    0.0         0.0        0.0        0.0         0.0
  C3H8                    0.0         0.0        0.0        0.0         0.0
  C4H10                   0.0         0.0        0.0        0.0         0.0
  C5H12                   0.0         0.0        0.0        0.0         0.0
  C6H14                   0.0         0.0        0.0        0.0         0.0
  MEA                     0.0         0.0        0.0        0.0         0.0
  H2O                     0.0         0.0        0.0        0.0         0.0
  AR                      0.0         0.0        0.0        0.0         0.0
TOTAL FLOW:
  KMOL/HR                56.6521      7.7529    48.8992    24.3149    264.3303
  KG/HR                1442.1882    142.9094  1299.2787   643.3393   2961.8613
  CUM/SEC              6.4231-04   6.8485-03  5.4112-04  2.7941-04   1.9874-02
STATE VARIABLES:
  TEMP    C            -169.0234   -182.0469  -172.0224  -171.5000   -170.7580
  PRES    BAR            27.3000      2.3000     5.4000    27.3470     27.3000
  VFRAC                   0.0         1.0000     0.0        0.0         1.0000
  LFRAC                   1.0000      0.0        1.0000     1.0000      0.0
  SFRAC                   0.0         0.0        0.0        0.0         0.0
ENTHALPY:
  J/KMOL             -1.0445+08 -6.7946+07 -1.1007+08 -9.9871+07 -3.9135+07
  J/KG               -4.1029+06 -3.6862+06 -4.1426+06 -3.7746+06 -3.4926+06
  WATT               -1.6437+06 -1.4633+05 -1.4951+06 -6.7455+05 -2.8735+06
ENTROPY:
  J/KMOL-K           -3.0682+04  1.6499+04 -3.3479+04 -1.9585+04 -2.5598+04
  J/KG-K             -1205.2466   895.1133 -1260.0177  -740.2158 -2284.4901
DENSITY:
  KMOL/CUM               24.5003      0.3144    25.1016    24.1733      3.6945
  KG/CUM                623.7030      5.7964   666.9655   639.5910     41.3977
AVG MW                   25.4568     18.4328    26.5705    26.4585     11.2051
```

Simulated capacity increase by using CO_2.

```
STREAM ID              LC          LD          LE          LF          LG
FROM :                 CO1         CO1         CO2         MIX1        SPLIT2
TO   :                 CO2         SPLIT2      MIX1        CO1         T21

SUBSTREAM: MIXED
PHASE:                 VAPOR       LIQUID      LIQUID      MIXED       LIQUID
COMPONENTS: KMOL/HR
  H2                  169.3174      5.6615      4.0906    174.9790      4.2099
  CO                   71.9319     76.4829     68.7517    148.4148     56.8727
  CO2                   0.0         0.0         0.0         0.0         0.0
  N2                   15.4632     12.6877     14.3722     28.1510      9.4346
  O2                    0.0         0.0         0.0         0.0         0.0
  CH4                   0.0         0.0         0.0      6.0613-13      0.0
  C2H6                  0.0         0.0         0.0         0.0         0.0
  C3H8                  0.0         0.0         0.0         0.0         0.0
  C4H10                 0.0         0.0         0.0         0.0         0.0
  C5H12                 0.0         0.0         0.0         0.0         0.0
  C6H14                 0.0         0.0         0.0         0.0         0.0
  MEA                   0.0         0.0         0.0         0.0         0.0
  H2O                   0.0         0.0         0.0         0.0         0.0
  AR                    0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR             256.7126     94.8322     87.2145    351.5449     70.5172
  KG/HR              2789.3300   2509.1236   2336.5923   5298.4536   1865.7843
  CUM/SEC            1.9209-02   1.0897-03   8.0462-04   1.8751-02   8.1032-04
STATE VARIABLES:
  TEMP   C           -171.5000   -171.5000   -201.5000   -174.3183   -171.5000
  PRES   BAR           27.3470     27.3470     27.3000     27.3000     27.3470
  VFRAC                 1.0000      0.0         0.0         0.6687      0.0
  LFRAC                 0.0         1.0000      1.0000      0.3312      1.0000
  SFRAC                 0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL            -3.6794+07  -9.9871+07  -9.9723+07  -5.4166+07  -9.9871+07
  J/KG              -3.3863+06  -3.7746+06  -3.7222+06  -3.5938+06  -3.7746+06
  WATT              -2.6238+06  -2.6308+06  -2.4159+06  -5.2894+06  -1.9563+06
ENTROPY:
  J/KMOL-K          -2.7578+04  -1.9585+04  -4.2191+04  -2.8965+04  -1.9585+04
  J/KG-K            -2538.0718   -740.2158  -1574.8191  -1921.8016   -740.2158
DENSITY:
  KMOL/CUM              3.7123     24.1733     30.1089      5.2077     24.1733
  KG/CUM               40.3366    639.5910    806.6591     78.4902    639.5910
AVG MW                 10.8655     26.4585     26.7913     15.0719     26.4585
```

Simulated capacity increase by using CO_2.

```
STREAM ID                   LIQ        MEASUMP      OUT         STM         STMFD
FROM :                      V2103      V2116        V2118       V2103       DRUMMIX
TO   :                      SPLIT      ----         ----        ----        V2103

SUBSTREAM: MIXED
PHASE:                      LIQUID     LIQUID       MIXED       VAPOR       MIXED
COMPONENTS: KMOL/HR
  H2                          0.0      1.9061-07     1.0232       0.0         0.0
  CO                          0.0      4.5312-08     0.4020       0.0         0.0
  CO2                         0.0      6.6406-09   1.1361-02      0.0         0.0
  N2                          0.0      5.2626-09   5.0782-02      0.0         0.0
  O2                          0.0        0.0          0.0         0.0         0.0
  CH4                         0.0      4.2721-08   3.5791-02      0.0         0.0
  C2H6                        0.0        0.0       1.1303-04      0.0         0.0
  C3H8                        0.0        0.0       5.2530-09      0.0         0.0
  C4H10                       0.0        0.0          0.0         0.0         0.0
  C5H12                       0.0        0.0          0.0         0.0         0.0
  C6H14                       0.0        0.0          0.0         0.0         0.0
  MEA                         0.0      1.2851-06   4.7153-03      0.0         0.0
  H2O                      7810.2630     0.2128       0.4329    343.2634   7810.2625
  AR                          0.0        0.0          0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                  7810.2630     0.2128       1.9609    343.2634   7810.2625
  KG/HR                    1.4070+05     3.8348      23.9115   6183.8913   1.4070+05
  CUM/SEC                  6.4892-02   1.4262-06   3.9312-04      0.1473      0.2227
STATE VARIABLES:
  TEMP     C                221.0000    40.0000      35.0000    221.0000    221.0000
  PRES     BAR               24.0094    10.3000      28.3000     24.0094     24.0094
  VFRAC                       0.0        0.0          0.7800      1.0000   4.8000-02
  LFRAC                       1.0000     1.0000       0.2199      0.0         0.9520
  SFRAC                       0.0        0.0          0.0         0.0         0.0
ENTHALPY:
  J/KMOL                   -2.7130+08 -2.8770+08  -9.0162+07  -2.3648+08  -2.6962+08
  J/KG                     -1.5059+07 -1.5970+07  -7.3940+06  -1.3127+07  -1.4967+07
  WATT                     -5.8858+08 -1.7012+04  -4.9112+04  -2.2548+07  -5.8496+08
ENTROPY:
  J/KMOL-K                 -1.2552+05 -1.6656+05  -3.6902+04  -5.5051+04  -1.2213+05
  J/KG-K                   -6967.2642 -9245.2469  -3026.2792  -3055.8504  -6779.5160
DENSITY:
  KMOL/CUM                   33.4325    41.4597      1.3856      0.6470      9.7406
  KG/CUM                    602.2870   746.9080     16.8958     11.6559    175.4781
AVG MW                       18.0150    18.0152     12.1938     18.0150     18.0150
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
146 147 150 2 201
-----------------

STREAM ID               146        147        150        2          201
FROM :                  B3         B5         B1         H2102      ----
TO   :                  CO2-MIX    B3         H2O-MIX    H2103      H2-MIX

SUBSTREAM: MIXED
PHASE:                  VAPOR      VAPOR      VAPOR      VAPOR      VAPOR
COMPONENTS: KMOL/HR
  H2                     8.9420     5.3075    39.6825  3.7117-05     0.0
  CO                     0.1000     0.1120     0.7553  1.2567-06  1.1067-02
  CO2                    1.4746     0.0        0.0        2.3270     0.0
  N2                     7.3121     7.3121     0.2763   260.6468     7.2751
  O2                  3.1858-28     0.0        0.0        9.2645     0.0
  CH4                   43.6486    41.1394     0.0     7.8087-31    41.1394
  C2H6                2.0503-03     1.4433     0.0        0.0        1.4433
  C3H8                3.5404-07     0.1882     0.0        0.0        0.1882
  C4H10               1.0303-10  7.0539-02     0.0        0.0     7.0539-02
  C5H12               1.7900-14  1.9958-02     0.0        0.0     1.9958-02
  C6H14               3.6504-18  2.3788-02     0.0        0.0     2.3788-02
  MEA                 1.5541-35     0.0        0.0        0.0        0.0
  H2O                   22.0418    24.9791     0.0      121.8739     0.0
  AR                     0.0        0.0        0.0        3.1215     0.0
TOTAL FLOW:
  KMOL/HR               83.5214    80.5962    40.7142   397.2340    50.1715
  KG/HR               1387.9667  1387.9652   108.8988  1.0021+04   923.4000
  CUM/SEC             9.5991-02  7.9312-02  7.7149-02     7.3419  1.5351-02
STATE VARIABLES:
  TEMP   C             471.1761   500.0000    13.3824   926.8516    15.0000
  PRES   BAR            15.0000    18.2000     3.5000     1.5000    21.0000
  VFRAC                  1.0000     1.0000     1.0000     1.0000     1.0000
  LFRAC                  0.0        0.0        0.0        0.0        0.0
  SFRAC                  0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL             -9.1835+07 -9.5168+07 -2.3797+06 -4.6430+07 -6.5305+07
  J/KG               -5.5262+06 -5.5262+06 -8.8970+05 -1.8406+06 -3.5483+06
  WATT               -2.1306+06 -2.1306+06 -2.6913+04 -5.1232+06 -9.1013+05
ENTROPY:
  J/KMOL-K           -2.9470+04 -3.3797+04 -8675.6728  3.5222+04 -9.5587+04
  J/KG-K             -1773.3499 -1962.5487 -3243.5914  1396.2718 -5193.5551
DENSITY:
  KMOL/CUM               0.2416     0.2822     0.1465  1.5029-02     0.9078
  KG/CUM                 4.0164     4.8611     0.3920     0.3791    16.7091
AVG MW                  16.6180    17.2212     2.6747    25.2260    18.4048
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
1 140 142 143 144
-----------------

STREAM ID               1           140         142         143         144
FROM :                  BURNER      B1          V2101       B2          ----
TO   :                  H2102       ----        B2          B5          B2

SUBSTREAM: MIXED
PHASE:                  VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                  3.7117-05   120.4674      5.3075      5.3075      0.0
  CO                  1.2567-06     2.2930      0.1120      0.1120      0.0
  CO2                   2.3270      0.0         0.0         0.0         0.0
  N2                  260.6468      0.8390      7.3121      7.3121      0.0
  O2                    9.2645      0.0         0.0         0.0         0.0
  CH4                 7.8087-31     0.0        41.1394     41.1394      0.0
  C2H6                  0.0         0.0         1.4433      1.4433      0.0
  C3H8                  0.0         0.0         0.1882      0.1882      0.0
  C4H10                 0.0         0.0       7.0539-02   7.0539-02     0.0
  C5H12                 0.0         0.0       1.9958-02   1.9958-02     0.0
  C6H14                 0.0         0.0       2.3788-02   2.3788-02     0.0
  MEA                   0.0         0.0         0.0         0.0         0.0
  H2O                 121.8739      0.0         0.0        24.9791     24.9791
  AR                    3.1215      0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR             397.2340    123.5994     55.6170     80.5962     24.9791
  KG/HR               1.0021+04   330.5929    937.9652   1387.9652    450.0000
  CUM/SEC               7.8199      0.2342    5.4951-02   7.0931-02   1.1112-02
STATE VARIABLES:
  TEMP    C          1005.0000     13.3824    500.0000    430.4931    220.0000
  PRES    BAR           1.5000      3.5000     18.2000     18.5000     23.2000
  VFRAC                 1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                 0.0         0.0         0.0         0.0         0.0
  SFRAC                 0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL             -4.3561+07  -2.3797+06  -3.6735+07  -9.8639+07  -2.3647+08
  J/KG               -1.7268+06  -8.8970+05  -2.1782+06  -5.7278+06  -1.3126+07
  WATT               -4.8066+06  -8.1702+04  -5.6753+05  -2.2083+06  -1.6408+06
ENTROPY:
  J/KMOL-K            3.7538+04  -8675.6728  -4.0735+04  -3.8637+04  -5.4783+04
  J/KG-K              1488.0866  -3243.5914  -2415.3734  -2243.5567  -3040.9421
DENSITY:
  KMOL/CUM            1.4110-02     0.1465      0.2811      0.3156      0.6244
  KG/CUM                0.3559      0.3920      4.7413      5.4355     11.2492
AVG MW                 25.2260      2.6747     16.8647     17.2212     18.0150
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
202 202B 203 204 204B
---------------------

STREAM ID                 202          202B         203          204          204B
FROM :                    B1           H2-MIX       H2104        V2114        CO2-MIX
TO   :                    H2-MIX       H2104        V2101        CO2-MIX      H2O-MIX

SUBSTREAM: MIXED
PHASE:                    VAPOR        VAPOR        VAPOR        VAPOR        VAPOR
COMPONENTS: KMOL/HR
  H2                       5.3075       5.3075       5.3075       4.0486      12.9907
  CO                       0.1010       0.1120       0.1120       6.0642       6.1643
  CO2                      0.0          0.0          0.0         25.9516      27.4263
  N2                     3.6965-02      7.3121       7.3121       1.0047       8.3169
  O2                       0.0          0.0          0.0          0.0        3.1858-28
  CH4                      0.0         41.1394      41.1394       8.1415      51.7901
  C2H6                     0.0          1.4433       1.4433     2.3864-10    2.0503-03
  C3H8                     0.0          0.1882       0.1882       0.0        3.5404-07
  C4H10                    0.0        7.0539-02    7.0539-02      0.0        1.0303-10
  C5H12                    0.0        1.9958-02    1.9958-02      0.0        1.7900-14
  C6H14                    0.0        2.3788-02    2.3788-02      0.0        3.6504-18
  MEA                      0.0          0.0          0.0          0.0        1.5541-35
  H2O                      0.0          0.0          0.0          0.1923      22.2342
  AR                       0.0          0.0          0.0          0.0          0.0
 TOTAL FLOW:
  KMOL/HR                  5.4455      55.6170      55.6170      45.4033     128.9248
  KG/HR                   14.5652     937.9652     937.9652    1482.3828    2870.3495
  CUM/SEC                1.0319-02    1.7106-02    5.1478-02    1.9573-02      0.1112
 STATE VARIABLES:
  TEMP   C                13.3824      14.1760     550.0000      40.0000     331.2364
  PRES   BAR               3.5000      21.0000      20.7000      16.2000      16.2000
  VFRAC                    1.0000       1.0000       1.0000       1.0000       1.0000
  LFRAC                    0.0          0.0          0.0          0.0          0.0
  SFRAC                    0.0          0.0          0.0          0.0          0.0
 ENTHALPY:
  J/KMOL                -2.3797+06   -5.9144+07   -3.3863+07   -2.5414+08   -1.4899+08
  J/KG                  -8.8970+05   -3.5070+06   -2.0079+06   -7.7838+06   -6.6922+06
  WATT                  -3599.6273   -9.1373+05   -5.2316+05   -3.2052+06   -5.3358+06
 ENTROPY:
  J/KMOL-K              -8675.6728   -8.5949+04   -3.8214+04   -1.3017+04   -1.8187+04
  J/KG-K                -3243.5914   -5096.3944   -2265.9007    -398.6928    -816.8994
 DENSITY:
  KMOL/CUM                 0.1465       0.9031       0.3001       0.6443       0.3218
  KG/CUM                   0.3920      15.2312       5.0613      21.0382       7.1649
 AVG MW                    2.6747      16.8647      16.8647      32.6492      22.2637
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
205 206 207 208 208B
--------------------

STREAM ID             205          206          207          208          208B
FROM :                ----         H2O-MIX      H2103        H2101        H2107
TO   :                H2O-MIX      H2103        H2101        H2107        H2O-MI

SUBSTREAM: MIXED
PHASE:                VAPOR        VAPOR        VAPOR        VAPOR        VAPOR
COMPONENTS: KMOL/HR
  H2                  0.0          52.6732      52.6732      170.5304     170.5304
  CO                  0.0          6.9196       6.9196       63.4034      63.4034
  CO2                 13.8604      41.2868      41.2868      28.3888      28.3888
  N2                  0.0          8.5933       8.5933       8.5933       8.5933
  O2                  0.0          3.1858-28    3.1858-28    0.0          0.0
  CH4                 0.0          51.7901      51.7901      8.2081       8.2081
  C2H6                0.0          2.0503-03    2.0503-03    2.1401-04    2.1401-04
  C3H8                0.0          3.5404-07    3.5404-07    1.3686-08    1.3686-08
  C4H10               0.0          1.0303-10    1.0303-10    1.2049-12    1.2049-12
  C5H12               0.0          1.7900-14    1.7900-14    7.1458-17    7.1458-17
  C6H14               0.0          3.6504-18    3.6504-18    4.8507-21    4.8507-21
  MEA                 0.0          1.5541-35    1.5541-35    2.1063-30    2.1063-30
  H2O                 99.9167      122.1509     122.1509     91.4633      91.4633
  AR                  0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR             113.7772     283.4162     283.4162     370.5876     370.5876
  KG/HR               2410.0000    5389.2484    5389.2484    5389.2355    5389.2355
  CUM/SEC             5.1371-02    0.2162       0.3296       0.8454       0.4220
STATE VARIABLES:
  TEMP   C            220.0000     248.1458     487.0000     860.0000     293.1850
  PRES   BAR          23.2000      15.6000      15.1000      11.5000      11.5000
  VFRAC               1.0000       1.0000       1.0000       1.0000       1.0000
  LFRAC               0.0          0.0          0.0          0.0          0.0
  SFRAC               0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL             -2.5467+08   -1.7036+08   -1.6066+08   -8.1999+07   -1.0198+08
  J/KG               -1.2023+07   -8.9589+06   -8.4489+06   -5.6386+06   -7.0128+06
  WATT               -8.0489+06   -1.3412+07   -1.2648+07   -8.4411+06   -1.0498+07
ENTROPY:
  J/KMOL-K           -4.5384+04   -2.2420+04   -6881.3373    3.8598+04    1.4313+04
  J/KG-K             -2142.6200   -1179.0385   -361.8840     2654.2028    984.2019
DENSITY:
  KMOL/CUM            0.6152       0.3640       0.2388       0.1217       0.2438
  KG/CUM              13.0316      6.9218       4.5417       1.7707       3.5466
AVG MW                21.1817      19.0153      19.0153      14.5424      14.5424
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
208C 209 209B 210 210B
----------------------

STREAM ID                 208C         209          209B         210          210B
FROM :                    H20-MIX2     M2102        H2110A       V2107        H2111
TO   :                    M2102        H2110A       V2107        H2111        V2108

SUBSTREAM: MIXED
PHASE:                    VAPOR        VAPOR        MIXED        VAPOR        VAPOR
COMPONENTS: KMOL/HR
  H2                     170.5304     170.5304     170.5304     170.5302     170.5302
  CO                      63.4034      63.4034      63.4034      63.4033      63.4033
  CO2                     28.3888      28.3888      28.3888      28.3724      28.3724
  N2                       8.5933       8.5933       8.5933       8.5933       8.5933
  O2                      0.0          0.0          0.0          0.0          0.0
  CH4                      8.2081       8.2081       8.2081       8.2081       8.2081
  C2H6                   2.1401-04    2.1401-04    2.1401-04    2.1401-04    2.1401-04
  C3H8                   1.3686-08    1.3686-08    1.3686-08    1.3686-08    1.3686-08
  C4H10                  1.2049-12    1.2049-12    1.2049-12    0.0          0.0
  C5H12                  7.1458-17    7.1458-17    7.1458-17    0.0          0.0
  C6H14                  4.8507-21    4.8507-21    4.8507-21    0.0          0.0
  MEA                    2.1063-30    2.1063-30    2.1063-30    0.0          0.0
  H2O                    196.9309     227.4611     227.4611       1.6028       1.6028
  AR                      0.0          0.0          0.0          0.0          0.0
 TOTAL FLOW:
  KMOL/HR                476.0553     506.5854     506.5854     280.7105     280.7105
  KG/HR                 7289.2355    7839.2355    7839.2355    3769.6748    3769.6748
  CUM/SEC                  0.5400       0.4799       0.3308       0.1903       0.1958
 STATE VARIABLES:
  TEMP    C              269.0083     182.8193     132.0000      40.0000      40.0000
  PRES    BAR             11.0000      11.0000      10.7000      10.7000      10.4000
  VFRAC                    1.0000       1.0000       0.7482       1.0000       1.0000
  LFRAC                   0.0          0.0          0.2517       0.0          0.0
  SFRAC                   0.0          0.0          0.0          0.0          0.0
 ENTHALPY:
  J/KMOL               -1.3182+08   -1.4088+08   -1.5283+08   -6.7935+07   -6.7934+07
  J/KG                 -8.6092+06   -9.1038+06   -9.8765+06   -5.0588+06   -5.0588+06
  WATT                 -1.7432+07   -1.9824+07   -2.1507+07   -5.2972+06   -5.2972+06
 ENTROPY:
  J/KMOL-K              2584.2472   -5638.3418   -3.4038+04   8938.4811    9177.9829
  J/KG-K                 168.7755    -364.3597   -2199.5920    665.6079     683.4425
 DENSITY:
  KMOL/CUM                 0.2448       0.2931       0.4252       0.4095       0.3981
  KG/CUM                   3.7492       4.5368       6.5812       5.5002       5.3465
 AVG MW                   15.3117      15.4746      15.4746      13.4290      13.4290
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
 211 212 213 213B 214
 --------------------

 STREAM ID                  211         212         213         213B        214
 FROM :                     V2108       V2105       V2106       H2112       VENTTA
 TO   :                     V2105       V2116       H2112       V2109       ----

 SUBSTREAM: MIXED
 PHASE:                     VAPOR       MIXED       VAPOR       MIXED       MIXED
 COMPONENTS: KMOL/HR
   H2                     170.5302    170.5290   1.2014-03   1.2014-03      0.0
   CO                      63.4033     63.4024   9.0682-04   9.0682-04      0.0
   CO2                     28.3724   1.1361-02     27.2665     27.2665     1.2976
   N2                       8.5933      8.5932   4.5131-05   4.5131-05  2.1817-06
   O2                       0.0         0.0         0.0         0.0         0.0
   CH4                      8.2081      8.2080   2.8970-05   2.8970-05      0.0
   C2H6                   2.1401-04   2.1401-04  2.3864-10   2.3864-10      0.0
   C3H8                   1.3686-08   1.3686-08     0.0         0.0         0.0
   C4H10                    0.0         0.0         0.0         0.0         0.0
   C5H12                    0.0         0.0         0.0         0.0         0.0
   C6H14                    0.0         0.0         0.0         0.0         0.0
   MEA                      0.0       4.7104-03  4.2717-05   4.2717-05  3.2763-05
   H2O                      1.6028      1.6879    173.8517    173.8517   5.3079-02
   AR                       0.0         0.0         0.0         0.0         0.0
 TOTAL FLOW:
   KMOL/HR                280.7105    252.4371    201.1205    201.1205      1.3507
   KG/HR                 3769.6748   2523.2971   4331.9718   4331.9718     58.0657
   CUM/SEC                  0.1958      0.1780      1.0377      0.1370   6.4686-03
 STATE VARIABLES:
   TEMP    C               40.0000     40.0419    110.4955     40.0000     40.0000
   PRES    BAR             10.4000     10.3000      1.7000      1.5000      1.5000
   VFRAC                    1.0000      0.9999      1.0000      0.1410      1.0000
   LFRAC                    0.0       2.3903-05     0.0         0.8589   2.5078-06
   SFRAC                    0.0         0.0         0.0         0.0         0.0
 ENTHALPY:
   J/KMOL               -6.7934+07  -3.1429+07  -2.5970+08  -3.0177+08  -3.8730+08
   J/KG                 -5.0588+06  -3.1443+06  -1.2057+07  -1.4010+07  -9.0092+06
   WATT                 -5.2972+06  -2.2039+06  -1.4508+07  -1.6859+07  -1.4531+05
 ENTROPY:
   J/KMOL-K              9177.9829   8948.3616  -3.0380+04  -1.4290+05    894.6224
   J/KG-K                 683.4425    895.2169  -1410.4489  -6634.5413     20.8105
 DENSITY:
   KMOL/CUM                 0.3981      0.3939   5.3835-02      0.4077   5.8003-02
   KG/CUM                   5.3465      3.9378      1.1595      8.7830      2.4934
 AVG MW                    13.4290      9.9957     21.5391     21.5391     42.9888
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
215 215B 216 216B 216C
----------------------

STREAM ID                  215         215B        216         216B        216C
FROM :                     V2109       VENTTANK    CO-MIX      K2103-1     H2113
TO   :                     VENTTANK    CO-MIX      K2103-1     H2113       V2113

SUBSTREAM: MIXED
PHASE:                     VAPOR       VAPOR       VAPOR       VAPOR       MIXED
COMPONENTS: KMOL/HR
  H2                     1.2015-03   1.2015-03      4.0487      4.0487      4.0486
  CO                     9.0692-04   9.0692-04      6.0642      6.0642      6.0642
  CO2                      27.2496     25.9520     25.9520     25.9520     25.9520
  N2                     4.5145-05   4.2964-05      1.0047      1.0047      1.0047
  O2                       0.0         0.0         0.0         0.0         0.0
  CH4                    3.0310-05   3.0310-05      8.1415      8.1415      8.1415
  C2H6                   2.3863-10   2.3863-10   2.3863-10   2.3863-10   2.3864-10
  C3H8                     0.0         0.0         0.0         0.0         0.0
  C4H10                    0.0         0.0         0.0         0.0         0.0
  C5H12                    0.0         0.0         0.0         0.0         0.0
  C6H14                    0.0         0.0         0.0         0.0         0.0
  MEA                    3.2763-05     0.0         0.0         0.0         0.0
  H2O                       1.1146      1.0615      1.0615      1.0615      1.0615
  AR                       0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                  28.3664     27.0157     46.2728     46.2728     46.2728
  KG/HR                  1219.3680   1161.3023   1498.0567   1498.0567   1498.0566
  CUM/SEC                   0.1358      0.1293      0.2182   4.6313-02   3.4322-02
STATE VARIABLES:
  TEMP    C                40.0000     40.0000     34.3187    145.0000     40.0000
  PRES    BAR               1.5000      1.5000      1.5000      9.6000      9.4000
  VFRAC                     1.0000      1.0000      1.0000      1.0000      0.9837
  LFRAC                    0.0         0.0         0.0         0.0       1.6265-02
  SFRAC                    0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                -3.8728+08  -3.8727+08  -2.5378+08  -2.4977+08  -2.5450+08
  J/KG                  -9.0093+06  -9.0093+06  -7.8389+06  -7.7152+06  -7.8612+06
  WATT                  -3.0516+06  -2.9063+06  -3.2620+06  -3.2105+06  -3.2713+06
ENTROPY:
  J/KMOL-K                918.0661    919.1569   6580.6246   2326.8681  -1.0727+04
  J/KG-K                   21.3572     21.3826    203.2662     71.8737   -331.3505
DENSITY:
  KMOL/CUM               5.8003-02   5.8003-02   5.8891-02      0.2775      0.3745
  KG/CUM                    2.4933      2.4933      1.9065      8.9851     12.1242
AVG MW                     42.9862     42.9860     32.3744     32.3744     32.3744
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
 216D 216E 216F 218 218B
 -----------------------

 STREAM ID              216D        216E        216F        218         218B
 FROM :                 V2113       K2103-3     H2114       V2116       K2104
 TO   :                 K2103-3     H2114       V2114       K2104       H2115

 SUBSTREAM: MIXED
 PHASE:                 VAPOR       VAPOR       MIXED       VAPOR       VAPOR
 COMPONENTS: KMOL/HR
   H2                    4.0486      4.0486      4.0486    170.5290    170.5290
   CO                    6.0642      6.0642      6.0642     63.4024     63.4024
   CO2                  25.9517     25.9517     25.9517   1.1361-02   1.1361-02
   N2                    1.0047      1.0047      1.0047      8.5932      8.5932
   O2                    0.0         0.0         0.0         0.0         0.0
   CH4                   8.1415      8.1415      8.1415      8.2080      8.2080
   C2H6               2.3864-10   2.3864-10   2.3864-10   2.1401-04   2.1401-04
   C3H8                  0.0         0.0         0.0      1.3686-08   1.3686-08
   C4H10                 0.0         0.0         0.0         0.0         0.0
   C5H12                 0.0         0.0         0.0         0.0         0.0
   C6H14                 0.0         0.0         0.0         0.0         0.0
   MEA                   0.0         0.0         0.0      4.7092-03   4.7092-03
   H2O                   0.3033      0.3033      0.3033      1.4763      1.4763
   AR                    0.0         0.0         0.0         0.0         0.0
 TOTAL FLOW:
   KMOL/HR              45.5143     45.5143     45.5143    252.2255    252.2255
   KG/HR              1484.3853   1484.3853   1484.3853   2519.4850   2519.4850
   CUM/SEC            3.3583-02   2.8339-02   1.9573-02     0.1780    8.6718-02
 STATE VARIABLES:
   TEMP   C             40.0000    145.0000     40.0000     40.0000    145.0000
   PRES   BAR            9.6000     15.4000     16.2000     10.3000     28.5000
   VFRAC                 1.0000      1.0000      0.9975      1.0000      1.0000
   LFRAC                 0.0         0.0      2.4401-03      0.0         0.0
   SFRAC                 0.0         0.0         0.0         0.0         0.0
 ENTHALPY:
   J/KMOL            -2.5396+08  -2.5003+08  -2.5422+08  -3.1255+07  -2.8156+07
   J/KG              -7.7869+06  -7.6666+06  -7.7948+06  -3.1289+06  -2.8187+06
   WATT              -3.2108+06  -3.1612+06  -3.2140+06  -2.1898+06  -1.9727+06
 ENTROPY:
   J/KMOL-K          -8336.0993  -1432.3927  -1.3391+04   8958.9903   8944.9214
   J/KG-K             -255.6023    -43.9201   -410.6092    896.8840    895.4755
 DENSITY:
   KMOL/CUM              0.3764      0.4461      0.6459      0.3935      0.8079
   KG/CUM               12.2778     14.5500     21.0659      3.9309      8.0704
 AVG MW                 32.6135     32.6135     32.6135      9.9890      9.9890
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
218C 219 220 224 224A
---------------------

STREAM ID              218C        219         220         224         224A
FROM :                 H2115       V2117       V2118       E21         K2105-1
TO   :                 V2117       V2118       E21         K2105-1     H2118

SUBSTREAM: MIXED
PHASE:                 MIXED       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                 170.5290    170.5290    169.5058   1.0714-03   1.0714-03
  CO                  63.4024     63.4024     63.0220     64.3243     64.3243
  CO2               1.1361-02   1.1361-02     0.0         0.0         0.0
  N2                   8.5932      8.5932      8.5417      7.6322      7.6322
  O2                   0.0         0.0         0.0         0.0         0.0
  CH4                  8.2080      8.2080      8.1588   2.0697-02   2.0697-02
  C2H6              2.1401-04   2.1401-04     0.0         0.0         0.0
  C3H8              1.3686-08   1.3686-08     0.0         0.0         0.0
  C4H10                0.0         0.0         0.0         0.0         0.0
  C5H12                0.0         0.0         0.0         0.0         0.0
  C6H14                0.0         0.0         0.0         0.0         0.0
  MEA               4.7092-03   4.6927-03     0.0         0.0         0.0
  H2O                  1.4763      0.4310      0.0         0.0         0.0
  AR                   0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR            252.2255    251.1801    249.2284     71.9784     71.9784
  KG/HR             2519.4850   2500.6520   2477.1415   2015.8630   2015.8630
  CUM/SEC           6.3905-02   6.4121-02   6.3633-02      0.2389      0.1036
STATE VARIABLES:
  TEMP   C            35.0000     35.0000     35.0000     21.4699    100.0000
  PRES   BAR          28.4000     28.3000     28.3000      2.0500      6.0000
  VFRAC                0.9958      1.0000      1.0000      1.0000      1.0000
  LFRAC             4.1499-03     0.0         0.0         0.0         0.0
  SFRAC                0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL           -3.1602+07  -3.0534+07  -3.0150+07  -9.8992+07  -9.6701+07
  J/KG             -3.1637+06  -3.0671+06  -3.0335+06  -3.5346+06  -3.4528+06
  WATT             -2.2141+06  -2.1305+06  -2.0873+06  -1.9792+06  -1.9334+06
ENTROPY:
  J/KMOL-K           -650.1411     77.0194    105.3257   7.6746+04   7.4700+04
  J/KG-K              -65.0856      7.7362     10.5969   2740.2918   2667.2242
DENSITY:
  KMOL/CUM             1.0963      1.0881      1.0879   8.3690-02      0.1929
  KG/CUM              10.9515     10.8330     10.8134      2.3438      5.4023
AVG MW                 9.9890      9.9556      9.9392     28.0064     28.0064
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
224B 224C 224D 225 226
----------------------

STREAM ID                   224B        224C        224D        225         226
FROM :                      H2118       K2105-2     H2119       CO-SPLIT    CO-SPLI
TO   :                      K2105-2     H2119       CO-SPLIT    E21         ----

SUBSTREAM: MIXED
PHASE:                      VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                      1.0714-03   1.0714-03   1.0714-03   1.7515-04   8.9630-04
  CO                        64.3243     64.3243     64.3243     10.5151     53.8092
  CO2                       0.0         0.0         0.0         0.0         0.0
  N2                        7.6322      7.6322      7.6322      1.2476      6.3846
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                     2.0697-02   2.0697-02   2.0697-02   3.3834-03   1.7314-02
  C2H6                      0.0         0.0         0.0         0.0         0.0
  C3H8                      0.0         0.0         0.0         0.0         0.0
  C4H10                     0.0         0.0         0.0         0.0         0.0
  C5H12                     0.0         0.0         0.0         0.0         0.0
  C6H14                     0.0         0.0         0.0         0.0         0.0
  MEA                       0.0         0.0         0.0         0.0         0.0
  H2O                       0.0         0.0         0.0         0.0         0.0
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                   71.9784     71.9784     71.9784     11.7663     60.2121
  KG/HR                   2015.8630   2015.8630   2015.8630    329.5331   1686.3299
  CUM/SEC                 8.6926-02   6.3128-02   5.4560-02   8.9189-03   4.5641-02
STATE VARIABLES:
  TEMP   C                  30.0000     90.0000     35.0000     35.0000     35.0000
  PRES   BAR                 5.8000      9.6000      9.4000      9.4000      9.4000
  VFRAC                      1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                     0.0         0.0         0.0         0.0         0.0
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                 -9.8766+07  -9.7008+07  -9.8640+07  -9.8640+07  -9.8640+07
  J/KG                   -3.5265+06  -3.4638+06  -3.5221+06  -3.5221+06  -3.5221+06
  WATT                   -1.9747+06  -1.9396+06  -1.9722+06  -3.2240+05  -1.6498+06
ENTROPY:
  J/KMOL-K                6.8853+04   6.9944+04   6.5247+04   6.5247+04   6.5247+04
  J/KG-K                  2458.4652   2497.4355   2329.6956   2329.6956   2329.6956
DENSITY:
  KMOL/CUM                   0.2300      0.3167      0.3664      0.3664      0.3664
  KG/CUM                     6.4418      8.8702     10.2632     10.2632     10.2632
AVG MW                      28.0064     28.0064     28.0064     28.0064     28.0064
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
 227 228 251 251B 253
 --------------------

 STREAM ID               227          228          251          251B         253
 FROM :                  E21          E21          ----         H2106        ----
 TO   :                  CO-MIX       B1           H2106        V2103        M2102

 SUBSTREAM: MIXED
 PHASE:                  VAPOR        VAPOR        LIQUID       LIQUID       LIQUID
 COMPONENTS: KMOL/HR
   H2                     4.0474     165.4575       0.0          0.0          0.0
   CO                     6.0633       3.1493       0.0          0.0          0.0
   CO2                    0.0          0.0          0.0          0.0          0.0
   N2                     1.0047       1.1523       0.0          0.0          0.0
   O2                     0.0          0.0          0.0          0.0          0.0
   CH4                    8.1415       0.0          0.0          0.0          0.0
   C2H6                   0.0          0.0          0.0          0.0          0.0
   C3H8                   0.0          0.0          0.0          0.0          0.0
   C4H10                  0.0          0.0          0.0          0.0          0.0
   C5H12                  0.0          0.0          0.0          0.0          0.0
   C6H14                  0.0          0.0          0.0          0.0          0.0
   MEA                    0.0          0.0          0.0          0.0          0.0
   H2O                    0.0          0.0        299.7502     299.7502      30.5301
   AR                     0.0          0.0          0.0          0.0          0.0
 TOTAL FLOW:
   KMOL/HR               19.2571     169.7592     299.7502     299.7502      30.5301
   KG/HR                336.7543     454.0570    5400.0000    5400.0000     550.0000
   CUM/SEC              6.8032-02      0.3216     2.1204-03    2.3230-03    2.1596-04
 STATE VARIABLES:
   TEMP   C              25.2967      13.3824     104.0000     180.0000     104.0000
   PRES   BAR             1.9500       3.5000      27.0000      26.8000      27.0000
   VFRAC                  1.0000       1.0000       0.0          0.0          0.0
   LFRAC                  0.0          0.0          1.0000       1.0000       1.0000
   SFRAC                  0.0          0.0          0.0          0.0          0.0
 ENTHALPY:
   J/KMOL             -6.6502+07  -2.3797+06  -2.8210+08  -2.7526+08  -2.8210+08
   J/KG               -3.8029+06  -8.8970+05  -1.5659+07  -1.5279+07  -1.5659+07
   WATT               -3.5573+05  -1.1221+05  -2.3489+07  -2.2919+07  -2.3924+06
 ENTROPY:
   J/KMOL-K           -1224.6329  -8675.6728  -1.5042+05  -1.3390+05  -1.5042+05
   J/KG-K               -70.0299  -3243.5914  -8349.6409  -7432.5015  -8349.6409
 DENSITY:
   KMOL/CUM            7.8628-02      0.1465      39.2685      35.8435      39.2685
   KG/CUM                 1.3749       0.3920     707.4237     645.7212     707.4237
 AVG MW                  17.4872       2.6747      18.0150      18.0150      18.0150
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
260 264 265 266 268
-------------------

STREAM ID               260          264          265          266          268
FROM :                  ----         V2107        V2108        COND-MIX     V2113
TO   :                  H20-MIX2     COND-MIX     COND-MIX     ----         CONDMIX

SUBSTREAM: MIXED
PHASE:                  VAPOR        LIQUID       MIXED        LIQUID       LIQUID
COMPONENTS: KMOL/HR
  H2                    0.0          1.9010-04    0.0          1.9010-04    8.5973-08
  CO                    0.0          4.2653-05    0.0          4.2653-05    7.6869-08
  CO2                   0.0          1.6399-02    0.0          1.6399-02    2.7490-04
  N2                    0.0          5.3172-06    0.0          5.3172-06    1.1728-08
  O2                    0.0          0.0          0.0          0.0          0.0
  CH4                   0.0          5.8329-05    0.0          5.8329-05    1.0771-06
  C2H6                  0.0          2.2731-09    0.0          2.2731-09    0.0
  C3H8                  0.0          0.0          0.0          0.0          0.0
  C4H10                 0.0          0.0          0.0          0.0          0.0
  C5H12                 0.0          0.0          0.0          0.0          0.0
  C6H14                 0.0          0.0          0.0          0.0          0.0
  MEA                   0.0          0.0          0.0          0.0          0.0
  H2O                 105.4676     225.8582       0.0        225.8582       0.7582
  AR                    0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR             105.4676     225.8749       0.0        225.8749       0.7584
  KG/HR              1900.0000    4069.5606       0.0       4069.5606      13.6712
  CUM/SEC            5.9003-02    1.5134-03       0.0       1.5137-03    5.0828-06
STATE VARIABLES:
  TEMP   C            208.0000      40.0000     MISSING       40.1538      40.0000
  PRES   BAR           18.3000      10.7000     10.4000        3.5000       9.6000
  VFRAC                 1.0000       0.0        MISSING        0.0          0.0
  LFRAC                 0.0          1.0000     MISSING        1.0000       1.0000
  SFRAC                 0.0          0.0        MISSING        0.0          0.0
ENTHALPY:
  J/KMOL            -2.3667+08   -2.8770+08     MISSING   -2.8770+08   -2.8774+08
  J/KG              -1.3137+07   -1.5969+07     MISSING   -1.5969+07   -1.5964+07
  WATT              -6.9336+06   -1.8051+07     MISSING   -1.8051+07   -6.0623+04
ENTROPY:
  J/KMOL-K          -5.3384+04   -1.6654+05     MISSING   -1.6648+05   -1.6649+05
  J/KG-K            -2963.3323   -9243.5005     MISSING   -9240.4213   -9236.6507
DENSITY:
  KMOL/CUM              0.4965      41.4592     MISSING       41.4493      41.4514
  KG/CUM                8.9449     746.9662     MISSING      746.7875     747.1381
AVG MW                 18.0150      18.0168     MISSING       18.0168      18.0244
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
269 270 281 281A 281B
---------------------

STREAM ID               269         270         281         281A        281B
FROM :                  V2114       V2117       ----        H2108       H2109A
TO   :                  CONDMIX2    ----        V2105       ----        H2108

SUBSTREAM: MIXED
PHASE:                  LIQUID      LIQUID      LIQUID      LIQUID      LIQUID
COMPONENTS: KMOL/HR
  H2                  2.1641-08   2.0867-06     0.0         0.0         0.0
  CO                  1.9067-08   4.6854-07     0.0         0.0         0.0
  CO2                 6.5917-05   8.3636-08     9.5819     10.6936     10.6936
  N2                  2.9135-09   5.8329-08     0.0         0.0         0.0
  O2                    0.0         0.0         0.0         0.0         0.0
  CH4                 2.6321-07   6.6006-07     0.0         0.0         0.0
  C2H6                  0.0       2.4640-11     0.0         0.0         0.0
  C3H8                  0.0         0.0         0.0         0.0         0.0
  C4H10                 0.0         0.0         0.0         0.0         0.0
  C5H12                 0.0         0.0         0.0         0.0         0.0
  C6H14                 0.0         0.0         0.0         0.0         0.0
  MEA                   0.0       1.6422-05    87.1169     87.1121     87.1121
  H2O                   0.1110      1.0453    775.1928    774.8650    774.8650
  AR                    0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR               0.1110      1.0453    871.8917    872.6708    872.6708
  KG/HR                 2.0024     18.8329    1.9708+04   1.9751+04   1.9751+04
  CUM/SEC             7.4427-07   6.9764-06   6.0353-03   8.1078-03   8.4903-03
STATE VARIABLES:
  TEMP    C            40.0000     35.0000     40.0000     40.0000     88.0000
  PRES    BAR          16.2000     28.3000     14.7000     14.7000      1.7000
  VFRAC                 0.0         0.0         0.0         0.0         0.0
  LFRAC                 1.0000      1.0000      1.0000      1.0000      1.0000
  SFRAC                 0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL             -2.8775+08 -2.8810+08 -2.8449+08 -2.8395+08 -2.7928+08
  J/KG               -1.5959+07 -1.5991+07 -1.2586+07 -1.2546+07 -1.2340+07
  WATT               -8877.0814 -8.3657+04 -6.8900+07 -6.8832+07 -6.7700+07
ENTROPY:
  J/KMOL-K           -1.6646+05 -1.6799+05 -2.4699+05 -2.2394+05 -2.0993+05
  J/KG-K             -9232.0216 -9324.4627 -1.0927+04 -9894.5010 -9275.8331
DENSITY:
  KMOL/CUM             41.4505     41.6232     40.1289     29.8981     28.5513
  KG/CUM              747.3714    749.8700    907.0601    676.6661    646.1847
AVG MW                 18.0304     18.0156     22.6036     22.6324     22.6324
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
281C 282 282B 284 285
---------------------

STREAM ID               281C        282         282B        284         285
FROM :                  V2106       V2105       H2109B      CONDMIX2    V2109
TO   :                  H2109A      H2109B      V2106       V2109       V2106

SUBSTREAM: MIXED
PHASE:                  LIQUID      LIQUID      MIXED       LIQUID      LIQUID
COMPONENTS: KMOL/HR
  H2                    0.0        1.2014-03   1.2014-03   1.0761-07   1.4412-09
  CO                    0.0        9.0682-04   9.0682-04   9.5936-08   6.6044-10
  CO2                  10.6936      37.9429     37.9429    3.4082-04   1.7234-02
  N2                    0.0        4.5131-05   4.5131-05   1.4642-08   3.0222-11
  O2                    0.0          0.0         0.0         0.0         0.0
  CH4                   0.0        2.8970-05   2.8970-05   1.3403-06   2.3433-10
  C2H6                  0.0        2.3864-10   2.3864-10     0.0         0.0
  C3H8                  0.0        2.6699-15   2.6699-15     0.0         0.0
  C4H10                 0.0          0.0         0.0         0.0         0.0
  C5H12                 0.0          0.0         0.0         0.0         0.0
  C6H14                 0.0          0.0         0.0         0.0         0.0
  MEA                  87.1121      87.1121     87.1121      0.0       9.9538-06
  H2O                 774.8650     775.1077    775.1077      0.8692     173.6063
  AR                    0.0          0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR             872.6708     900.1651    900.1651      0.8695     173.6236
  KG/HR              1.9751+04    2.0954+04   2.0954+04     15.6737    3128.2775
  CUM/SEC            6.6500-03    6.5685-03   3.9219-02   5.8288-06   1.1635-03
STATE VARIABLES:
  TEMP     C          117.9567      69.3631    104.0000     40.1910     40.0000
  PRES     BAR          1.7000      10.4000     10.4000      1.5000      1.5000
  VFRAC                 0.0          0.0      4.2005-02      0.0         0.0
  LFRAC                 1.0000       1.0000      0.9579      1.0000      1.0000
  SFRAC                 0.0          0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL           -2.7826+08  -2.8792+08  -2.8086+08  -2.8774+08  -2.8772+08
  J/KG             -1.2295+07  -1.2369+07  -1.2065+07  -1.5963+07  -1.5969+07
  WATT             -6.7452+07  -7.1994+07  -7.0228+07  -6.9500+04  -1.3877+07
ENTROPY:
  J/KMOL-K         -2.0057+05  -2.2593+05  -1.9895+05  -1.6641+05  -1.6652+05
  J/KG-K           -8861.8678  -9705.5860  -8546.7070  -9232.2332  -9241.9675
DENSITY:
  KMOL/CUM             36.4526      38.0676      6.3756     41.4389     41.4520
  KG/CUM              825.0106     886.1483    148.4134    746.9455    746.8649
AVG MW                 22.6324      23.2782     23.2782     18.0251     18.0175
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
 3 4 5 6 7
 ---------

 STREAM ID                  3           4           5           6           7
 FROM :                     H2103       H2104       H2105A      H2105B      H2106
 TO   :                     H2104       H2105A      H2105B      H2106       ----

 SUBSTREAM: MIXED
 PHASE:                     VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
 COMPONENTS: KMOL/HR
   H2                     3.7117-05   3.7117-05   3.7117-05   3.7117-05   3.7117-05
   CO                     1.2567-06   1.2567-06   1.2567-06   1.2567-06   1.2567-06
   CO2                      2.3270      2.3270      2.3270      2.3270      2.3270
   N2                     260.6468    260.6468    260.6468    260.6468    260.6468
   O2                       9.2645      9.2645      9.2645      9.2645      9.2645
   CH4                    7.8087-31   7.8087-31   7.8087-31   7.8087-31   7.8087-31
   C2H6                     0.0         0.0         0.0         0.0         0.0
   C3H8                     0.0         0.0         0.0         0.0         0.0
   C4H10                    0.0         0.0         0.0         0.0         0.0
   C5H12                    0.0         0.0         0.0         0.0         0.0
   C6H14                    0.0         0.0         0.0         0.0         0.0
   MEA                      0.0         0.0         0.0         0.0         0.0
   H2O                    121.8739    121.8739    121.8739    121.8739    121.8739
   AR                       3.1215      3.1215      3.1215      3.1215      3.1215
 TOTAL FLOW:
   KMOL/HR                397.2340    397.2340    397.2340    397.2340    397.2340
   KG/HR                  1.0021+04   1.0021+04   1.0021+04   1.0021+04   1.0021+04
   CUM/SEC                  6.1686      5.5515      5.0404      4.2528      3.2719
 STATE VARIABLES:
   TEMP   C               735.0473    634.1897    550.6559    421.9694    261.8248
   PRES   BAR               1.5000      1.5000      1.5000      1.5000      1.5000
   VFRAC                    1.0000      1.0000      1.0000      1.0000      1.0000
   LFRAC                    0.0         0.0         0.0         0.0         0.0
   SFRAC                    0.0         0.0         0.0         0.0         0.0
 ENTHALPY:
   J/KMOL                -5.3349+07  -5.6889+07  -5.9758+07  -6.4061+07  -6.9227+07
   J/KG                  -2.1148+06  -2.2552+06  -2.3689+06  -2.5395+06  -2.7443+06
   WATT                  -5.8867+06  -6.2772+06  -6.5938+06  -7.0687+06  -7.6387+06
 ENTROPY:
   J/KMOL-K               2.8943+04   2.5244+04   2.1928+04   1.6250+04   7809.6778
   J/KG-K                 1147.3298   1000.7259    869.2447    644.1855    309.5883
 DENSITY:
   KMOL/CUM               1.7888-02   1.9876-02   2.1892-02   2.5946-02   3.3724-02
   KG/CUM                   0.4512      0.5013      0.5522      0.6545      0.8507
 AVG MW                    25.2260     25.2260     25.2260     25.2260     25.2260
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
A B BIN C D
-----------

STREAM ID               A            B            BIN          C            D
FROM :                  SPLIT        H2102        ----         SPLIT        H2105A
TO   :                  H2102        DRUMMIX      BURNER       H2105A       DRUMMIX

SUBSTREAM: MIXED
PHASE:                  LIQUID       MIXED        VAPOR        LIQUID       MIXED
COMPONENTS: KMOL/HR
  H2                     0.0          0.0         121.8254      0.0          0.0
  CO                     0.0          0.0           2.3027      0.0          0.0
  CO2                    0.0          0.0           0.0         0.0          0.0
  N2                     0.0          0.0         260.6468      0.0          0.0
  O2                     0.0          0.0          71.3772      0.0          0.0
  CH4                    0.0          0.0         2.4310-02     0.0          0.0
  C2H6                   0.0          0.0           0.0         0.0          0.0
  C3H8                   0.0          0.0           0.0         0.0          0.0
  C4H10                  0.0          0.0           0.0         0.0          0.0
  C5H12                  0.0          0.0           0.0         0.0          0.0
  C6H14                  0.0          0.0           0.0         0.0          0.0
  MEA                    0.0          0.0           0.0         0.0          0.0
  H2O                  681.8751     681.8751        0.0       681.8751     681.8649
  AR                     0.0          0.0           3.1215      0.0          0.0
TOTAL FLOW:
  KMOL/HR              681.8751     681.8751      459.2980    681.8751     681.8649
  KG/HR               1.2284+04    1.2284+04     1.0021+04   1.2284+04    1.2284+04
  CUM/SEC             5.6654-03    1.9445-02       1.6619    5.6654-03    1.9445-02
STATE VARIABLES:
  TEMP    C            221.0000     221.0000      40.0000     221.0000     221.0000
  PRES    BAR           24.0094      24.0094       2.0000      24.0094      24.0094
  VFRAC                  0.0        4.8000-02      1.0000       0.0        4.8000-02
  LFRAC                  1.0000       0.9520       0.0          1.0000       0.9520
  SFRAC                  0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL             -2.7130+08 -2.6962+08 -1.3052+05 -2.7130+08 -2.6962+08
  J/KG               -1.5059+07 -1.4967+07 -5982.4219 -1.5059+07 -1.4967+07
  WATT               -5.1386+07 -5.1070+07 -1.6652+04 -5.1386+07 -5.1069+07
ENTROPY:
  J/KMOL-K           -1.2552+05 -1.2213+05  4700.2516 -1.2552+05 -1.2213+05
  J/KG-K             -6967.2642 -6779.5164   215.4359 -6967.2642 -6779.5164
DENSITY:
  KMOL/CUM              33.4325      9.7406   7.6766-02    33.4325      9.7406
  KG/CUM               602.2870    175.4783     1.6748    602.2870    175.4783
AVG MW                  18.0150     18.0150    21.8174     18.0150     18.0150
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
E F G H L10
-----------

STREAM ID               E          F          G          H          L10
FROM :                  SPLIT      H2105B     SPLIT      H2107      V31
TO   :                  H2105B     DRUMMIX    H2107      DRUMMIX    MIX2

SUBSTREAM: MIXED
PHASE:                  LIQUID     MIXED      LIQUID     MIXED      VAPOR
COMPONENTS: KMOL/HR
  H2                     0.0        0.0        0.0        0.0        1.3802
  CO                     0.0        0.0        0.0        0.0        1.5707
  CO2                    0.0        0.0        0.0        0.0        0.0
  N2                     0.0        0.0        0.0        0.0        0.3822
  O2                     0.0        0.0        0.0        0.0        0.0
  CH4                    0.0        0.0        0.0        0.0     5.5478-13
  C2H6                   0.0        0.0        0.0        0.0        0.0
  C3H8                   0.0        0.0        0.0        0.0        0.0
  C4H10                  0.0        0.0        0.0        0.0        0.0
  C5H12                  0.0        0.0        0.0        0.0        0.0
  C6H14                  0.0        0.0        0.0        0.0        0.0
  MEA                    0.0        0.0        0.0        0.0        0.0
  H2O                 1022.8127  1022.7973  4432.1885  4432.1885      0.0
  AR                     0.0        0.0        0.0        0.0        0.0
TOTAL FLOW:
  KMOL/HR             1022.8127  1022.7973  4432.1885  4432.1885     3.3332
  KG/HR               1.8426+04  1.8426+04  7.9846+04  7.9846+04    57.4859
  CUM/SEC             8.4982-03  2.9167-02  3.6825-02     0.1263  2.9257-03
STATE VARIABLES:
  TEMP    C            221.0000   221.0000   221.0000   220.9948  -182.9165
  PRES    BAR           24.0094    24.0094    24.0094    24.0094     2.3000
  VFRAC                  0.0    4.8000-02     0.0    4.8000-02     1.0000
  LFRAC                  1.0000     0.9520     1.0000     0.9520     0.0
  SFRAC                  0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL             -2.7130+08 -2.6962+08 -2.7130+08 -2.6963+08 -5.8026+07
  J/KG               -1.5059+07 -1.4967+07 -1.5059+07 -1.4967+07 -3.3646+06
  WATT               -7.7079+07 -7.6603+07 -3.3401+08 -3.3195+08 -5.3726+04
ENTROPY:
  J/KMOL-K           -1.2552+05 -1.2213+05 -1.2552+05 -1.2213+05  9822.3771
  J/KG-K             -6967.2642 -6779.5164 -6967.2642 -6779.5729   569.5337
DENSITY:
  KMOL/CUM              33.4325     9.7406    33.4325     9.7408     0.3164
  KG/CUM               602.2870   175.4783   602.2870   175.4806     5.4580
AVG MW                  18.0150    18.0150    18.0150    18.0150    17.2463
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
 L11 L13 L2 L22 L28
 ------------------

 STREAM ID                 L11         L13         L2          L22         L28
 FROM :                    T24         V47         E21         E23A        V6
 TO   :                    T22MIX      MIX2        E22         E21         T23

 SUBSTREAM: MIXED
 PHASE:                    LIQUID      MIXED       VAPOR       VAPOR       MIXED
 COMPONENTS: KMOL/HR
   H2                  3.3576-04   1.0488-16    169.5058    165.4575      2.6678
   CO                    20.0260   2.0751-03     63.0220      3.1493     41.4093
   CO2                   0.0         0.0         0.0         0.0         0.0
   N2                     3.2569   5.2416-05      8.5417      1.1523      4.1219
   O2                    0.0         0.0         0.0         0.0         0.0
   CH4                 1.0083-03      8.0655      8.1588     0.0          8.1588
   C2H6                  0.0         0.0         0.0         0.0         0.0
   C3H8                  0.0         0.0         0.0         0.0         0.0
   C4H10                 0.0         0.0         0.0         0.0         0.0
   C5H12                 0.0         0.0         0.0         0.0         0.0
   C6H14                 0.0         0.0         0.0         0.0         0.0
   MEA                   0.0         0.0         0.0         0.0         0.0
   H2O                   0.0         0.0         0.0         0.0         0.0
   AR                    0.0         0.0         0.0         0.0         0.0
 TOTAL FLOW:
   KMOL/HR               23.2844      8.0676    249.2284    169.7592     56.3579
   KG/HR                652.1853    129.4550   2477.1415    454.0570   1411.6139
   CUM/SEC             2.7401-04   1.3819-04   2.1770-02   9.7230-02   3.5953-03
 STATE VARIABLES:
   TEMP   C            -169.2568   -151.3295   -157.6000   -176.1000   -176.5239
   PRES   BAR             7.6000      2.1500     28.1000      3.9000      5.4700
   VFRAC                 0.0       4.9670-03      1.0000      1.0000      0.1462
   LFRAC                  1.0000      0.9950     0.0         0.0          0.8538
   SFRAC                 0.0         0.0         0.0         0.0         0.0
 ENTHALPY:
   J/KMOL             -1.0609+08  -8.9035+07  -3.5809+07  -7.4449+06  -1.0336+08
   J/KG               -3.7878+06  -5.5487+06  -3.6028+06  -2.7834+06  -4.1267+06
   WATT               -6.8621+05  -1.9953+05  -2.4791+06  -3.5107+05  -1.6182+06
 ENTROPY:
   J/KMOL-K           -1.6536+04  -1.8353+05  -2.8668+04  -3.7983+04  -3.6057+04
   J/KG-K              -590.3831  -1.1438+04  -2884.3464  -1.4201+04  -1439.5751
 DENSITY:
   KMOL/CUM              23.6046     16.2173      3.1800      0.4849      4.3542
   KG/CUM               661.1542    260.2266     31.6070      1.2972    109.0621
 AVG MW                  28.0095     16.0461      9.9392      2.6747     25.0473
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
L29 L3 L30 L31 L33
------------------

STREAM ID                 L29          L3           L30          L31          L33
FROM :                    T23          E22          V9           T24          V8
TO   :                    V29          T21          T24          V31          T22

SUBSTREAM: MIXED
PHASE:                    VAPOR        MIXED        MIXED        VAPOR        MIXED
COMPONENTS: KMOL/HR
  H2                        2.6672     169.5058       1.3805       1.3802   6.1273-04
  CO                        4.4905      63.0220      18.4633       1.5707     36.9187
  CO2                       0.0          0.0          0.0          0.0          0.0
  N2                        0.6224       8.5417       3.2674       0.3822       3.4994
  O2                        0.0          0.0          0.0          0.0          0.0
  CH4                     7.5965-02      8.1588       0.0        5.5478-13      8.0828
  C2H6                      0.0          0.0          0.0          0.0          0.0
  C3H8                      0.0          0.0          0.0          0.0          0.0
  C4H10                     0.0          0.0          0.0          0.0          0.0
  C5H12                     0.0          0.0          0.0          0.0          0.0
  C6H14                     0.0          0.0          0.0          0.0          0.0
  MEA                       0.0          0.0          0.0          0.0          0.0
  H2O                       0.0          0.0          0.0          0.0          0.0
  AR                        0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR                   7.8562     249.2284      23.1112       3.3332      48.5017
  KG/HR                   149.8133    2477.1415     611.4703      57.4859    1261.8005
  CUM/SEC                 2.9641-03   1.9781-02   1.0070-03   8.7966-04   4.9050-03
STATE VARIABLES:
  TEMP    C              -177.5619   -164.8000   -176.6341   -177.5691   -181.3971
  PRES    BAR               5.4000      28.0000       7.8500       7.6000       2.3830
  VFRAC                     1.0000       0.9774       0.1329       1.0000       0.1110
  LFRAC                     0.0        2.2554-02      0.8670       0.0          0.8889
  SFRAC                     0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL                 -6.9862+07  -3.6146+07  -9.9024+07  -5.8027+07  -1.0853+08
  J/KG                   -3.6636+06  -3.6366+06  -3.7427+06  -3.3646+06  -4.1719+06
  WATT                   -1.5246+05  -2.5024+06  -6.3571+05  -5.3727+04  -1.4622+06
ENTROPY:
  J/KMOL-K                1.1175+04  -3.1668+04  -1.8745+04    441.2539  -4.0678+04
  J/KG-K                  586.0345   -3186.1100   -708.4910     25.5853   -1563.5849
DENSITY:
  KMOL/CUM                  0.7362       3.4997       6.3748       1.0525       2.7467
  KG/CUM                   14.0397      34.7848     168.6645      18.1528      71.4583
AVG MW                     19.0694       9.9392      26.4576      17.2463      26.0155
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
L35 L36 L37 L38 L39
-------------------

STREAM ID             L35          L36          L37          L38          L39
FROM :                E21          SPLIT1       E22B         SPLIT1       SPLIT1
TO   :                SPLIT1       E22B         V37          E24          V39

SUBSTREAM: MIXED
PHASE:                VAPOR        VAPOR        VAPOR        VAPOR        VAPOR
COMPONENTS: KMOL/HR
  H2               1.7515-04    2.7323-05    2.7323-05    9.5631-05    5.2194-05
  CO                 10.5151       1.6403       1.6403       5.7412       3.1335
  CO2                 0.0          0.0          0.0          0.0          0.0
  N2                  1.2476       0.1946       0.1946       0.6812       0.3718
  O2                  0.0          0.0          0.0          0.0          0.0
  CH4              3.3834-03    5.2782-04    5.2782-04    1.8474-03    1.0083-03
  C2H6                0.0          0.0          0.0          0.0          0.0
  C3H8                0.0          0.0          0.0          0.0          0.0
  C4H10               0.0          0.0          0.0          0.0          0.0
  C5H12               0.0          0.0          0.0          0.0          0.0
  C6H14               0.0          0.0          0.0          0.0          0.0
  MEA                 0.0          0.0          0.0          0.0          0.0
  H2O                 0.0          0.0          0.0          0.0          0.0
  AR                  0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR            11.7663       1.8355       1.8355       6.4244       3.5063
  KG/HR             329.5331      51.4071      51.4071     179.9250      98.2008
  CUM/SEC          3.0025-03    4.6839-04    4.3866-04    1.6394-03    8.9475-04
STATE VARIABLES:
  TEMP    C        -155.1000    -155.1000    -160.8000    -155.1000    -155.1000
  PRES    BAR         9.2000       9.2000       9.1000       9.2000       9.2000
  VFRAC               1.0000       1.0000       1.0000       1.0000       1.0000
  LFRAC               0.0          0.0          0.0          0.0          0.0
  SFRAC               0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL          -1.0452+08   -1.0452+08   -1.0472+08   -1.0452+08   -1.0452+08
  J/KG            -3.7318+06   -3.7318+06   -3.7390+06   -3.7318+06   -3.7318+06
  WATT            -3.4160+05   -5.3290+04   -5.3392+04   -1.8651+05   -1.0180+05
ENTROPY:
  J/KMOL-K         3.5433+04    3.5433+04    3.3762+04    3.5433+04    3.5433+04
  J/KG-K           1265.1585    1265.1585    1205.5077    1265.1585    1265.1585
DENSITY:
  KMOL/CUM            1.0885       1.0885       1.1623       1.0885       1.0885
  KG/CUM             30.4869      30.4869      32.5531      30.4869      30.4869
AVG MW               28.0064      28.0064      28.0064      28.0064      28.0064
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
L4 L40 L41 L42 L43
------------------

STREAM ID                L4          L40         L41         L42         L43
FROM :                   CO2         V39         E24         V41         V37
TO   :                   E23A        T24         V41         T22MIX      T22MIX

SUBSTREAM: MIXED
PHASE:                   VAPOR       VAPOR       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  H2                    165.4575   5.2194-05   9.5631-05   9.5631-05   2.7323-05
  CO                      3.1493      3.1335      5.7412      5.7412      1.6403
  CO2                     0.0         0.0         0.0         0.0         0.0
  N2                      1.1523      0.3718      0.6812      0.6812      0.1946
  O2                      0.0         0.0         0.0         0.0         0.0
  CH4                     0.0      1.0083-03   1.8474-03   1.8474-03   5.2782-04
  C2H6                    0.0         0.0         0.0         0.0         0.0
  C3H8                    0.0         0.0         0.0         0.0         0.0
  C4H10                   0.0         0.0         0.0         0.0         0.0
  C5H12                   0.0         0.0         0.0         0.0         0.0
  C6H14                   0.0         0.0         0.0         0.0         0.0
  MEA                     0.0         0.0         0.0         0.0         0.0
  H2O                     0.0         0.0         0.0         0.0         0.0
  AR                      0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR               169.7592      3.5063      6.4244      6.4244      1.8355
  KG/HR                 454.0570     98.2008    179.9250    179.9250     51.4071
  CUM/SEC              9.4906-03   1.0383-03   1.6065-03   5.9692-03   1.6354-03
STATE VARIABLES:
  TEMP    C            -201.5000   -156.8291   -157.6000   -167.5125   -171.2923
  PRES    BAR            27.3000      7.9500      9.1000      2.5000      2.5000
  VFRAC                   1.0000      1.0000      1.0000      1.0000      1.0000
  LFRAC                   0.0         0.0         0.0         0.0         0.0
  SFRAC                   0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL              -8.2016+06  -1.0451+08  -1.0460+08  -1.0460+08  -1.0472+08
  J/KG                -3.0663+06  -3.7318+06  -3.7348+06  -3.7348+06  -3.7390+06
  WATT                -3.8675+05  -1.0180+05  -1.8666+05  -1.8666+05  -5.3392+04
ENTROPY:
  J/KMOL-K            -6.2914+04   3.6491+04   3.4787+04   4.4561+04   4.3436+04
  J/KG-K              -2.3522+04   1302.9424   1242.0889   1591.1113   1550.9302
DENSITY:
  KMOL/CUM                4.9686      0.9380      1.1108      0.2989      0.3117
  KG/CUM                 13.2896     26.2724     31.1114      8.3728      8.7316
AVG MW                    2.6747     28.0064     28.0064     28.0064     28.0064
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
L44 L46 L47 L48 L49
-------------------

STREAM ID              L44         L46         L47         L48         L49
FROM :                 T22MIX      E25-27      T22         MIX2        T22
TO   :                 E25-27      T22         V47         E21         E21

SUBSTREAM: MIXED
PHASE:                 MIXED       LIQUID      LIQUID      MIXED       VAPOR
COMPONENTS: KMOL/HR
  H2                 4.5872-04   4.5872-04   1.0488-16     4.0474    1.0714-03
  CO                   27.4076     27.4076   2.0751-03     6.0633      64.3243
  CO2                  0.0         0.0         0.0         0.0          0.0
  N2                    4.1328      4.1328   5.2416-05     1.0047       7.6322
  O2                   0.0         0.0         0.0         0.0          0.0
  CH4                3.3834-03   3.3834-03     8.0655      8.1415    2.0697-02
  C2H6                 0.0         0.0         0.0         0.0          0.0
  C3H8                 0.0         0.0         0.0         0.0          0.0
  C4H10                0.0         0.0         0.0         0.0          0.0
  C5H12                0.0         0.0         0.0         0.0          0.0
  C6H14                0.0         0.0         0.0         0.0          0.0
  MEA                  0.0         0.0         0.0         0.0          0.0
  H2O                  0.0         0.0         0.0         0.0          0.0
  AR                   0.0         0.0         0.0         0.0          0.0
TOTAL FLOW:
  KMOL/HR              31.5443     31.5443      8.0676     19.2571      71.9784
  KG/HR               883.5176    883.5176    129.4550    336.7543    2015.8630
  CUM/SEC            1.0005-02   3.2511-04   8.9359-05   1.2264-02   6.1283-02
STATE VARIABLES:
  TEMP   C            -183.1444   -184.5000   -150.6756   -172.6032   -184.0300
  PRES   BAR             2.5000      2.3250      2.2500      2.1500      2.2500
  VFRAC                  0.4043      0.0         0.0         0.6034      1.0000
  LFRAC                  0.5956      1.0000      1.0000      0.3965      0.0
  SFRAC                  0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL            -1.0571+08 -1.0808+08 -8.9035+07 -7.5845+07 -1.0510+08
  J/KG              -3.7742+06 -3.8587+06 -5.5487+06 -4.3372+06 -3.7527+06
  WATT              -9.2626+05 -9.4702+05 -1.9953+05 -4.0571+05 -2.1014+06
ENTROPY:
  J/KMOL-K            235.1010 -2.6093+04 -1.8353+05 -6.5744+04  4.0241+04
  J/KG-K                8.3938  -931.6042 -1.1438+04 -3759.5362  1436.8414
DENSITY:
  KMOL/CUM              0.8757     26.9521     25.0788      0.4361      0.3262
  KG/CUM               24.5288    754.8952    402.4184      7.6271      9.1372
AVG MW                 28.0087     28.0087     16.0461     17.4872     28.0064
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
L6 L7 L8 L9 LB
--------------

STREAM ID                   L6          L7          L8          L9          LB
FROM :                      T21         V29         T23         SPLIT2      T21
TO   :                      V6          MIX2        V8          V9          MIX1

SUBSTREAM: MIXED
PHASE:                      LIQUID      VAPOR       LIQUID      LIQUID      VAPOR
COMPONENTS: KMOL/HR
  H2                        2.6678      2.6672  6.1273-04      1.3805    170.8418
  CO                       41.4093      4.4905    36.9187     18.4633     75.1591
  CO2                       0.0         0.0         0.0         0.0         0.0
  N2                        4.1219      0.6224      3.4994      3.2674     13.8957
  O2                        0.0         0.0         0.0         0.0         0.0
  CH4                       8.1588  7.5965-02      8.0828      0.0     4.4772-13
  C2H6                      0.0         0.0         0.0         0.0         0.0
  C3H8                      0.0         0.0         0.0         0.0         0.0
  C4H10                     0.0         0.0         0.0         0.0         0.0
  C5H12                     0.0         0.0         0.0         0.0         0.0
  C6H14                     0.0         0.0         0.0         0.0         0.0
  MEA                       0.0         0.0         0.0         0.0         0.0
  H2O                       0.0         0.0         0.0         0.0         0.0
  AR                        0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR                  56.3579      7.8562     48.5017     23.1112    259.8967
  KG/HR                  1411.6139    149.8133   1261.8005    611.4703   2838.8867
  CUM/SEC                6.3119-04   7.0041-03   5.3431-04   2.6565-04   1.9508-02
STATE VARIABLES:
  TEMP    C              -169.0964   -181.1061   -171.3306   -171.5000   -171.3117
  PRES    BAR              27.3000      2.3000      5.4000     27.3470     27.3000
  VFRAC                     0.0         1.0000      0.0         0.0         1.0000
  LFRAC                     1.0000      0.0         1.0000      1.0000      0.0
  SFRAC                     0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL                -1.0336+08 -6.9861+07 -1.0853+08 -9.9024+07 -3.7786+07
  J/KG                  -4.1267+06 -3.6635+06 -4.1719+06 -3.7427+06 -3.4592+06
  WATT                  -1.6182+06 -1.5246+05 -1.4622+06 -6.3572+05 -2.7279+06
ENTROPY:
  J/KMOL-K              -3.7730+04  1.7899+04 -4.1162+04 -2.0135+04 -2.6796+04
  J/KG-K                -1506.3322   938.6122 -1582.1958  -761.0243 -2453.1805
DENSITY:
  KMOL/CUM                 24.8023      0.3115     25.2153     24.1661      3.7006
  KG/CUM                  621.2319      5.9414    655.9905    639.3788     40.4229
AVG MW                     25.0473     19.0694     26.0155     26.4576     10.9231
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
LC LD LE LF LG
--------------

STREAM ID              LC          LD          LE          LF          LG
FROM :                 CO1         CO1         CO2         MIX1        SPLIT2
TO   :                 CO2         SPLIT2      MIX1        CO1         T21

SUBSTREAM: MIXED
PHASE:                 VAPOR       LIQUID      LIQUID      MIXED       LIQUID
COMPONENTS: KMOL/HR
  H2                  169.5810      5.3843      4.1235    174.9653      4.0038
  CO                   71.5056     72.0097     68.3562    143.5153     53.5464
  CO2                   0.0         0.0         0.0         0.0         0.0
  N2                   16.3949     12.7434     15.2426     29.1384      9.4760
  O2                    0.0         0.0         0.0         0.0         0.0
  CH4                   0.0         0.0         0.0      4.4772-13      0.0
  C2H6                  0.0         0.0         0.0         0.0         0.0
  C3H8                  0.0         0.0         0.0         0.0         0.0
  C4H10                 0.0         0.0         0.0         0.0         0.0
  C5H12                 0.0         0.0         0.0         0.0         0.0
  C6H14                 0.0         0.0         0.0         0.0         0.0
  MEA                   0.0         0.0         0.0         0.0         0.0
  H2O                   0.0         0.0         0.0         0.0         0.0
  AR                    0.0         0.0         0.0         0.0         0.0
TOTAL FLOW:
  KMOL/HR             257.4816     90.1375     87.7223    347.6191     67.0263
  KG/HR              2804.0201   2384.8299   2349.9632   5188.8500   1773.3595
  CUM/SEC            1.9258-02   1.0361-03   8.0929-04   1.8421-02   7.7044-04
STATE VARIABLES:
  TEMP   C           -171.5000   -171.5000   -201.5000   -174.9624   -171.5000
  PRES   BAR           27.3470     27.3470     27.3000     27.3000     27.3470
  VFRAC                 1.0000      0.0         0.0         0.6661      0.0
  LFRAC                 0.0         1.0000      1.0000      0.3338      1.0000
  SFRAC                 0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL            -3.6520+07 -9.9024+07 -9.8714+07 -5.3161+07 -9.9024+07
  J/KG              -3.3535+06 -3.7427+06 -3.6849+06 -3.5614+06 -3.7427+06
  WATT              -2.6120+06 -2.4794+06 -2.4054+06 -5.1333+06 -1.8437+06
ENTROPY:
  J/KMOL-K          -2.7760+04 -2.0135+04 -4.2864+04 -3.0114+04 -2.0135+04
  J/KG-K            -2549.1155   -761.0243 -1600.0736 -2017.4628   -761.0243
DENSITY:
  KMOL/CUM              3.7139     24.1661     30.1097      5.2419     24.1661
  KG/CUM               40.4452    639.3788    806.5977     78.2448    639.3788
AVG MW                 10.8901     26.4576     26.7886     14.9268     26.4576
```

Capacity increase of 20% by using a pre-reformer and extra CO_2.

```
LIQ MEASUMP OUT STM STMFD
-------------------------

STREAM ID            LIQ          MEASUMP      OUT          STM          STMFD
FROM :               V2103        V2116        V2118        V2103        DRUMMIX
TO   :               SPLIT        ----         ----         ----         V2103

SUBSTREAM: MIXED
PHASE:               LIQUID       LIQUID       MIXED        VAPOR        MIXED
COMPONENTS: KMOL/HR
  H2                   0.0        1.9042-07      1.0231       0.0          0.0
  CO                   0.0        4.2828-08      0.3804       0.0          0.0
  CO2                  0.0        6.6332-09    1.1361-02      0.0          0.0
  N2                   0.0        5.3378-09    5.1560-02      0.0          0.0
  O2                   0.0          0.0          0.0          0.0          0.0
  CH4                  0.0        5.8723-08    4.9248-02      0.0          0.0
  C2H6                 0.0          0.0        2.1401-04      0.0          0.0
  C3H8                 0.0          0.0        1.3686-08      0.0          0.0
  C4H10                0.0          0.0          0.0          0.0          0.0
  C5H12                0.0          0.0          0.0          0.0          0.0
  C6H14                0.0          0.0          0.0          0.0          0.0
  MEA                  0.0        1.2770-06    4.6927-03      0.0          0.0
  H2O               6818.7515       0.2116       0.4310     299.6862    6818.6876
  AR                   0.0          0.0          0.0          0.0          0.0
TOTAL FLOW:
  KMOL/HR           6818.7515       0.2116       1.9516     299.6862    6818.6876
  KG/HR             1.2284+05       3.8121      23.5105    5398.8474    1.2284+05
  CUM/SEC           5.6654-02   1.4178-06    3.9118-04      0.1286       0.1944
STATE VARIABLES:
  TEMP    C          221.0000      40.0000      35.0000     221.0000     221.0000
  PRES    BAR         24.0094      10.3000      28.3000      24.0094      24.0094
  VFRAC                0.0          0.0          0.7799       1.0000    4.7995-02
  LFRAC                1.0000       1.0000       0.2200       0.0          0.9520
  SFRAC                0.0          0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL           -2.7130+08  -2.8770+08  -8.9605+07  -2.3648+08  -2.6962+08
  J/KG             -1.5059+07  -1.5970+07  -7.4384+06  -1.3127+07  -1.4967+07
  WATT             -5.1386+08  -1.6911+04  -4.8578+04  -1.9686+07  -5.1069+08
ENTROPY:
  J/KMOL-K         -1.2552+05  -1.6656+05  -3.8272+04  -5.5051+04  -1.2213+05
  J/KG-K           -6967.2642  -9245.2464  -3177.0782  -3055.8504  -6779.5357
DENSITY:
  KMOL/CUM            33.4325      41.4597       1.3859       0.6470       9.7413
  KG/CUM             602.2870     746.9079      16.6950      11.6559     175.4911
AVG MW                18.0150      18.0152      12.0462      18.0150      18.0150
```

Appendix 6

Design of new heat exchangers in the MEA-section.

H-2109 A/B	tube side rich MEA (282)	shell side lean MEA (281)
old flows (kg/hr)	21094.7	19707.9
new flows (kg/hr)	24688.47	23058.30
specific heat (kcal/kg °C)	0.930	0.88
temperatures in/out (°C)	120/88	72/103

U, overall heat transfer coeffient (kcal/m^2 °C hr)	615
ΔT_{lm}, log mean temperature difference (°C)	16.5
$_Ft$, temperature correction factor	0.82
ΔT_m, true temperature difference (°C)	13.5
A, old surface installed (m^2)	70.4

The following formula has been used to globally estimate the new temperatures using the old unchanged heat exchangers in combination with the new larger flows.

$U*A*\Delta T_{lm}=(\text{flow in tubes})*C_p*(T_1-T_2)=(\text{flow in shell})*C_p*(t_2-t_1)$ form. A6.1

Iteration gives:

	rich MEA	lean MEA
new temperatures (°C)	120-90	72-101

H-2108	tube side cooling water	shell side lean MEA (281)
old flows (kg/hr)	85593	21958.3
new flows (kg/hr)	–	23058.30
specific heat (kcal/kg °C)	0.998	0.905
temperatures in/out (°C)	25/-	88/40

U, overall heat transfer coeffient (kcal/m^2 °C hr)	700
$_{F}t$, temperature correction factor	0.89
A, old surface installed (m^2)	50

Formula A6.1 has been used to estimate the new temperatures using the unchanged heat exchanger.

Iteration gives:

	cooling water	lean MEA
new temperatures (°C)	25-30	88-40

With this result comes a new cooling water flow of 200731.98 kg/hr and a cooling water velocity of 0.9 m/s. This velocity exceeds the maximum allowable velocity of 0.5 m/s.

The calculation of the maximum flows in the absorber and stripping column.

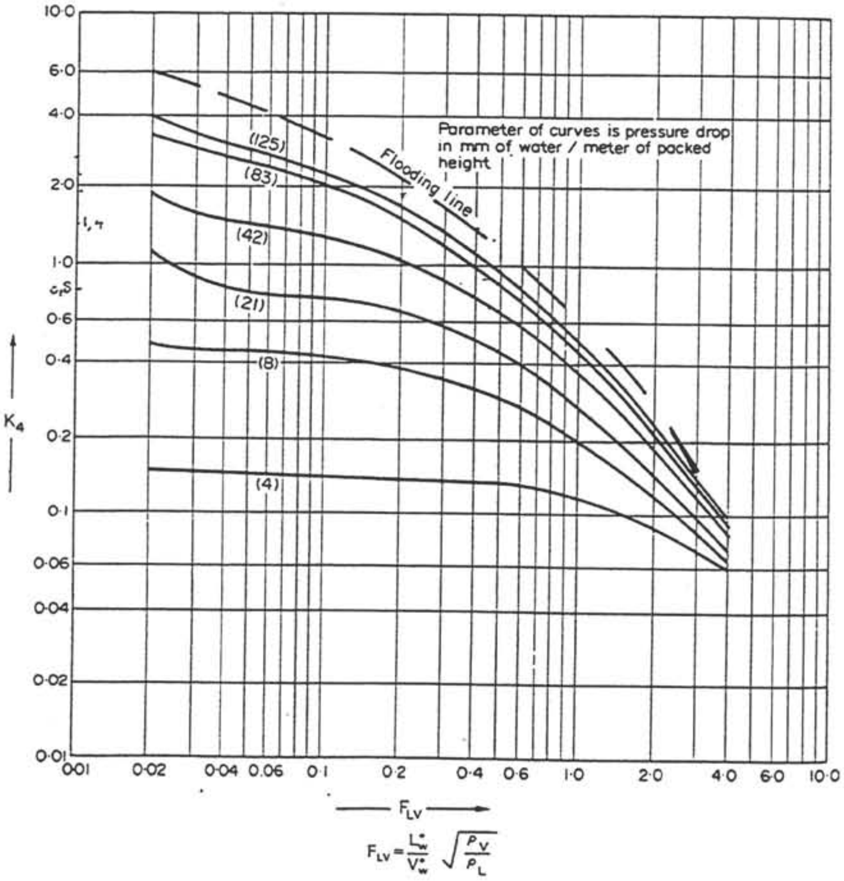


fig. A6.1

The term K_4 is the function:

$$K_4 = \frac{42.9(V_w^*)^2 F_p \left(\frac{\mu_l}{\rho_l}\right)^{0.1}}{\rho_v(\rho_l-\rho_v)} \qquad \text{form. 6.2}$$

V_w = gas mass flow-rate per unit column cross sectional area, kg/m^{2}s
F_p = packing factor, characteristic of the size and type of packing
ν_l = liquid viscosity, Ns/m^2
ρ_l,ρ_v = liquid and vapour densities, kg/m^3

$$0.8=\frac{42.9(vapourflow,kg/s)^2 22(\frac{6.67*10^{-4}}{1076.2})}{(\frac{\pi}{4}0.75^2)^2 5.66(1076.2-5.66)}$$

For the absorber F_{lv} = 0.43 so K_4 = 0.8 at 70% flooding.With the current diameter the absorber has a maximum vapour flow of 7365,63 kg/hr.

So the absorber is at half of its maximum capacity in the current proces.

For the stripper F_{lv}=0.20 so K_4 = 1.9 With the current diameter and at almost 90% flooding the maximum vapour flow is 5184 kg/hr.

$$1.9=42.9(vapourflow,kg/s)^2 29(\frac{3.95*10^{-4}}{824,6118})^{0.1}$$

With an actual flow of 4473.6 kg/hr 17% capacity increase is possible but this is at a very high percentage flooding.

	MEA-absorber V-2105	MEA-stripper V-2106
F_{lv}	0.43	0.196
K_4	0.8	1.9
Max. vapour flow (kg/s)	7365.63	5200
Possible capacity increase (%)	109	16

The new flows in the stripper are the following:

(kg/hr)	KTI 281	New 281
CO_2	421.7	485
MEA	5321.1	6120
H_2O	13965.1	15920
Total mass flow	19707.9	22525

The new flows in the absorber are the following:

	KTI 212	New 212
H_2	300.5	326.6
CO	1498.1	1811.32
CO_2	1380.6	1615,68
N_2	245.4	225,4
CH_4	69	86,72
H_2O	27.9	31,4
Total mass flow	2138.7	4097,12

port for Block: V2105
escription:

Stage	LIQUID SIGMAMX	LIQUID RHOMX	VAPOR RHOMX	LIQUID MUMX	VAPOR MUMX	LIQUID MASSFLMX	VAPOR MASSFLMX
	N/M	KG/CUM	KG/CUM	N-SEC/SQM	N-SEC/SQM	KG/SEC	KG/SEC
_1	.0881417	907.0558	3.896868	5.65301E-4	1.40398E-5	5.474465	.5948598
_2	.0881387	907.0505	3.898998	5.65281E-4	1.40402E-5	5.474528	.5949079
_3	.0881346	907.0432	3.901176	5.65254E-4	1.40408E-5	5.474614	.5949711
_4	.0881291	907.0331	3.903423	5.65218E-4	1.40415E-5	5.474731	.5950573
_5	.0881215	907.0194	3.905762	5.65168E-4	1.40426E-5	5.474891	.5951746
_6	.0881113	907.0008	3.908228	5.65100E-4	1.40439E-5	5.475106	.5953338
_7	.0880975	906.9756	3.910861	5.65009E-4	1.40458E-5	5.475397	.5955491
_8	.0880788	906.9414	3.913721	5.64886E-4	1.40483E-5	5.475790	.5958402
_9	.0880536	906.8953	3.916885	5.64719E-4	1.40516E-5	5.476321	.5962333
_10	.0880197	906.8329	3.920458	5.64495E-4	1.40561E-5	5.477036	.5967636
_11	.0879739	906.7486	3.924580	5.64192E-4	1.40622E-5	5.478000	.5974787
_12	.0879122	906.6346	3.929437	5.63784E-4	1.40704E-5	5.479300	.5984432
_13	.0878289	906.4805	3.935282	5.63233E-4	1.40814E-5	5.481055	.5997437
_14	.0877165	906.2715	3.942443	5.62489E-4	1.40963E-5	5.483424	.6014981
_15	.0875639	905.9862	3.951346	5.61479E-4	1.41164E-5	5.486629	.6038671
_16	.0873537	905.5866	3.962456	5.60085E-4	1.41441E-5	5.491002	.6070727
_17	.0870436	904.9662	3.975760	5.58016E-4	1.41842E-5	5.497170	.6114449
_18	.0864608	903.6369	3.987306	5.54064E-4	1.42557E-5	5.507290	.6176137
_19	.0847227	899.0018	3.970738	5.42024E-4	1.44553E-5	5.534908	.6277335
_20	.0758731	887.4863	3.839470	4.85324E-4	1.51915E-5	5.854966	.6553509

port for Block: V2106
escription:

Stage	LIQUID SIGMAMX	LIQUID RHOMX	VAPOR RHOMX	LIQUID MUMX	VAPOR MUMX	LIQUID MASSFLMX	VAPOR MASSFLMX
	N/M	KG/CUM	KG/CUM	N-SEC/SQM	N-SEC/SQM	KG/SEC	KG/SEC
_1	.0737715	915.7708	1.510871	4.49126E-4	1.59247E-5	.9140364	.6588332
_2	.0705134	905.5043	1.131136	4.29653E-4	1.41703E-5	.9317327	1.572870
_3	.0704665	904.8457	1.128907	4.29423E-4	1.41566E-5	1.265030	1.590499
_4	.0700196	896.8499	1.122500	4.27446E-4	1.41176E-5	1.279534	1.649576
_5	.0639577	839.4263	1.091829	4.00805E-4	1.39529E-5	6.710503	1.217759
_6	.0638935	838.2835	1.053035	4.00317E-4	1.36796E-5	6.716703	1.240083
_7	.0638905	837.7270	1.034668	4.00252E-4	1.35445E-5	6.719707	1.246283
_8	.0639014	837.3967	1.024062	4.00290E-4	1.34647E-5	6.721461	1.249287
_9	.0639156	837.1726	1.017038	4.00357E-4	1.34111E-5	6.722644	1.251041
_10	.0639306	837.0046	1.011891	4.00433E-4	1.33714E-5	6.723507	1.252224
_11	.0639459	836.8678	1.007792	4.00514E-4	1.33395E-5	6.724185	1.253087
_12	.0639618	836.7483	1.004283	4.00600E-4	1.33121E-5	6.724760	1.253765
_13	.0639790	836.6368	1.001081	4.00695E-4	1.32868E-5	6.725276	1.254340
_14	.0639985	836.5258	.9979685	4.00803E-4	1.32621E-5	6.725777	1.254856
_15	.0640222	836.4078	.9947418	4.00936E-4	1.32364E-5	6.726311	1.255357
_16	.0640528	836.2663	.9911574	4.01110E-4	1.32075E-5	6.727025	1.255890
_17	.0640698	835.8208	.9868947	4.01268E-4	1.31728E-5	6.732074	1.256605

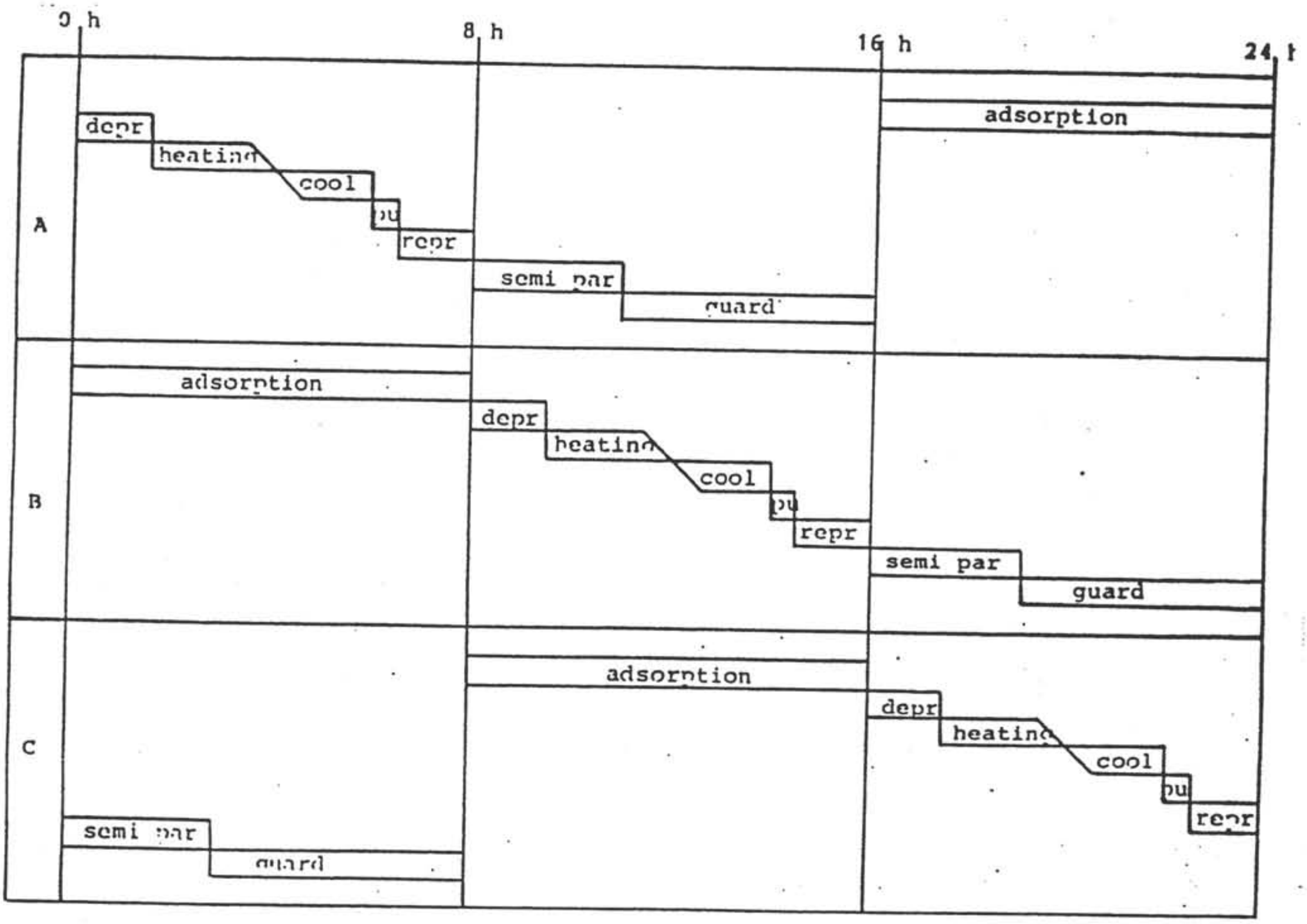


Fig. A6-2: sequence chart process drying

APPENDIX 7

Capacities of the columns

The actual capacities of the columns in the coldbox are estimated with the following equations and diagrams:

$$F_{lg}=\frac{M_l}{M_g}\sqrt{\frac{\rho_g}{\rho_l}}$$ form. A7.1

With this equation the C_{tr} is determinded from the Fair diagram.

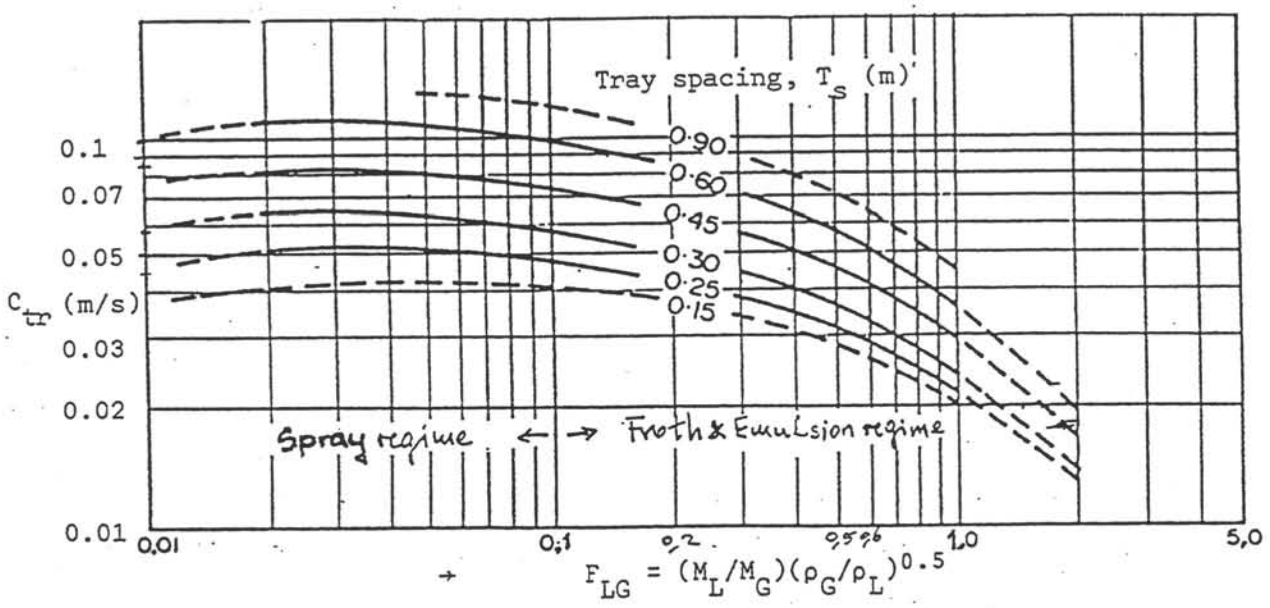


figure A7.1 Flooding gas capacity, sieve (and valve) trays

$$U_{g,max}=C_{tr},\nu\sqrt{\frac{\rho_l-\rho_g}{\rho_g}}$$ form. A7.2

This is the Souders equation which gives the maximum gas velocity of the gas in meter per second.
The C_{tr} is multiplied by the surface tension correction factor (STCF), because of the low liquid surface tension, which gives a deviation from the standard case.

$$C_{tr,new}=C_{tr}(\frac{\sigma}{0.02})^{0.2} \qquad \text{form. A7.3}$$

$$M_{g,max}=\rho_g U_{g,max}(\frac{\pi}{4}d_{col}^2) \qquad \text{form. A7.4}$$

This gives the maximum gas flow in kg/s.

	T 21	T 22	T 23	T 24
F_{lg}	0.15	0.044	1.89	0.44
C_{tr}	0.066	0.070	0.018	0.045
STFC	0.75	0.82	0.82	0.74
$U_{g,max}$ (m/s)	0.201	0.518	0.114	0.154
$M_{g,max}$ (kg/s)	0.938	0.595	0.168	0.572
$M_{g,old}$ (kg/s)	0.500	0.347	0.0164	0.0587
maximum capacity increase (%)	87.5	71.4	925	874.6

ort for Block: T21
scription:

Stage	LIQUID SIGMAMX N/M	LIQUID RHOMX KG/CUM	VAPOR RHOMX KG/CUM	LIQUID MASSFLMX KG/SEC	VAPOR MASSFLMX KG/SEC	LIQUID MUMX N-SEC/SQM	VAPOR MUMX N-SEC/SQM
_1	4.79088E-3	652.6718	36.66274	.3054832	.4863845	7.35368E-5	6.35757E-6
_2	4.74532E-3	650.7390	37.08353	.3060007	.4992052	7.30601E-5	6.39620E-6
_3	4.74407E-3	650.5099	37.08773	.3057463	.4997225	7.30445E-5	6.39917E-6
_4	4.74566E-3	650.4575	37.06915	.3055508	.4994685	7.30584E-5	6.39908E-6
_5	4.74663E-3	650.4266	37.05930	.3054394	.4992735	7.30660E-5	6.39896E-6
_6	4.74702E-3	650.4003	37.05664	.3053814	.4991625	7.30675E-5	6.39901E-6
_7	4.74705E-3	650.3757	37.05833	.3053545	.4991047	7.30654E-5	6.39916E-6
_8	4.74688E-3	650.3522	37.06253	.3053454	.4990778	7.30612E-5	6.39938E-6
_9	4.74660E-3	650.3292	37.06817	.3053465	.4990686	7.30558E-5	6.39963E-6
_10	4.74625E-3	650.3066	37.07463	.3053534	.4990696	7.30497E-5	6.39991E-6
_11	4.74586E-3	650.2842	37.08155	.3053637	.4990763	7.30433E-5	6.40020E-6
_12	4.74545E-3	650.2618	37.08875	.3053757	.4990864	7.30366E-5	6.40049E-6
_13	4.74503E-3	650.2394	37.09608	.3053879	.4990981	7.30298E-5	6.40079E-6
_14	4.74463E-3	650.2167	37.10342	.3053967	.4991101	7.30232E-5	6.40109E-6
_15	4.74438E-3	650.1921	37.11044	.3053853	.4991186	7.30182E-5	6.40139E-6
_16	4.74486E-3	650.1585	37.11560	.3052723	.4991070	7.30207E-5	6.40167E-6
_17	4.74895E-3	650.0796	37.11144	.3046550	.4989939	7.30609E-5	6.40186E-6
_18	4.77106E-3	649.7726	37.06098	.3015641	.4983765	7.32882E-5	6.40162E-6
_19	4.88223E-3	648.2548	36.78384	.2870288	.4952856	7.44282E-5	6.39922E-6
_20	5.41872E-3	639.1665	35.46829	.2569722	.4807500	7.96364E-5	6.38667E-6

eport for Block: T22
Description:

Stage	LIQUID SIGMAMX N/M	LIQUID RHOMX KG/CUM	VAPOR RHOMX KG/CUM	LIQUID MASSFLMX KG/SEC	VAPOR MASSFLMX KG/SEC	LIQUID MUMX N-SEC/SQM	VAPOR MUMX N-SEC/SQM
_1	7.31197E-3	753.2163	9.133204	.1384531	.3470472	1.11930E-4	5.76710E-
_2	7.31579E-3	752.9691	9.126254	.1383641	.3470086	1.11940E-4	5.76724E-
_3	7.31701E-3	752.8975	9.124261	.1383384	.3469197	1.11943E-4	5.76727E-
_4	7.31743E-3	752.8748	9.123677	.1383290	.3468940	1.11944E-4	5.76729E-
_5	7.31777E-3	752.8546	9.123430	.1383139	.3468845	1.11947E-4	5.76732E-
_6	7.31930E-3	752.7674	9.122880	.1382357	.3468695	1.11965E-4	5.76749E-
_7	7.32934E-3	752.2568	9.119863	.1377752	.3467912	1.12072E-4	5.76851E-
_8	7.39643E-3	749.2249	9.102093	.1351342	.3463308	1.12695E-4	5.77455E-
_9	7.80410E-3	732.2524	9.015192	.3522641	.3201784	1.15834E-4	5.80856E-
_10	7.84098E-3	730.5352	8.999117	.3493320	.3202085	1.16066E-4	5.81129E-
_11	8.31009E-3	711.3594	8.886272	.3199710	.3172764	1.19027E-4	5.84672E-
_12	.0110806	566.1318	7.894073	.0320555	.2879155	1.26574E-4	6.12208E-

```
Report for Block: T23
 Description:

    Stage  LIQUID      LIQUID      VAPOR       LIQUID      VAPOR       LIQUID      VAPOR
           SIGMAMX     RHOMX       RHOMX       MASSFLMX    MASSFLMX    MUMX        MUMX
           ----------  ----------  ----------  ----------  ----------  ----------  ----------
           ----------  ----------  ----------  ----------  ----------  ----------  ----------
           N/M         KG/CUM      KG/CUM      KG/SEC      KG/SEC      N-SEC/SQM   N-SEC/SQ
           ----------  ----------  ----------  ----------  ----------  ----------  ----------
     _1    7.62474E-3 714.1853    11.70613    .2417437    .0163610    1.11528E-4 5.77722E
     _2    7.60289E-3 713.7339    11.78829    .2420287    1.13261E-3 1.11296E-4 5.78930E
     _3    7.32268E-3 707.7805    12.89407    .2456082    1.41756E-3 1.08324E-4 5.94174E
     _4    6.33154E-3 682.7448    17.84108    .2406111    4.99709E-3 9.79938E-5 6.46688E

eport for Block: T24
Description:

  Stage  LIQUID      LIQUID      VAPOR       LIQUID      VAPOR       LIQUID      VAPOR
         SIGMAMX     RHOMX       RHOMX       MASSFLMX    MASSFLMX    MUMX        MUMX
         ----------  ----------  ----------  ----------  ----------  ----------  ----------
         ----------  ----------  ----------  ----------  ----------  ----------  ----------
         N/M         KG/CUM      KG/CUM      KG/SEC      KG/SEC      N-SEC/SQM   N-SEC/SQM
         ----------  ----------  ----------  ----------  ----------  ----------  ----------
   _1    6.53091E-3 674.5717    26.25645    .1185112    .0377395    8.21173E-5 6.85642E-6
   _2    4.68666E-3 662.1656    29.47594    .1217341    .0553528    7.86710E-5 7.06115E-6
   _3    4.33531E-3 661.2773    29.63363    .1218169    .0585758    7.85070E-5 7.07235E-6
   _4    4.29080E-3 660.8510    29.60289    .1207022    .0586585    7.85221E-5 7.07358E-6
   _5    4.28863E-3 660.8447    29.60244    .1190000    1.70217E-3 7.85228E-5 7.07359E-6
```

APPENDIX 8. SIMULATION AND RESULTS OF CRYOGENIC METHODS I & II

A8.1. Simulation and results of cryogenic method II on Aspen Plus

Before using Aspen Plus, the patent was first simulated on ChemCad, in order to gain more sufficient specifications to make simulation on Aspen Plus succesful.
On Aspen Plus, only the separating part of the patent was simulated. The reason why the simulation of the heat balance is omitted, is that Aspen Plus does not have a suitable enthalpy routine for simulating multiflow heat exchangers, because of the inaccurateness of the enthalpy calculations (see chapter 12).
Figure A8.1 on the next page shows the adapted flowsheet of the second method. The stream and equipment numbers are not the same as the numbers shown on the flowsheet.

Results

The main streams of this method are listed in Table A8-1 on page A8-35.
According to the print-outs the following conclusions can be made:

- About 80% of the N_2 can be removed from the natural gas feed.
- Only 3.3% nitrogen remains in the new feed stream.
- The CH_4-purity of the natural gas feed stream raised from 81.3% to 91.8%.
- Only 0.03 kmol/hr CH_4 leaves the plant with the nitrogen stream (ID 16), which is only 0.068% of the CH_4-feed stream

confidential

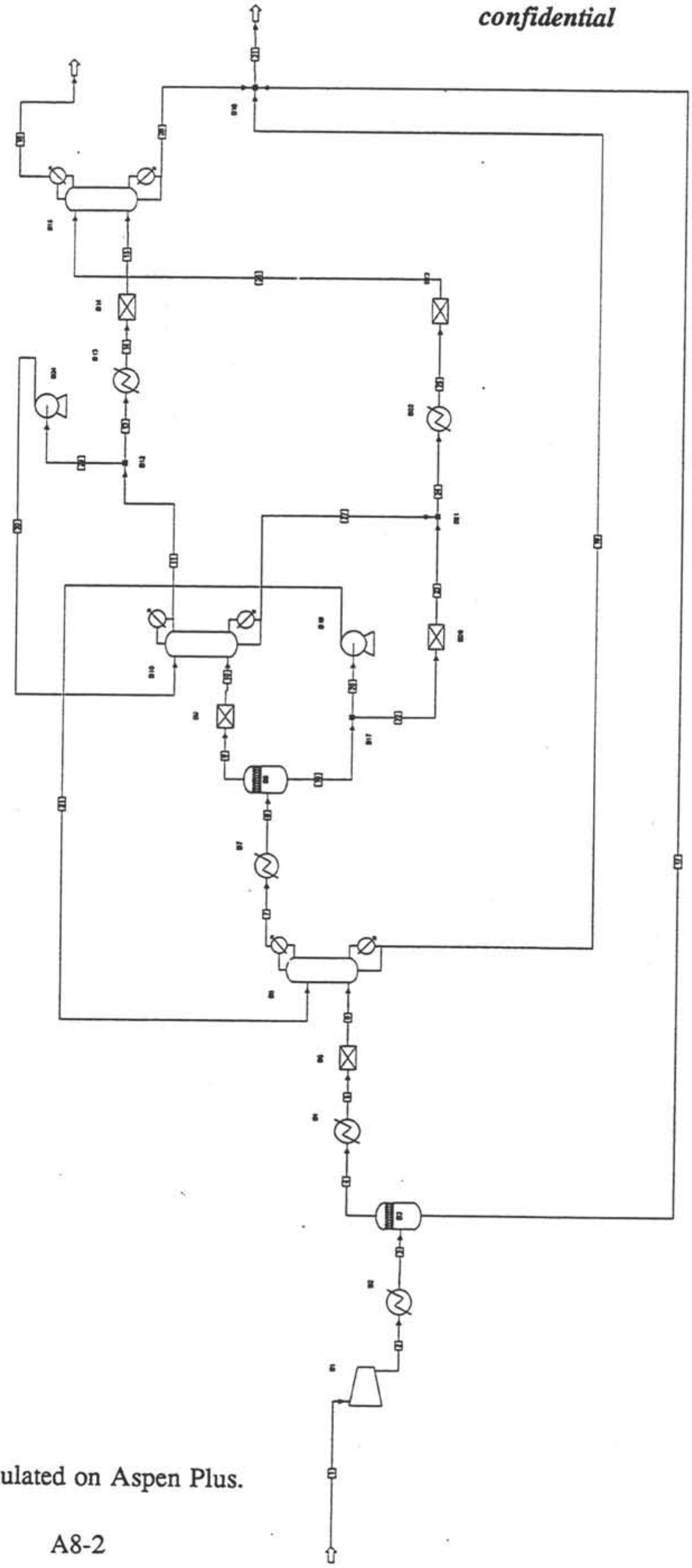


Fig. A8.1. Flowsheet of method II simulated on Aspen Plus.

```
                              U-O-S BLOCK SECTION

BLOCK:  B1        MODEL: COMPR
-----------------------------
   INLET STREAM:              1
   OUTLET STREAM:             2
   PROPERTY OPTION SET:       SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                          ***  MASS AND ENERGY BALANCE  ***
                                        IN              OUT          RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )                 53.1084         53.1084                  0.
       MASS(KG/SEC  )                0.274843        0.274843                  0.
       ENTHALPY(WATT     )       -0.100652E+07     -959938.          -0.462820E-01

                               ***  INPUT DATA  ***

    GAS PHASE CALCULATION
    NO FLASH PERFORMED
    TYPE : POLYTROPIC CENTRIFUGAL COMPRESSOR
    PRESSURE RATIO                                                  2.40000
    OUTLET TEMPERATURE        C                                   103.116
    MECHANICAL EFFICIENCY                                           1.00000

                               ***  RESULTS  ***

    INDICATED  HORSEPOWER REQUIREMENT  WATT                     46,583.9
    BRAKE      HORSEPOWER REQUIREMENT  WATT                     46,583.9
    NET WORK, WATT                                             -46,583.9
    CALCULATED OUTLET PRES  BAR                                     48.0000
    CALC EFFICIENCY (POLYTR/ISENTR)                                  0.73510
    OUTLET VAPOR FRACTION                                            1.00000

BLOCK:  B10       MODEL: RADFRAC
-------------------------------
    INLETS    - 10        STAGE  5
                30        STAGE  2
    OUTLETS   - 11        STAGE  1
                27        STAGE  6
   PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                          ***  MASS AND ENERGY BALANCE  ***
                                        IN              OUT          RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )                 5.46843         5.46844        -0.592896E-06
       MASS(KG/SEC  )              0.373975E-01    0.373975E-01      -0.587825E-06
       ENTHALPY(WATT     )          -42758.6        -46792.9           0.862164E-01
```

```
ASPEN PLUS   VER: SUN-4    REL: 8.5-4    INST: DELFTUOT  05/02/93  PAGE
                             U-O-S BLOCK SECTION

BLOCK:  B10       MODEL: RADFRAC (CONTINUED)


                         *********************
                         ****  INPUT DATA ****
                         *********************

 ****   INPUT PARAMETERS   ****

  NUMBER OF STAGES                                              6
  ALGORITHM OPTION                                           STANDARD
  ABSORBER OPTION                                            NO
  INITIALIZATION OPTION                                      STANDARD
  HYDRAULIC PARAMETER CALCULATIONS                           NO
  INSIDE LOOP CONVERGENCE METHOD                             BROYDEN
  DESIGN SPECIFICATION METHOD                                NESTED
  MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS                       25
  MAXIMUM NO. OF INSIDE LOOP ITERATIONS                        10
  MAXIMUM NUMBER OF FLASH ITERATIONS                           50
  FLASH TOLERANCE                                               0.000100000
  OUTSIDE LOOP CONVERGENCE TOLERANCE                            0.000100000

 ****   COL-SPECS   ****

  MOLAR VAPOR DIST / TOTAL DIST                                 0.0
  MOLAR REFLUX RATIO                                            0.82151
  REBOILER DUTY                        WATT                   404.750

 ****   PROFILES   ****

  P-SPEC         STAGE   1  PRES, BAR                          28.0000
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 9
                                  U-O-S BLOCK SECTION

BLOCK:  B10       MODEL: RADFRAC (CONTINUED)

                               *******************
                               ****  RESULTS  ****
                               *******************

   TOP STAGE TEMPERATURE            C                           -149.434
   BOTTOM STAGE TEMPERATURE         C                           -122.473
   TOP STAGE LIQUID FLOW            KMOL/HR                        5.30635
   BOTTOM STAGE LIQUID FLOW         KMOL/HR                        1.96602
   TOP STAGE VAPOR FLOW             KMOL/HR                        0.0
   BOTTOM STAGE VAPOR FLOW          KMOL/HR                        1.56339
   MOLAR REFLUX RATIO                                              1.51505
   MOLAR BOILUP RATIO                                              0.79521
   CONDENSER DUTY (W/O SUBCOOL)     WATT                      -6,012.93
   REBOILER DUTY                    WATT                       1,978.72

  ****   MANIPULATED VARIABLES   ****

   REBOILER DUTY                    WATT                       1,978.72
   MOLAR REFLUX RATIO                                              1.51505

  ****    DESIGN SPECIFICATIONS   ****

NO  SPEC-TYPE      UNIT         SPECIFIED VALUE   CALCULATED VALUE   ABS. ERROR
 1  MOLE-FRAC                    0.30000           0.30000             0.10055E-08
 2  MOLE-FRAC                    0.50000E-01       0.50000E-01        -0.58788E-09


  ****   MAXIMUM FINAL RELATIVE ERRORS    ****

   DEW POINT                              0.44439E-05  STAGE=  2
   BUBBLE POINT                           0.72003E-05  STAGE=  3
   COMPONENT MASS BALANCE                 0.36807E-06  STAGE=  1 COMP=N2
   ENERGY BALANCE                         0.34618E-04  STAGE=  2

  ****    PROFILES    ****


                                               ENTHALPY
STAGE TEMPERATURE      PRESSURE                J/KMOL                HEAT DUTY
        C              BAR              LIQUID         VAPOR          WATT

  1   -149.43          28.000        -0.12691E+08 -0.81658E+07   -6012.9298
  2   -146.92          28.200        -0.18742E+08 -0.10234E+08
  3   -141.95          28.400        -0.30973E+08 -0.14435E+08
  4   -133.81          28.600        -0.47611E+08 -0.22233E+08
  5   -130.25          28.800        -0.53083E+08 -0.26087E+08
  6   -122.47          29.000        -0.63074E+08 -0.35963E+08    1978.7217
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4      INST: DELFTUOT  05/02/93  PAGE

                                  U-O-S BLOCK SECTION

BLOCK:  B10        MODEL: RADFRAC (CONTINUED)

STAGE        FLOW RATE                         FEED RATE                       PRODUCT RATE
              KMOL/HR                           KMOL/HR                          KMOL/HR
       LIQUID        VAPOR          LIQUID      VAPOR      MIXED          LIQUID      VAPOR
   1  5.306           0.                                                    3.5024
   2  5.730         8.809            1.7512
   3  4.386         7.482
   4  3.600         6.138                        3.6521
   5  3.529         1.699         .65043-01
   6  1.966         1.563                                                   1.9660

                             ****   X-PROFILE              ****
  STAGE        CH4            C2H6          N2             O2             CO2
     1     .50000E-01     .61921E-13    .94975        .25016E-03     .13923E-11
     2     .12652         .15372E-11    .87316        .31890E-03     .23382E-10
     3     .28207         .41403E-10    .71756        .36405E-03     .42158E-09
     4     .49628         .10701E-08    .50339        .33852E-03     .72854E-08
     5     .56775         .15966E-08    .43191        .34559E-03     .98664E-08
     6     .69969         .27739E-08    .30000        .31188E-03     .16888E-07

                             ****   Y-PROFILE              ****
  STAGE        CH4            C2H6          N2             O2             CO2
     1     .20907E-01     .33152E-14    .97890        .19466E-03     .10775E-12
     2     .50000E-01     .61921E-13    .94975        .25016E-03     .13923E-11
     3     .10861         .11932E-11    .89109        .30281E-03     .18288E-10
     4     .21586         .29609E-10    .78381        .33155E-03     .30176E-09
     5     .26828         .49054E-10    .73135        .36522E-03     .45067E-09
     6     .40182         .11609E-09    .59779        .38799E-03     .10365E-08

                             ****   K-VALUES               ****
  STAGE        CH4            C2H6          N2             O2             CO2
     1     .41813         .53536E-01    1.0307        .77812         .77383E-01
     2     .39518         .40281E-01    1.0877        .78444         .59543E-01
     3     .38503         .28815E-01    1.2418        .83177         .43374E-01
     4     .43495         .27669E-01    1.5571        .97942         .41418E-01
     5     .47254         .30724E-01    1.6933        1.0568         .45678E-01
     6     .57429         .41852E-01    1.9926        1.2440         .61374E-01

BLOCK:  B12        MODEL: FSPLIT
------------------------------
  INLET STREAM:              11
  OUTLET STREAMS:            13          29
  PROPERTY OPTION SET:       SYSOP3      REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE   ***
                                     IN                   OUT              RELATIVE DIFF.
  TOTAL BALANCE
     MOLE(KMOL/HR )              3.50242             3.50242                   0.
     MASS(KG/SEC  )            0.266724E-01        0.266724E-01                0.
     ENTHALPY(WATT      )      -12347.0            -12347.0                    0.

                             ***  INPUT DATA  ***
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 11
                              U-O-S BLOCK SECTION

BLOCK:  B12       MODEL: FSPLIT (CONTINUED)

 FRACTION OF FLOW                    STRM=13        FRAC=          0.50000

                            ***  RESULTS  ***

 STREAM= 13             SPLIT=           0.50000    KEY=  0
         29                              0.50000          0
BLOCK:  B13       MODEL: HEATER
------------------------------
   INLET STREAM:             13
   OUTLET STREAM:            14
   PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                        IN              OUT           RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )               1.75121          1.75121             0.
       MASS(KG/SEC  )              0.133362E-01     0.133362E-01     0.130076E-15
       ENTHALPY(WATT     )         -6173.52         -6221.28         0.767771E-02

                            ***  INPUT DATA  ***
   TWO    PHASE  PV  FLASH
   SPECIFIED PRESSURE                 BAR                             27.0000
   VAPOR FRACTION                                                      0.0
   MAXIMUM NO. ITERATIONS                                             30
   CONVERGENCE TOLERANCE                                               0.000100000

                             ***  RESULTS  ***
   OUTLET TEMPERATURE     C                                            -150.24
   OUTLET PRESSURE        BAR                                           27.000
   HEAT DUTY              WATT                                         -47.765
   VAPOR FRACTION                                                            0.


   V-L PHASE EQUILIBRIUM :

      COMP                 F(I)          X(I)          Y(I)          K(I)
      CH4              0.50000E-01   0.50000E-01   0.19645E-01   0.39291
      C2H6             0.56346E-13   0.56346E-13   0.24485E-14   0.43453E-01
      N2               0.94975       0.94975       0.98016        1.0321
      O2               0.25016E-03   0.25016E-03   0.19104E-03   0.76370
      CO2              0.11648E-11   0.11648E-11   0.74908E-13   0.64310E-01
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 12
                            U-O-S BLOCK SECTION

BLOCK:  B14       MODEL: HEATER
------------------------------
  INLET STREAM:              14
  OUTLET STREAM:             15
  PROPERTY OPTION SET:       SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                    IN                OUT           RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )            1.75121           1.75121                  0.
      MASS(KG/SEC  )           0.133362E-01      0.133362E-01              0.
      ENTHALPY(WATT     )      -6221.28          -6221.28          -0.337016E-06

                           ***  INPUT DATA  ***
  TWO    PHASE  PQ  FLASH
  SPECIFIED PRESSURE                BAR                               2.33000
  SPECIFIED HEAT DUTY               WATT                              0.0
  MAXIMUM NO. ITERATIONS                                             30
  CONVERGENCE TOLERANCE                                               0.000100000

                            ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                           -186.68
  OUTLET PRESSURE       BAR                                           2.3300
  VAPOR FRACTION                                                      0.52882


  V-L PHASE EQUILIBRIUM :

     COMP                 F(I)            X(I)            Y(I)            K(I)
     CH4                  0.50000E-01     0.10102         0.45441E-02     0.44984E-
     C2H6                 0.56346E-13     0.11958E-12     0.28990E-17     0.24242E-
     N2                   0.94975         0.89861         0.99532          1.1077
     O2                   0.25016E-03     0.37405E-03     0.13978E-03     0.37370
     CO2                  0.11648E-11     0.24719E-11     0.13122E-15     0.53083E-
BLOCK:  B15       MODEL: RADFRAC
------------------------------
   INLETS    - 15           STAGE   4
               26           STAGE   2
   OUTLETS   - 16           STAGE   1
               28           STAGE   5
 PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE
```

```
                              U-O-S BLOCK SECTION

BLOCK:  B15      MODEL: RADFRAC (CONTINUED)

                         ***  MASS AND ENERGY BALANCE  ***
                                     IN              OUT            RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )             16.3147          16.3147          0.217761E-15
      MASS(KG/SEC  )           0.939035E-01     0.939035E-01       0.591151E-15
      ENTHALPY(WATT     )      -264610.         -257924.          -0.252700E-01


                            *********************
                            ****  INPUT DATA  ****
                            *********************

  ****    INPUT PARAMETERS    ****

   NUMBER OF STAGES                                               5
   ALGORITHM OPTION                                             STANDARD
   ABSORBER OPTION                                              NO
   INITIALIZATION OPTION                                        STANDARD
   HYDRAULIC PARAMETER CALCULATIONS                             NO
   INSIDE LOOP CONVERGENCE METHOD                               BROYDEN
   DESIGN SPECIFICATION METHOD                                  NESTED
   MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS                         25
   MAXIMUM NO. OF INSIDE LOOP ITERATIONS                          10
   MAXIMUM NUMBER OF FLASH ITERATIONS                             50
   FLASH TOLERANCE                                                 0.000100000
   OUTSIDE LOOP CONVERGENCE TOLERANCE                              0.000100000

  ****    COL-SPECS    ****

   MOLAR VAPOR DIST / TOTAL DIST                                   1.00000
   MOLAR REFLUX RATIO                                              0.42481
   REBOILER DUTY                        WATT                  13,097.5

  ****    PROFILES    ****

   P-SPEC          STAGE   1  PRES, BAR                            1.50000
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 1
                            U-O-S BLOCK SECTION

BLOCK:  B15       MODEL: RADFRAC (CONTINUED)

                          *******************
                          ****  RESULTS  ****
                          *******************

   TOP STAGE TEMPERATURE             C                           -190.717
   BOTTOM STAGE TEMPERATURE          C                           -154.181
   TOP STAGE LIQUID FLOW             KMOL/HR                        4.75544
   BOTTOM STAGE LIQUID FLOW          KMOL/HR                      10.2204
   TOP STAGE VAPOR FLOW              KMOL/HR                        6.09426
   BOTTOM STAGE VAPOR FLOW           KMOL/HR                        6.12364
   MOLAR REFLUX RATIO                                               0.78031
   MOLAR BOILUP RATIO                                               0.59916
   CONDENSER DUTY (W/O SUBCOOL)      WATT                      -8,854.12
   REBOILER DUTY                     WATT                      15,541.1

  ****   MANIPULATED VARIABLES   ****

   REBOILER DUTY                     WATT                      15,541.1
   MOLAR REFLUX RATIO                                               0.78031

  ****   DESIGN SPECIFICATIONS   ****

NO  SPEC-TYPE      UNIT       SPECIFIED VALUE    CALCULATED VALUE    ABS. ERROR
 1  MOLE-FRAC                   0.30000E-01        0.29982E-01       0.18348E-04
 2  MOLE-FRAC                   0.99500            0.99500           0.97063E-07


  ****   MAXIMUM FINAL RELATIVE ERRORS   ****

   DEW POINT                         0.86568E-04  STAGE=  5
   BUBBLE POINT                      0.26321E-03  STAGE=  2
   COMPONENT MASS BALANCE            0.92157E-08  STAGE=  2 COMP=CH4
   ENERGY BALANCE                    0.41431E-04  STAGE=  3

  ****   PROFILES   ****


                                               ENTHALPY
STAGE TEMPERATURE      PRESSURE                J/KMOL              HEAT DUTY
        C              BAR            LIQUID            VAPOR        WATT

  1  -190.72           1.5000      -0.23072E+08 -0.67438E+07   -8854.1177
  2  -181.79           1.7500      -0.62149E+08 -0.98671E+07
  3  -177.95           2.0000      -0.67550E+08 -0.11770E+08
  4  -167.79           2.2500      -0.79425E+08 -0.23268E+08
  5  -154.18           2.5000      -0.86829E+08 -0.57933E+08    .15541+05
```

```
                                U-O-S BLOCK SECTION

BLOCK:  B15      MODEL: RADFRAC (CONTINUED)

STAGE     FLOW RATE                     FEED RATE                   PRODUCT RATE
           KMOL/HR                       KMOL/HR                       KMOL/HR
     LIQUID      VAPOR          LIQUID    VAPOR    MIXED         LIQUID    VAPOR
  1  4.755       6.094                    2.4953                             6.0942
  2  16.30       8.354          12.0681
  3  16.00       7.834                    0.9305
  4  16.34       6.599           0.8206
  5  10.22       6.124                                           10.2204

                            ****  X-PROFILE          ****
   STAGE     CH4           C2H6         N2           O2           CO2
      1    .14065       .22718E-11  .85894       .41507E-03  .14428E-10
      2    .63900       .22316E-07  .36060       .39702E-03  .95132E-07
      3    .70973       .22744E-07  .28969       .58096E-03  .96958E-07
      4    .86648       .22291E-07  .13292       .59102E-03  .95095E-07
      5    .96971       .35597E-07  .29982E-01   .30834E-03  .15174E-06

                            ****  Y-PROFILE          ****
   STAGE     CH4           C2H6         N2           O2           CO2
      1    .48577E-02     0.        .99500       .14242E-03     0.
      2    .49421E-01  .59849E-12   .95032       .26155E-03  .39305E-11
      3    .75870E-01  .12167E-11   .92365       .47989E-03  .78221E-11
      4    .23142      .70233E-11   .76760       .97771E-03  .44141E-10
      5    .69420      .84400E-10   .30474       .10628E-02  .54755E-09

                            ****  K-VALUES           ****
   STAGE     CH4           C2H6         N2           O2           CO2
      1    .34534E-01  .88838E-05  1.1584       .34310       .18871E-04
      2    .77344E-01  .26850E-04  2.6346       .65855       .41351E-04
      3    .10691      .53552E-04  3.1875       .82593       .80764E-04
      4    .26707      .31501E-03  5.7748       1.6543       .46411E-03
      5    .71582      .23700E-02  10.165       3.4469       .36067E-02

BLOCK:  B16      MODEL: MIXER
-----------------------------
   INLET STREAMS:           17          18          28
   OUTLET STREAM:           31
   PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                     IN              OUT          RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )             47.0146          47.0146               0.
       MASS(KG/SEC  )            0.227521         0.227521               0.
       ENTHALPY(WATT     )    -0.114290E+07    -0.114290E+07    -0.353128E-05
```

```
                                U-O-S BLOCK SECTION

BLOCK:  B16      MODEL: MIXER (CONTINUED)

                              ***  INPUT DATA  ***
  TWO    PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                              30
  CONVERGENCE TOLERANCE                                                0.000100000
  OUTLET PRESSURE   BAR                                              15.0000

BLOCK:  B17      MODEL: FSPLIT
------------------------------
  INLET STREAM:              19
  OUTLET STREAMS:            20          22
  PROPERTY OPTION SET:       SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                          ***  MASS AND ENERGY BALANCE  ***
                                       IN                OUT           RELATIVE DIFF
   TOTAL BALANCE
      MOLE(KMOL/HR )              16.2548           16.2548                    0.
      MASS(KG/SEC  )             0.901189E-01      0.901189E-01                0.
      ENTHALPY(WATT     )         -274641.          -274641.            0.211941E-15

                              ***  INPUT DATA  ***

 FRACTION OF FLOW                      STRM=20          FRAC=           0.22500

                              ***  RESULTS  ***

 STREAM= 20              SPLIT=             0.22500    KEY=  0
         22                                 0.77500          0

BLOCK:  B18      MODEL: PUMP
----------------------------
  INLET STREAM:              20
  OUTLET STREAM:             21
  PROPERTY OPTION SET:       SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                          ***  MASS AND ENERGY BALANCE  ***
                                       IN                OUT           RELATIVE DIFF
   TOTAL BALANCE
      MOLE(KMOL/HR )              3.65733           3.65733                    0.
      MASS(KG/SEC  )             0.202767E-01      0.202767E-01        0.171105E-15
      ENTHALPY(WATT     )         -61794.3          -61775.6            -0.302297E-03
```

```
                                 U-O-S BLOCK SECTION

BLOCK:  B18      MODEL: PUMP (CONTINUED)

                             ***  INPUT DATA  ***
   OUTLET PRESSURE (BAR     )                                   32.5000
   DRIVER EFFICIENCY                                             1.00000

   FLASH SPECIFICATIONS:
   LIQUID PHASE CALCULATION
   NO FLASH PERFORMED
   MAXIMUM NUMBER OF ITERATIONS                                  30
   TOLERANCE                                                     0.000100000

                              ***  RESULTS  ***
   VOLUMETRIC FLOW RATE (CUM/SEC )                               0.552301-04
   PRESSURE CHANGE (BAR     )                                    1.00000
   FLUID POWER (WATT     )                                       5.52301
   BRAKE POWER (WATT     )                                      18.6804
   ELECTRICITY (WATT     )                                      18.6804
   PUMP EFFICIENCY USED                                          0.29566
   NET WORK (WATT     )                                        -18.6804

BLOCK:  B2       MODEL: HEATER
------------------------------
  INLET STREAM:            2
  OUTLET STREAM:           3
  PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                        IN             OUT         RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )               53.1084         53.1084                0.
      MASS(KG/SEC  )              0.274843        0.274843                0.
      ENTHALPY(WATT     )         -959938.     -0.109029E+07       0.119558

                             ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE           C                             -80.0000
  SPECIFIED PRESSURE              BAR                            47.5000
  MAXIMUM NO. ITERATIONS                                         30
  CONVERGENCE TOLERANCE                                           0.000100000
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4      INST: DELFTUOT  05/02/93  PAGE 18
                               U-O-S BLOCK SECTION

BLOCK:  B2        MODEL: HEATER (CONTINUED)

                             ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                           -80.000
  OUTLET PRESSURE       BAR                                          47.500
  HEAT DUTY             WATT                                       -0.13035E+06
  VAPOR FRACTION                                                    0.90064


  V-L PHASE EQUILIBRIUM :

     COMP                F(I)            X(I)            Y(I)            K(I)
     CH4                0.81305         0.76520         0.81833          1.0694
     C2H6               0.28492E-01     0.10314         0.20257E-01     0.19639
     C3H8               0.37152E-02     0.24988E-01     0.13683E-02     0.54754E-
     C4H10              0.13931E-02     0.12269E-01     0.19315E-03     0.15741E-
     C5H12              0.39148E-03     0.37888E-02     0.16673E-04     0.44000E-
     C6H14              0.50257E-03     0.50001E-02     0.63826E-05     0.12763E-
     N2                 0.14344         0.57286E-01     0.15294          2.6700
     O2                 0.11769E-03     0.69774E-04     0.12297E-03      1.7625
     CO2                0.88991E-02     0.28251E-01     0.67641E-02     0.23942
BLOCK:  B20       MODEL: HEATER
------------------------------
  INLET STREAM:            22
  OUTLET STREAM:           23
  PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                    IN              OUT            RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )             12.5975          12.5975              0.
      MASS(KG/SEC  )            0.698421E-01     0.698421E-01     0.198702E-15
      ENTHALPY(WATT     )       -212847.         -212847.          0.133706E-05

                       ***  INPUT DATA  ***
  TWO    PHASE  PQ  FLASH
  SPECIFIED PRESSURE            BAR                              28.5000
  SPECIFIED HEAT DUTY           WATT                              0.0
  MAXIMUM NO. ITERATIONS                                         30
  CONVERGENCE TOLERANCE                                           0.000100000
```

```
                              U-O-S BLOCK SECTION

BLOCK:  B20       MODEL: HEATER (CONTINUED)

                            ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                       -123.60
  OUTLET PRESSURE       BAR                                      28.500
  VAPOR FRACTION                                                0.59809E-01


  V-L PHASE EQUILIBRIUM :

     COMP             F(I)            X(I)             Y(I)             K(I)
     CH4            0.67294         0.69115          0.38658          0.55931
     C2H6           0.28447E-07     0.30183E-07      0.11650E-08      0.38600E-01
     N2             0.32683         0.30861          0.61313           1.9867
     O2             0.23561E-03     0.23241E-03      0.28591E-03       1.2302
     CO2            0.12047E-06     0.12768E-06      0.72647E-08      0.56900E-01

BLOCK:  B21       MODEL: MIXER
-----------------------------
  INLET STREAMS:            23          27
  OUTLET STREAM:            24
  PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                      IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )             14.5635         14.5635              0.
      MASS(KG/SEC  )            0.805673E-01    0.805673E-01     -0.689004E-15
      ENTHALPY(WATT     )       -247293.        -247293.          0.147643E-05

                            ***  INPUT DATA  ***
  TWO     PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                       30
  CONVERGENCE TOLERANCE                                         0.000100000
  OUTLET PRESSURE   BAR                                       28.5000

BLOCK:  B22       MODEL: HEATER
------------------------------
  INLET STREAM:             24
  OUTLET STREAM:            25
  PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE
```

```
                              U-O-S BLOCK SECTION

BLOCK:  B22        MODEL: HEATER (CONTINUED)

                        ***  MASS AND ENERGY BALANCE  ***
                                      IN                 OUT            RELATIVE DIFF
  TOTAL BALANCE
     MOLE(KMOL/HR )                14.5635             14.5635              0.
     MASS(KG/SEC  )              0.805673E-01        0.805673E-01           0.
     ENTHALPY(WATT     )         -247293.            -258390.           0.429436E-01

                           ***  INPUT DATA  ***
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE                C                            -161.150
 SPECIFIED PRESSURE                   BAR                            28.0000
 MAXIMUM NO. ITERATIONS                                              30
 CONVERGENCE TOLERANCE                                                0.000100000

                            ***  RESULTS  ***
 OUTLET TEMPERATURE      C                                           -161.15
 OUTLET PRESSURE         BAR                                           28.000
 HEAT DUTY               WATT                                        -11096.
 VAPOR FRACTION                                                            0.


 V-L PHASE EQUILIBRIUM :

    COMP
                         F(I)             X(I)             Y(I)             K(I)
    CH4              0.67655          0.67655          0.19999          0.90044E-
    C2H6             0.24981E-07      0.24981E-07      0.81017E-10      0.95570E-
    N2               0.32321          0.32321          0.79978          0.76429
    O2               0.24590E-03      0.24590E-03      0.23810E-03      0.29802
    CO2              0.10649E-06      0.10649E-06      0.38900E-09      0.10843E-
BLOCK:  B23        MODEL: HEATER
------------------------------
  INLET STREAM:               25
  OUTLET STREAM:              26
  PROPERTY OPTION SET:        SYSOP3     REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                      IN                 OUT            RELATIVE DIFF.
  TOTAL BALANCE
     MOLE(KMOL/HR )                14.5635             14.5635              0.
     MASS(KG/SEC  )              0.805673E-01        0.805673E-01           0.
     ENTHALPY(WATT     )         -258390.            -258389.          -0.246774E-05
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 21
                                U-O-S BLOCK SECTION

BLOCK:  B23       MODEL: HEATER (CONTINUED)

                          ***  INPUT DATA  ***
  TWO    PHASE  PQ  FLASH
  SPECIFIED PRESSURE              BAR                            2.00000
  SPECIFIED HEAT DUTY             WATT                           0.0
  MAXIMUM NO. ITERATIONS                                        30
  CONVERGENCE TOLERANCE                                          0.000100000

                           ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                        -174.92
  OUTLET PRESSURE       BAR                                       2.0000
  VAPOR FRACTION                                                 0.15871


  V-L PHASE EQUILIBRIUM :

     COMP               F(I)           X(I)           Y(I)           K(I)
     CH4                0.67655        0.78236        0.11564        0.14780
     C2H6               0.24981E-07    0.29693E-07    0.27838E-11    0.93738E-0
     N2                 0.32321        0.21739        0.88410         4.0671
     O2                 0.24590E-03    0.24322E-03    0.26014E-03    1.0696
     CO2                0.10649E-06    0.12658E-06    0.17458E-10    0.13791E-0
BLOCK:  B24       MODEL: PUMP
---------------------------
  INLET STREAM:            29
  OUTLET STREAM:           30
  PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                   IN             OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )            1.75121         1.75121               0.
      MASS(KG/SEC  )          0.133362E-01    0.133362E-01     0.130076E-15
      ENTHALPY(WATT     )     -6173.52        -6168.38         -0.832438E-03

                          ***  INPUT DATA  ***
   OUTLET PRESSURE (BAR      )                               28.5000
   DRIVER EFFICIENCY                                          1.00000

   FLASH SPECIFICATIONS:
   LIQUID PHASE CALCULATION
   NO FLASH PERFORMED
   MAXIMUM NUMBER OF ITERATIONS                               30
   TOLERANCE                                                  0.000100000
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE

                              U-O-S BLOCK SECTION

BLOCK:  B24       MODEL: PUMP (CONTINUED)

                            ***  RESULTS  ***
    VOLUMETRIC FLOW RATE (CUM/SEC )                              0.303778-04
    PRESSURE CHANGE (BAR      )                                  0.50000
    FLUID POWER (WATT     )                                      1.51889
    BRAKE POWER (WATT     )                                      5.13732
    ELECTRICITY (WATT     )                                      5.13732
    PUMP EFFICIENCY USED                                         0.29566
    NET WORK (WATT     )                                        -5.13732

BLOCK:  B3        MODEL: FLASH2
------------------------------
   INLET STREAM:              3
   OUTLET VAPOR STREAM:       4
   OUTLET LIQUID STREAM:      17
   PROPERTY OPTION SET:       SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                      IN             OUT          RELATIVE DIFF
   TOTAL BALANCE
      MOLE(KMOL/HR )               53.1084         53.1084               0.
      MASS(KG/SEC  )               0.274843        0.274843         0.163440E-08
      ENTHALPY(WATT     )       -0.109029E+07   -0.109029E+07            0.

                           ***  INPUT DATA  ***
   TWO    PHASE  TP  FLASH
   SPECIFIED TEMPERATURE C                                      -80.0000
   SPECIFIED PRESSURE    BAR                                     47.5000
   MAXIMUM NO. ITERATIONS                                        30
   CONVERGENCE TOLERANCE                                          0.000100000
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 23
                              U-O-S BLOCK SECTION

BLOCK:  B3        MODEL: FLASH2 (CONTINUED)

                            ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                        -80.000
  OUTLET PRESSURE       BAR                                       47.500
  HEAT DUTY             WATT                                          0.
  VAPOR FRACTION                                                 0.90064


  V-L PHASE EQUILIBRIUM :

     COMP                F(I)          X(I)          Y(I)          K(I)
     CH4               0.81305       0.76520       0.81833       1.0694
     C2H6              0.28492E-01   0.10314       0.20257E-01   0.19639
     C3H8              0.37152E-02   0.24988E-01   0.13683E-02   0.54754E-01
     C4H10             0.13931E-02   0.12269E-01   0.19315E-03   0.15741E-01
     C5H12             0.39148E-03   0.37888E-02   0.16673E-04   0.44000E-02
     C6H14             0.50257E-03   0.50001E-02   0.63826E-05   0.12763E-02
     N2                0.14344       0.57286E-01   0.15294       2.6700
     O2                0.11769E-03   0.69774E-04   0.12297E-03   1.7625
     CO2               0.88991E-02   0.28251E-01   0.67641E-02   0.23942
BLOCK:  B4        MODEL: HEATER
------------------------------
  INLET STREAM:            4
  OUTLET STREAM:           5
  PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                    IN            OUT         RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )             47.8314        47.8314              0.
      MASS(KG/SEC  )            0.244431       0.244431      -0.113552E-15
      ENTHALPY(WATT     )       -952223.       -995184.        0.431686E-01

                           ***  INPUT DATA  ***
  TWO    PHASE  PV  FLASH
  SPECIFIED PRESSURE              BAR                          47.0000
  VAPOR FRACTION                                                 0.0
  MAXIMUM NO. ITERATIONS                                       500
  CONVERGENCE TOLERANCE                                          0.000100000
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4    INST: DELFTUOT  05/02/93  PAGE 2
                            U-O-S BLOCK SECTION

BLOCK:  B4         MODEL: HEATER (CONTINUED)

                          ***  RESULTS  ***
 OUTLET TEMPERATURE     C                                          -92.387
 OUTLET PRESSURE        BAR                                         47.000
 HEAT DUTY              WATT                                       -42961.
 VAPOR FRACTION                                                         0.


 V-L PHASE EQUILIBRIUM :

    COMP                F(I)            X(I)            Y(I)            K(I)
    CH4              0.81833         0.81833         0.74902         0.91540
    C2H6             0.20257E-01     0.20257E-01     0.62748E-02     0.30979
    C3H8             0.13683E-02     0.13683E-02     0.18186E-03     0.13292
    C4H10            0.19315E-03     0.19315E-03     0.11222E-04     0.58104E-
    C5H12            0.16673E-04     0.16673E-04     0.41165E-06     0.24692E-
    C6H14            0.63826E-05     0.63826E-05     0.67510E-07     0.10579E-
    N2               0.15294         0.15294         0.24184          1.5814
    O2               0.12297E-03     0.12297E-03     0.15644E-03      1.2722
    CO2              0.67641E-02     0.67641E-02     0.25090E-02     0.37095
BLOCK:  B5         MODEL: HEATER
------------------------------
 INLET STREAM:            5
 OUTLET STREAM:           6
 PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                  IN                OUT          RELATIVE DIFF.
 TOTAL BALANCE
    MOLE(KMOL/HR )             47.8314            47.8314                0.
    MASS(KG/SEC  )            0.244431           0.244431                0.
    ENTHALPY(WATT      )      -995184.           -995184.         0.105697E-06

                         ***  INPUT DATA  ***
TWO    PHASE  PQ  FLASH
SPECIFIED PRESSURE              BAR                            32.9000
SPECIFIED HEAT DUTY             WATT                            0.0
MAXIMUM NO. ITERATIONS                                         30
CONVERGENCE TOLERANCE                                           0.000100000
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4      INST: DELFTUOT  05/02/93  PAGE 25
                                U-O-S BLOCK SECTION

BLOCK:  B5        MODEL: HEATER (CONTINUED)

                              ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                            -102.07
  OUTLET PRESSURE       BAR                                           32.900
  VAPOR FRACTION                                                      0.31399


  V-L PHASE EQUILIBRIUM :

     COMP                 F(I)            X(I)            Y(I)            K(I)
     CH4               0.81833         0.85540         0.73732         0.86198
     C2H6              0.20257E-01     0.28182E-01     0.29414E-02     0.10437
     C3H8              0.13683E-02     0.19763E-02     0.39947E-04     0.20212E-01
     C4H10             0.19315E-03     0.28104E-03     0.11432E-05     0.40676E-02
     C5H12             0.16673E-04     0.24295E-04     0.18769E-07     0.77248E-03
     C6H14             0.63826E-05     0.93033E-05     0.13947E-08     0.14991E-03
     N2                0.15294         0.10477         0.25820          2.4646
     O2                0.12297E-03     0.10299E-03     0.16663E-03      1.6179
     CO2               0.67641E-02     0.92520E-02     0.13283E-02     0.14357
BLOCK:  B6        MODEL: RADFRAC
-------------------------------
   INLETS    - 6          STAGE   8
               21         STAGE   2
   OUTLETS   - 7          STAGE   1
               18         STAGE  10
  PROPERTY OPTION SET:   SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                         ***  MASS AND ENERGY BALANCE  ***
                                      IN               OUT          RELATIVE DIFF.
   TOTAL BALANCE
     MOLE(KMOL/HR )               51.4887          51.4892         -0.873958E-05
     MASS(KG/SEC  )              0.264707         0.264710         -0.977278E-05
     ENTHALPY(WATT      )     -0.105696E+07    -0.104888E+07       -0.764883E-02
```

```
                              U-O-S BLOCK SECTION

BLOCK:  B6        MODEL: RADFRAC (CONTINUED)


                          *********************
                          ****  INPUT DATA ****
                          *********************

 ****   INPUT PARAMETERS   ****

  NUMBER OF STAGES                                                     10
  ALGORITHM OPTION                                                   STANDARD
  ABSORBER OPTION                                                    NO
  INITIALIZATION OPTION                                              STANDARD
  HYDRAULIC PARAMETER CALCULATIONS                                   NO
  INSIDE LOOP CONVERGENCE METHOD                                     BROYDEN
  DESIGN SPECIFICATION METHOD                                        NESTED
  MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS                               25
  MAXIMUM NO. OF INSIDE LOOP ITERATIONS                                10
  MAXIMUM NUMBER OF FLASH ITERATIONS                                   50
  FLASH TOLERANCE                                                       0.000100000
  OUTSIDE LOOP CONVERGENCE TOLERANCE                                    0.000100000

 ****   COL-SPECS    ****

  MOLAR VAPOR DIST / TOTAL DIST                                         1.00000
  MOLAR REFLUX RATIO                                                    1.02800
  REBOILER DUTY                            WATT                    35,463.9

 ****    PROFILES    ****

  P-SPEC            STAGE   1  PRES, BAR                              32.0000
```

```
                                    U-O-S BLOCK SECTION

BLOCK:  B6       MODEL: RADFRAC (CONTINUED)

                                  *******************
                                  ****  RESULTS  ****
                                  *******************

   TOP STAGE TEMPERATURE          C                          -109.926
   BOTTOM STAGE TEMPERATURE       C                           -94.2057
   TOP STAGE LIQUID FLOW          KMOL/HR                      20.5308
   BOTTOM STAGE LIQUID FLOW       KMOL/HR                      31.5172
   TOP STAGE VAPOR FLOW           KMOL/HR                      19.9716
   BOTTOM STAGE VAPOR FLOW        KMOL/HR                      27.8142
   MOLAR REFLUX RATIO                                           1.02800
   MOLAR BOILUP RATIO                                           0.88251
   CONDENSER DUTY (W/O SUBCOOL)   WATT                     -25,351.0
   REBOILER DUTY                  WATT                      33,441.8

  ****  MANIPULATED VARIABLES   ****

   REBOILER DUTY                  WATT                      33,441.8

  ****   DESIGN SPECIFICATIONS   ****

NO  SPEC-TYPE     UNIT        SPECIFIED VALUE  CALCULATED VALUE  ABS. ERROR
 1  MOLE-FRAC                  0.30000E-01      0.30000E-01      -0.31455E-08


  ****  MAXIMUM FINAL RELATIVE ERRORS    ****

   DEW POINT                           0.20609E-06  STAGE=  1
   BUBBLE POINT                        0.12126E-05  STAGE=  1
   COMPONENT MASS BALANCE              0.31919E-07  STAGE=  2 COMP=N2
   ENERGY BALANCE                      0.10821E-05  STAGE=  2

  ****   PROFILES   ****

                                               ENTHALPY
STAGE TEMPERATURE    PRESSURE                  J/KMOL              HEAT DUTY
      C              BAR                 LIQUID       VAPOR         WATT

  1  -109.93         32.000         -0.72023E+08 -0.52372E+08  -.25351+05
  2  -105.35         32.111         -0.75863E+08 -0.60080E+08
  3  -103.28         32.222         -0.77461E+08 -0.63619E+08
  5  -102.30         32.444         -0.78090E+08 -0.65069E+08
  6  -102.10         32.556         -0.78263E+08 -0.65195E+08
  7  -101.76         32.667         -0.78848E+08 -0.65268E+08
  8  -99.623         32.778         -0.81729E+08 -0.67412E+08
  9  -97.224         32.889         -0.83475E+08 -0.71552E+08
 10  -94.206         33.000         -0.86619E+08 -0.75584E+08   .33442+05
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 28

                              U-O-S BLOCK SECTION

BLOCK:  B6         MODEL: RADFRAC (CONTINUED)

STAGE      FLOW RATE                     FEED RATE                    PRODUCT RATE
            KMOL/HR                       KMOL/HR                       KMOL/HR
       LIQUID       VAPOR        LIQUID    VAPOR       MIXED       LIQUID     VAPOR
  1  20.53        19.97                                                       19.9720
  2  24.96        40.50         3.6573
  3  25.40        41.28
  5  25.69        41.92
  6  25.59        42.01
  7  24.67        41.90                    15.0897
  8  58.49        25.90        32.7416
  9  59.33        26.98
 10  31.52        27.81                                              31.5171

                        ****   X-PROFILE          ****
 STAGE       CH4          C2H6         C3H8         C4H10        C5H12        C6H14
    1      .82420      .27081E-06   .38504E-12   .13900E-17   .20492E-23   .14844E-2
    2      .87698      .13878E-05   .91424E-11   .15543E-15   .11576E-20   .41825E-2
    3      .89916      .71541E-05   .21996E-09   .17006E-13   .61049E-18   .10486E-2
    5      .90720      .17364E-03   .11280E-06   .17233E-09   .13683E-12   .50618E-1
    6      .90674      .84370E-03   .24984E-05   .16814E-07   .62182E-10   .10573E-1
    7      .90299      .41196E-02   .55979E-04   .16700E-05   .28943E-07   .22742E-0
    8      .89971      .17754E-01   .11354E-02   .15848E-03   .13644E-04   .52201E-0
    9      .92159      .18472E-01   .11362E-02   .15682E-03   .13463E-04   .51474E-0
   10      .92653      .30742E-01   .20766E-02   .29314E-03   .25303E-04   .96864E-0

                        ****   X-PROFILE          ****
 STAGE       N2           O2           CO2
    1      .17562      .16993E-03   .82063E-06
    2      .12288      .13562E-03   .31218E-05
    3      .10071      .11527E-03   .11760E-04
    5      .92374E-01  .10288E-03   .15126E-03
    6      .91777E-01  .10134E-03   .53509E-03
    7      .90832E-01  .10023E-03   .19031E-02
    8      .75040E-01  .93591E-04   .60932E-02
    9      .52132E-01  .79906E-04   .64194E-02
   10      .30000E-01  .59104E-04   .10265E-01

                        ****   Y-PROFILE          ****
 STAGE       CH4          C2H6         C3H8         C4H10        C5H12        C6H14
    1      .62095      .23424E-07   .61143E-14   .42169E-20   .11118E-26   .14646E-3
    2      .72398      .14883E-06   .19820E-12   .70666E-18   .10393E-23   .75250E-2
    3      .77118      .84809E-06   .55319E-11   .93996E-16   .70008E-21   .25294E-2
    5      .79027      .21695E-04   .30772E-08   .10625E-11   .18027E-15   .14439E-1
    6      .79150      .10621E-03   .68990E-07   .10540E-09   .83689E-13   .30959E-1
    7      .79093      .51523E-03   .15257E-05   .10268E-07   .37972E-10   .64566E-1
    8      .81452      .22217E-02   .30350E-04   .93735E-06   .16912E-07   .13792E-0
    9      .86837      .25800E-02   .35784E-04   .11518E-05   .21901E-07   .18842E-0
   10      .91598      .45688E-02   .70627E-04   .23586E-05   .45867E-07   .40250E-0
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 29

                              U-O-S BLOCK SECTION

BLOCK:  B6         MODEL: RADFRAC (CONTINUED)

                         ****   Y-PROFILE            ****
 STAGE      N2           O2          CO2
   1    .37881       .24439E-03  .99703E-07
   2    .27581       .20665E-03  .46514E-06
   3    .22864       .17939E-03  .19255E-05
   5    .20952       .16094E-03  .25996E-04
   6    .20814       .15860E-03  .92555E-04
   7    .20807       .15780E-03  .32680E-03
   8    .18203       .15356E-03  .10434E-02
   9    .12766       .13388E-03  .12189E-02
  10    .77210E-01   .10348E-03  .20614E-02

                         ****   K-VALUES             ****
 STAGE      CH4          C2H6        C3H8        C4H10       C5H12       C6H14
   1    .75339       .86494E-01  .15879E-01  .30337E-02  .54254E-03  .98667E-04
   2    .82554       .10724      .21679E-01  .45466E-02  .89779E-03  .17992E-03
   3    .85767       .11855      .25149E-01  .55271E-02  .11468E-02  .24122E-03
   5    .87111       .12494      .27280E-01  .61656E-02  .13175E-02  .28526E-03
   6    .87291       .12589      .27614E-01  .62687E-02  .13459E-02  .29281E-03
   7    .87591       .12507      .27255E-01  .61484E-02  .13120E-02  .28391E-03
   8    .90531       .12514      .26731E-01  .59147E-02  .12395E-02  .26422E-03
   9    .94226       .13967      .31494E-01  .73443E-02  .16268E-02  .36606E-03
  10    .98862       .14862      .34011E-01  .80462E-02  .18127E-02  .41553E-03

                         ****   K-VALUES             ****
 STAGE      N2           O2          CO2
   1    2.1569       1.4382      .12149
   2    2.2445       1.5237      .14900
   3    2.2703       1.5563      .16373
   5    2.2681       1.5644      .17186
   6    2.2679       1.5650      .17297
   7    2.2907       1.5743      .17171
   8    2.4258       1.6408      .17124
   9    2.4488       1.6755      .18988
  10    2.5737       1.7508      .20081

BLOCK:  B7         MODEL: HEATER
------------------------------
  INLET STREAM:              7
  OUTLET STREAM:             8
  PROPERTY OPTION SET:       SYSOP3     REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                        IN            OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )               19.9720         19.9720            0.
      MASS(KG/SEC  )               0.114180        0.114180           0.
      ENTHALPY(WATT       )       -290546.        -311231.          0.664621E-01
```

```
                              U-O-S BLOCK SECTION

BLOCK:  B7          MODEL: HEATER (CONTINUED)

                         ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE           C                          -121.407
  SPECIFIED PRESSURE              BAR                          31.5000
  MAXIMUM NO. ITERATIONS                                       30
  CONVERGENCE TOLERANCE                                         0.000100000

                          ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                      -121.41
  OUTLET PRESSURE       BAR                                      31.500
  HEAT DUTY             WATT                                   -20685.
  VAPOR FRACTION                                                0.18612


  V-L PHASE EQUILIBRIUM :

     COMP               F(I)          X(I)          Y(I)          K(I)
     CH4              0.62095       0.67294       0.39362       0.58492
     C2H6             0.23426E-07   0.28447E-07   0.14672E-08   0.51575E-
     C3H8             0.13582E-13   0.16659E-13   0.12802E-15   0.76848E-
     N2               0.37881       0.32683       0.60610         1.8545
     O2               0.24439E-03   0.23561E-03   0.28280E-03     1.2003
     CO2              0.99715E-07   0.12047E-06   0.89327E-08   0.74146E-
BLOCK:  B8          MODEL: FLASH2
------------------------------
   INLET STREAM:            8
   OUTLET VAPOR STREAM:     9
   OUTLET LIQUID STREAM:    19
   PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                     IN            OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )             19.9720        19.9720         0.135192E-13
      MASS(KG/SEC  )             0.114180       0.114180        0.291703E-13
      ENTHALPY(WATT      )      -311231.       -311231.        -0.147749E-13

                         ***  INPUT DATA  ***
 TWO    PHASE  TP  FLASH
 SPECIFIED TEMPERATURE C                                     -121.407
 SPECIFIED PRESSURE    BAR                                     31.5000
 MAXIMUM NO. ITERATIONS                                        30
 CONVERGENCE TOLERANCE                                          0.000100000
```

```
                              U-O-S BLOCK SECTION

BLOCK:  B8         MODEL: FLASH2 (CONTINUED)

                          ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                     -121.41
  OUTLET PRESSURE       BAR                                    31.500
  HEAT DUTY             WATT                                       0.
  VAPOR FRACTION                                              0.18612


  V-L PHASE EQUILIBRIUM :

    COMP               F(I)          X(I)          Y(I)          K(I)
    CH4              0.62095       0.67294       0.39362       0.58492
    C2H6             0.23426E-07   0.28447E-07   0.14672E-08   0.51575E-01
    C3H8             0.13582E-13   0.16659E-13   0.12802E-15   0.76848E-02
    N2               0.37881       0.32683       0.60610        1.8545
    O2               0.24439E-03   0.23561E-03   0.28280E-03    1.2003
    CO2              0.99715E-07   0.12047E-06   0.89327E-08   0.74146E-01
BLOCK:  B9         MODEL: HEATER
-------------------------------
  INLET STREAM:             9
  OUTLET STREAM:            10
  PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE  ***
                                  IN             OUT          RELATIVE DIFF.
  TOTAL BALANCE
     MOLE(KMOL/HR )             3.71722         3.71722              0.
     MASS(KG/SEC  )           0.240613E-01    0.240613E-01           0.
     ENTHALPY(WATT     )      -36590.2        -36590.2        -0.135820E-06

                       ***  INPUT DATA  ***
 TWO    PHASE  PQ  FLASH
 SPECIFIED PRESSURE              BAR                      28.9000
 SPECIFIED HEAT DUTY             WATT                      0.0
 MAXIMUM NO. ITERATIONS                                   30
 CONVERGENCE TOLERANCE                                     0.000100000
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4      INST: DELFTUOT  05/02/93  PAGE 32
                                 U-O-S BLOCK SECTION

BLOCK:  B9          MODEL: HEATER (CONTINUED)

                                  ***  RESULTS  ***
  OUTLET TEMPERATURE     C
  OUTLET PRESSURE        BAR                                      -123.24
  VAPOR FRACTION                                                   28.900
                                                                  0.98304


  V-L PHASE EQUILIBRIUM :

     COMP
     CH4                  F(I)           X(I)           Y(I)           K(I)
     C2H6               0.39362        0.68957        0.38851        0.56340
     N2                 0.14672E-08    0.25969E-07    0.10444E-08    0.40219E-01
     O2                 0.60610        0.31020        0.61121         1.9704
     CO2                0.28280E-03    0.23112E-03    0.28369E-03     1.2274
                        0.89327E-08    0.11902E-06    0.70333E-08    0.59093E-01
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 33

                               STREAM SECTION

1 10 11 13 14
-------------

STREAM ID            1           10           11           13           14
FROM :               ----        B9           B10          B12          B13
TO   :               B1          B10          B12          B13          B14

SUBSTREAM: MIXED
PHASE:               VAPOR       MIXED        LIQUID       LIQUID       LIQUID
COMPONENTS: KMOL/HR
  CH4                  43.1797      1.4631       0.1751  8.7561-02  8.7561-02
  C2H6                  1.5131  5.4537-09  1.9735-13  9.8674-14  9.8674-14
  C3H8                  0.1973      0.0          0.0          0.0          0.0
  C4H10              7.3985-02      0.0          0.0          0.0          0.0
  C5H12              2.0791-02      0.0          0.0          0.0          0.0
  C6H14              2.6691-02      0.0          0.0          0.0          0.0
  N2                    7.6178      2.2530       3.3264       1.6632       1.6632
  O2                 6.2502-03  1.0512-03  8.7617-04  4.3809-04  4.3809-04
  CO2                   0.4726  3.3205-08  4.0795-12  2.0398-12  2.0398-12
TOTAL FLOW:
  KMOL/HR              53.1083      3.7172       3.5024       1.7512       1.7512
  KG/SEC                0.2748  2.4061-02  2.6672-02  1.3336-02  1.3336-02
  CUM/SEC            1.7079-02  2.9622-04  6.0756-05  3.0378-05  2.9597-05
STATE VARIABLES:
  TEMP   C             15.0000   -123.2436   -149.4342   -149.4342   -150.2351
  PRES   BAR           20.0000     28.9000     28.0000     28.0000     27.0000
  VFRAC                 1.0000      0.9830       0.0          0.0          0.0
  LFRAC                 0.0     1.6961-02      1.0000       1.0000       1.0000
  SFRAC                 0.0         0.0          0.0          0.0          0.0
ENTHALPY:
  J/KMOL           -6.8228+07 -3.5436+07 -1.2691+07 -1.2691+07 -1.2789+07
  J/KG             -3.6622+06 -1.5207+06 -4.6291+05 -4.6291+05 -4.6650+05
  WATT             -1.0065+06 -3.6590+04 -1.2347+04 -6173.5184 -6221.2836
ENTROPY:
  J/KMOL-K         -9.4159+04 -8.1977+04 -8.3488+04 -8.3488+04 -8.4234+04
  J/KG-K           -5054.0421 -3517.9462 -3045.2735 -3045.2745 -3072.4847
DENSITY:
  KMOL/CUM              0.8637      3.4857     16.0132      16.0132      16.4359
  KG/CUM               16.0920     81.2270    439.0113     439.0116     450.5983
AVG MW                 18.6304     23.3025     27.4154      27.4154      27.4154
```

```
ASPEN PLUS    VER: SUN-4      REL: 8.5-4      INST: DELFTUOT  05/02/93  PAGE

                                  STREAM SECTION

15 16 17 18 19
--------------

STREAM ID                 15          16          17          18          19
FROM :                    B14         B15         B3          B6          B8
TO   :                    B15         ----        B16         B16         B17

SUBSTREAM: MIXED
PHASE:                    MIXED       VAPOR       LIQUID      LIQUID      LIQUID
COMPONENTS: KMOL/HR
  CH4                  8.7561-02   2.9604-02      4.0379     29.2015      10.938
  C2H6                 9.8674-14   1.2303-16      0.5442      0.9689   4.6240-0
  C3H8                    0.0         0.0         0.1318   6.5447-02      0.0
  C4H10                   0.0         0.0      6.4746-02   9.2388-03      0.0
  C5H12                   0.0         0.0      1.9993-02   7.9749-04      0.0
  C6H14                   0.0         0.0      2.6386-02   3.0529-04      0.0
  N2                      1.6632      6.0637      0.3023      0.9455       5.312
  O2                   4.3809-04   8.6794-04   3.6819-04   1.8628-03   3.8297-0
  CO2                  2.0398-12   1.6600-15      0.1490      0.3235   1.9583-0
TOTAL FLOW:
  KMOL/HR                 1.7512      6.0942      5.2769     31.5171      16.254
  KG/SEC               1.3336-02   4.7324-02   3.0412-02      0.1505   9.0119-0
  CUM/SEC              7.4602-04   7.3438-03   8.7516-05   5.3491-04   2.4547-0
STATE VARIABLES:
  TEMP    C             -186.6798   -190.7165    -80.0000    -94.2056   -121.407
  PRES    BAR              2.3300      1.5000     47.5000     33.0000     31.500
  VFRAC                    0.5288      1.0000      0.0         0.0         0.0
  LFRAC                    0.4711      0.0         1.0000      1.0000      1.000
  SFRAC                    0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL              -1.2789+07 -6.7438+06 -9.4191+07 -8.6619+07 -6.0826+0
  J/KG                -4.6650+05 -2.4123+05 -4.5399+06 -5.0377+06 -3.0475+0
  WATT                -6221.2815 -1.1416+04 -1.3807+05 -7.5833+05 -2.7464+0
ENTROPY:
  J/KMOL-K            -7.7101+04 -4.1539+04 -1.6793+05 -1.5548+05 -1.3217+0
  J/KG-K              -2812.3125 -1485.9117 -8093.9812 -9042.4387 -6622.154
DENSITY:
  KMOL/CUM                 0.6520      0.2305     16.7492     16.3667      18.394
  KG/CUM                  17.8765      6.4441    347.5005    281.4105     367.132
AVG MW                    27.4154     27.9554     20.7472     17.1940      19.958
```

```
ASPEN PLUS    VER: SUN-4      REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE 35
                                STREAM SECTION

2 20 21 22 23
-------------

STREAM ID                   2           20          21          22          23
FROM :                      B1          B17         B18         B17         B20
TO   :                      B2          B18         B6          B20         B21

SUBSTREAM: MIXED
PHASE:                      VAPOR       LIQUID      LIQUID      LIQUID      MIXED
COMPONENTS: KMOL/HR
  CH4                     43.1797      2.4611      2.4611      8.4773      8.4773
  C2H6                     1.5131  1.0404-07   1.0404-07   3.5836-07   3.5836-07
  C3H8                     0.1973      0.0         0.0         0.0         0.0
  C4H10                 7.3985-02      0.0         0.0         0.0         0.0
  C5H12                 2.0791-02      0.0         0.0         0.0         0.0
  C6H14                 2.6691-02      0.0         0.0         0.0         0.0
  N2                       7.6178      1.1953      1.1953      4.1172      4.1172
  O2                    6.2502-03  8.6169-04   8.6169-04   2.9680-03   2.9680-03
  CO2                      0.4726  4.4062-07   4.4062-07   1.5177-06   1.5177-06
TOTAL FLOW:
  KMOL/HR                 53.1083      3.6573      3.6573     12.5974     12.5974
  KG/SEC                   0.2748  2.0277-02   2.0277-02   6.9842-02   6.9842-02
  CUM/SEC               9.4941-03  5.5230-05   5.5295-05   1.9024-04   2.3405-04
STATE VARIABLES:
  TEMP   C               103.1160  -121.4070   -121.1247   -121.4070   -123.6012
  PRES    BAR             48.0000    31.5000     32.5000     31.5000     28.5000
  VFRAC                    1.0000     0.0         0.0         0.0      5.9809-02
  LFRAC                    0.0        1.0000      1.0000      1.0000      0.9401
  SFRAC                    0.0        0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL               -6.5070+07 -6.0826+07  -6.0807+07  -6.0826+07  -6.0826+07
  J/KG                 -3.4927+06 -3.0475+06  -3.0466+06  -3.0475+06  -3.0475+06
  WATT                 -9.5994+05 -6.1794+04  -6.1776+04  -2.1285+05  -2.1285+05
ENTROPY:
  J/KMOL-K             -9.1728+04 -1.3217+05  -1.3209+05  -1.3217+05  -1.3205+05
  J/KG-K               -4923.5423 -6622.1546  -6617.8835  -6622.1546  -6616.1550
DENSITY:
  KMOL/CUM                 1.5538    18.3944     18.3727     18.3944     14.9508
  KG/CUM                  28.9486   367.1320    366.6996    367.1320    298.4019
AVG MW                    18.6304    19.9588     19.9588     19.9588     19.9588
```

```
ASPEN PLUS   VER: SUN-4      REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE

                                    STREAM SECTION

24 25 26 27 28
--------------

STREAM ID               24          25          26          27          28
FROM :                  B21         B22         B23         B10         B15
TO   :                  B22         B23         B15         B21         B16

SUBSTREAM: MIXED
PHASE:                  MIXED       LIQUID      MIXED       LIQUID      LIQUID
COMPONENTS: KMOL/HR
  CH4                    9.8529      9.8529      9.8529      1.3756      9.9108
  C2H6                  3.6382-07   3.6382-07   3.6382-07   5.4536-09   3.6382-07
  C3H8                  0.0         0.0         0.0         0.0         0.0
  C4H10                 0.0         0.0         0.0         0.0         0.0
  C5H12                 0.0         0.0         0.0         0.0         0.0
  C6H14                 0.0         0.0         0.0         0.0         0.0
  N2                     4.7070      4.7070      4.7070      0.5898      0.3064
  O2                    3.5812-03   3.5812-03   3.5812-03   6.1317-04   3.1514-03
  CO2                   1.5509-06   1.5509-06   1.5509-06   3.3202-08   1.5509-06
TOTAL FLOW:
  KMOL/HR               14.5635     14.5635     14.5635      1.9660     10.2204
  KG/SEC                8.0567-02   8.0567-02   8.0567-02   1.0725-02   4.6579-02
  CUM/SEC               2.6405-04   1.5676-04   2.6239-03   2.8824-05   1.1170-04
STATE VARIABLES:
  TEMP    C           -123.5024   -161.1500   -174.9204   -122.4728   -154.1806
  PRES    BAR           28.5000     28.0000      2.0000     29.0000      2.5000
  VFRAC                 5.3068-02   0.0         0.1587      0.0         0.0
  LFRAC                  0.9469      1.0000      0.8412      1.0000      1.0000
  SFRAC                  0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL              -6.1129+07 -6.3872+07 -6.3872+07 -6.3074+07 -8.6829+07
  J/KG                -3.0694+06 -3.2071+06 -3.2071+06 -3.2117+06 -5.2922+06
  WATT                -2.4729+05 -2.5839+05 -2.5839+05 -3.4446+04 -2.4651+05
ENTROPY:
  J/KMOL-K            -1.3253+05 -1.5330+05 -1.5159+05 -1.3565+05 -1.8135+05
  J/KG-K              -6654.7664 -7697.5162 -7611.7420 -6907.0263 -1.1053+04
DENSITY:
  KMOL/CUM              15.3204     25.8057      1.5417     18.9467     25.4167
  KG/CUM               305.1171    513.9386     30.7056    372.0937    417.0070
AVG MW                  19.9157     19.9157     19.9157     19.6389     16.4068
```

```
                               STREAM SECTION

29 3 30 31 4
------------

STREAM ID                 29          3           30          31          4
FROM :                    B12         B2          B24         B16         B3
TO   :                    B24         B3          B10         ----        B4

SUBSTREAM: MIXED
PHASE:                    LIQUID      MIXED       LIQUID      MIXED       VAPOR
COMPONENTS: KMOL/HR
  CH4                   8.7561-02     43.1797   8.7561-02     43.1503     39.1417
  C2H6                  9.8674-14      1.5131   9.8674-14      1.5131      0.9689
  C3H8                    0.0          0.1973     0.0          0.1973   6.5447-02
  C4H10                   0.0       7.3985-02     0.0       7.3984-02   9.2388-03
  C5H12                   0.0       2.0791-02     0.0       2.0791-02   7.9749-04
  C6H14                   0.0       2.6691-02     0.0       2.6691-02   3.0529-04
  N2                       1.6632      7.6178      1.6632      1.5542      7.3155
  O2                    4.3809-04   6.2502-03   4.3809-04   5.3823-03   5.8820-03
  CO2                   2.0398-12      0.4726   2.0398-12      0.4726      0.3235
TOTAL FLOW:
  KMOL/HR                  1.7512     53.1083      1.7512     47.0145     47.8314
  KG/SEC                1.3336-02      0.2748   1.3336-02      0.2275      0.2444
  CUM/SEC               3.0378-05   2.6732-03   3.0411-05   2.0317-03   2.5857-03
STATE VARIABLES:
  TEMP   C              -149.4342    -80.0000   -149.2685   -115.8763    -80.0000
  PRES    BAR             28.0000     47.5000     28.5000     15.0000     47.5000
  VFRAC                   0.0          0.9006     0.0          0.1677      1.0000
  LFRAC                    1.0000   9.9362-02      1.0000      0.8323     0.0
  SFRAC                   0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL               -1.2691+07 -7.3906+07 -1.2680+07 -8.7514+07 -7.1668+07
  J/KG                 -4.6291+05 -3.9670+06 -4.6253+05 -5.0233+06 -3.8957+06
  WATT                 -6173.5184 -1.0903+06 -6168.3793 -1.1429+06 -9.5222+05
ENTROPY:
  J/KMOL-K             -8.3488+04 -1.2531+05 -8.3427+04 -1.6065+05 -1.2060+05
  J/KG-K               -3045.2745 -6725.8631 -3043.0718 -9221.0652 -6555.6428
DENSITY:
  KMOL/CUM                16.0132      5.5185     15.9955      6.4280      5.1384
  KG/CUM                 439.0116    102.8126    438.5270    111.9870     94.5309
AVG MW                    27.4154     18.6304     27.4154     17.4217     18.3969
```

```
ASPEN PLUS   VER: SUN-4     REL: 8.5-4     INST: DELFTUOT  05/02/93  PAGE
                                STREAM SECTION

5 6 7 8 9
---------

STREAM ID                 5          6          7          8          9
FROM :                    B4         B5         B6         B7         B8
TO   :                    B5         B6         B7         B8         B9

SUBSTREAM: MIXED
PHASE:                  LIQUID     MIXED      VAPOR      MIXED      VAPOR
COMPONENTS: KMOL/HR
  CH4                   39.1417    39.1417    12.4016    12.4016     1.4631
  C2H6                   0.9689     0.9689  4.6786-07  4.6786-07  5.4537-09
  C3H8                6.5447-02  6.5447-02  2.7126-13  2.7126-13    0.0
  C4H10               9.2388-03  9.2388-03  1.9514-19  1.9514-19    0.0
  C5H12               7.9749-04  7.9749-04  5.3779-26  5.3779-26    0.0
  C6H14               3.0529-04  3.0529-04  7.4010-32  7.4010-32    0.0
  N2                     7.3155     7.3155     7.5655     7.5655     2.2530
  O2                  5.8820-03  5.8820-03  4.8810-03  4.8810-03  1.0512-03
  CO2                    0.3235     0.3235  1.9915-06  1.9915-06  3.3205-08
TOTAL FLOW:
  KMOL/HR               47.8314    47.8314    19.9720    19.9720     3.7172
  KG/SEC                 0.2444     0.2444     0.1141     0.1141  2.4061-02
  CUM/SEC             9.6303-04  1.6785-03  1.5088-03  5.1430-04  2.6883-04
STATE VARIABLES:
  TEMP    C            -92.3867  -102.0710  -109.9262  -121.4070  -121.4070
  PRES    BAR           47.0000    32.9000    32.0000    31.5000    31.5000
  VFRAC                 0.0         0.3139     1.0000     0.1861     1.0000
  LFRAC                 1.0000      0.6860    0.0         0.8138    0.0
  SFRAC                 0.0        0.0        0.0        0.0        0.0
ENTHALPY:
  J/KMOL             -7.4902+07 -7.4902+07 -5.2372+07 -5.6100+07 -3.5436+07
  J/KG               -4.0714+06 -4.0714+06 -2.5446+06 -2.7258+06 -1.5207+06
  WATT               -9.9518+05 -9.9518+05 -2.9055+05 -3.1123+05 -3.6590+04
ENTROPY:
  J/KMOL-K           -1.3796+05 -1.3719+05 -9.9377+04 -1.2292+05 -8.2448+04
  J/KG-K             -7499.2351 -7457.3461 -4828.5361 -5972.2615 -3538.1620
DENSITY:
  KMOL/CUM              13.7965     7.9155     3.6769    10.7870     3.8408
  KG/CUM               253.8137   145.6224    75.6752   222.0102    89.5024
AVG MW                  18.3969    18.3969    20.5812    20.5812    23.3025
```

Table A8-1. Main streams of cryogenic method II.

COMPONENTS [kmol/hr]	STREAM ID 1	STREAM ID 31
CH_4	43.1797	43.1503
C_2H_6	1.5131	1.5131
C_3H_8	0.1973	0.1973
C_4H_{10}	7.3985-02	7.3984-02
C_5H_{12}	2.0791-02	2.0791-02
C_6H_{14}	2.6691-02	2.6691-02
N_2	7.6178	1.5542
O_2	6.2502-03	5.3823-03
CO_2	0.4726	0.4726
Total flow [kmol/hr]	53.1083	47.0145
Temperature [°C]	15.00	-115.8763
Pressure [bar]	20.00	15.00
Phase	VAPOR	MIXED

A8.2. Simulation and results of cryogenic method I on Aspen Plus

Cryogenic method I was simulated on Aspen Plus. The stream and equipment numbers are not the same as the numbers on the flowsheet shown in figure 8.1. The numbers used in this appendix are the numbers used in the Aspen Plus simulation.
The most important streams are printed in table A8.2 on the next page. Stream 1 in this table is the feed stream of the plant. Streams 8 and 23 are the nitrogen-poor and the nitrogen-rich flow respectively. The flowsheet of Aspen Plus is shown in figure A8.2 on page A8-38. Further all results of the Aspen Plus simulation are shown on the following pages.

Block B9 and B10 are respectivily the reboiler and the condensor of the column. Block B19 is the condensor in the middle of the column. Block B21 is defined in the simulating, but it works as a compressor. Defining this block as compressor gave some simulation problems.

Results
The simulation of method I gave the following results:

- 81.6 mol % N_2 is removed from the feed
- the new feed stream contains 3.2 mol % N_2
- the purity of CH_4 in the feed stream goes from 81.3 % to 91.7 %
- 2.5 kmol CH_4 leaves the process in stream 23 (this is 5.8 % of the total CH_4 flow)

Table A8.2. Main streams of cryogenic method I.

COMPONENTS [kmol/hr]	STREAM ID 1	STREAM ID 8	STREAM ID 23
CH_4	43.29	40.7839	2.5059
C_2H_6	1.517	1.5170	7.3088-18
C_3H_8	0.198	0.1980	6.2150-33
C_4H_{10}	7.4-02	7.4-02	0.0
C_5H_{12}	2.1-02	2.1-02	0.0
C_6H_{14}	2.67-02	2.67-02	0.0
N_2	7.62	1.4030	6.2169
O_2	6.0-03	3.3911-03	2.6089-03
CO_2	0.47	0.47	1.0341-15
Total flow [kmol/hr]	53.223	44.4971	8.7255
Temperature [°C]	15.00	18.0845	15.00
Pressure [bar]	54.00	5.7688	2.00
Phase	VAPOR	VAPOR	VAPOR

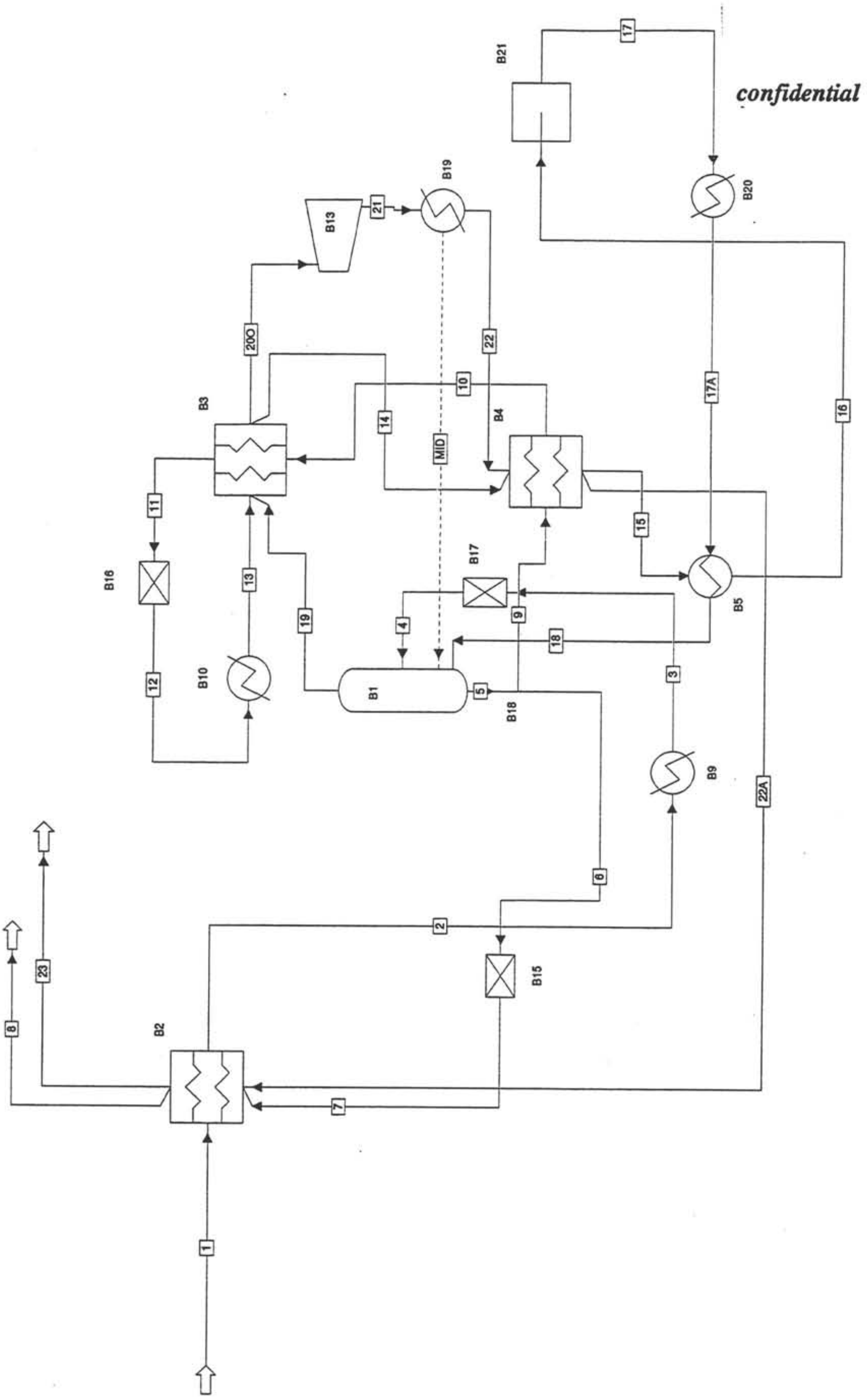


Fig. A8.2. Flowsheet of method I simulated on Aspen Plus.

```
BLOCK:  B2        MODEL: MHEATX
------------------------------

   HOT SIDE:     INLET STREAM     OUTLET STREAM
                 ------------     -------------
                 1                2

   COLD SIDE:    INLET STREAM     OUTLET STREAM
                 ------------     -------------
                 7                8
                 22A              23

   PROPERTIES FOR STREAM 1
   PROPERTY OPTION SET:   SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

   PROPERTIES FOR STREAM 22A
   PROPERTY OPTION SET:   SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

   PROPERTIES FOR STREAM 7
   PROPERTY OPTION SET:   SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                    IN             OUT          RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )             106.445        106.445               0.
       MASS(KG/HR   )             1982.60        1982.60               0.
       ENTHALPY(WATT    )      -0.216216E+07  -0.216216E+07    0.529260E-07

                           ***  INPUT DATA  ***

   SPECIFICATIONS FOR STREAM 1          :
   TWO    PHASE   TP  FLASH
   SPECIFIED TEMPERATURE CHANGE      C                      -120.000
   PRESSURE DROP                     BAR                       0.0
   MAXIMUM NO. ITERATIONS                                    500
   CONVERGENCE TOLERANCE                                       0.000100000
```

```
BLOCK:  B2       MODEL: MHEATX (CONTINUED)

  SPECIFICATIONS FOR STREAM 22A      :
  ONE    PHASE  TP  FLASH   SPECIFIED PHASE IS  VAPOR
  SPECIFIED TEMPERATURE CHANGE    C                           125.000
  PRESSURE DROP                   BAR                           0.0
  MAXIMUM NO. ITERATIONS                                      500
  CONVERGENCE TOLERANCE                                         0.000100000

  SPECIFICATIONS FOR STREAM 7        :
  ONE    PHASE      FLASH   SPECIFIED PHASE IS  VAPOR
  MAXIMUM NO. ITERATIONS                                      500
  CONVERGENCE TOLERANCE                                         0.000100000

                         ***  RESULTS  ***

 INLET       OUTLET       OUTLET        OUTLET
 STREAM      TEMPERATURE  PRESSURE      VAPOR FRAC     DUTY
             C            BAR                          WATT

 1          -105.00        54.000            0.       -.14099E+06
 22A          15.000        2.0000        1.0000        9318.0
 7            18.085        5.7688        1.0000       0.13168E+06


         ------------------------------------------
         |                                        |
 1       |                                        |
 ------> |                                        |------->
    15.0 |                                        | -105.0
         |                                        |
 22A     |                                        |
 ------> |                                        |------->
  -110.0 |                                        |   15.0
         |                                        |
         |                                        | 7
 <------ |                                        |<-------
    18.1 |                                        | -135.0
         |                                        |
         ------------------------------------------
```

```
BLOCK:  B3        MODEL: MHEATX
------------------------------

  HOT SIDE:     INLET STREAM     OUTLET STREAM
                ------------     -------------
                10               11

  COLD SIDE:    INLET STREAM     OUTLET STREAM
                ------------     -------------
                13               14
                19               200

  PROPERTIES FOR STREAM 10
  PROPERTY OPTION SET:   SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

  PROPERTIES FOR STREAM 19
  PROPERTY OPTION SET:   SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

  PROPERTIES FOR STREAM 13
  PROPERTY OPTION SET:   SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                     ***  MASS AND ENERGY BALANCE  ***
                                  IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )           18.6137         18.6137                0.
      MASS(KG/HR   )           387.077         387.077                0.
      ENTHALPY(WATT    )      -296630.        -296630.         0.463637E-09

                         ***  INPUT DATA  ***


  SPECIFICATIONS FOR STREAM 10        :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE CHANGE      C                           -7.00000
  PRESSURE DROP                     BAR                          0.0
  MAXIMUM NO. ITERATIONS                                       500
  CONVERGENCE TOLERANCE                                          0.000100000
```

```
BLOCK:  B3        MODEL: MHEATX (CONTINUED)

  SPECIFICATIONS FOR STREAM 19         :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE CHANGE     C                            30.0000
  PRESSURE DROP                    BAR                           0.0
  MAXIMUM NO. ITERATIONS                                       500
  CONVERGENCE TOLERANCE                                           0.000100000

  SPECIFICATIONS FOR STREAM 13         :
  TWO    PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                       500
  CONVERGENCE TOLERANCE                                           0.000100000

                                *** RESULTS ***

   INLET        OUTLET       OUTLET        OUTLET
   STREAM       TEMPERATURE  PRESSURE      VAPOR FRAC      DUTY
                C            BAR                           WATT

   10          -110.07        28.000           0.        -777.92
   19          -99.855        27.500        1.0000        3334.5
   13          -112.14        2.0000       0.98979       -2556.6

          ------------------------------------------
         |                                          |
  10     |                                          |
-------> |                                          |------->
  -103.1 |                                          | -110.1
         |                                          |
  19     |                                          |
-------> |                                          |------->
  -129.9 |                                          |  -99.9
         |                                          |
         |                                          | 13
<------- |                                          |<-------
  -112.1 |                                          |  -63.4
         |                                          |
          ------------------------------------------
```

```
BLOCK:  B4        MODEL: MHEATX
------------------------------

  HOT SIDE:     INLET STREAM     OUTLET STREAM
                ------------     -------------
                9                10

  COLD SIDE:    INLET STREAM     OUTLET STREAM
                ------------     -------------
                14               15
                22               22A

  PROPERTIES FOR STREAM 9
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

  PROPERTIES FOR STREAM 22
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

  PROPERTIES FOR STREAM 14
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                   ***  MASS AND ENERGY BALANCE  ***
                                IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )         18.6137         18.6137              0.
      MASS(KG/HR   )         387.077         387.077              0.
      ENTHALPY(WATT    )    -295256.        -295256.          0.451046E-08

                       ***  INPUT DATA  ***

  SPECIFICATIONS FOR STREAM 9        :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE CHANGE     C                         -3.50000
  PRESSURE DROP                    BAR                        0.0
  MAXIMUM NO. ITERATIONS                                    500
  CONVERGENCE TOLERANCE                                       0.000100000
```

```
BLOCK:  B4        MODEL: MHEATX (CONTINUED)

  SPECIFICATIONS FOR STREAM 22        :
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE CHANGE    C                      10.0000
  PRESSURE DROP                   BAR                     0.0
  MAXIMUM NO. ITERATIONS                                500
  CONVERGENCE TOLERANCE                                   0.000100000

  SPECIFICATIONS FOR STREAM 14        :
  TWO    PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                500
  CONVERGENCE TOLERANCE                                   0.000100000

                          ***  RESULTS  ***

 INLET       OUTLET       OUTLET         OUTLET
 STREAM      TEMPERATURE  PRESSURE       VAPOR FRAC       DUTY
             C            BAR                             WATT

 9          -103.07        28.000           0.           -429.62
 22         -110.00        2.0000        1.0000           748.15
 14         -116.72        2.0000        0.98513         -318.53


        ------------------------------------------
        |                                        |
 9      |                                        |
------->|                                        |------->
  -99.6 |                                        | -103.1
        |                                        |
 22     |                                        |
------->|                                        |------->
 -120.0 |                                        | -110.0
        |                                        |
        |                                        | 14
<-------|                                        |<-------
 -116.7 |                                        | -112.1
        |                                        |
        ------------------------------------------


BLOCK:  B1        MODEL: RADFRAC
-------------------------------
   INLETS    - 4        STAGE  16
               18       STAGE  19
               MID      STAGE  10
   OUTLETS   - 19       STAGE   1
               5        STAGE  20
```

```
BLOCK:  B1        MODEL: RADFRAC (CONTINUED)
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                          ***  MASS AND ENERGY BALANCE  ***
                                      IN                OUT           RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )               58.1668          58.1668          0.131838E-05
      MASS(KG/HR   )               1077.62          1077.62          0.128652E-05
      ENTHALPY(WATT     )      -0.130696E+07    -0.126896E+07    -0.290763E-01


                             **********************
                             ****  INPUT DATA  ****
                             **********************

  ****   INPUT PARAMETERS   ****

   NUMBER OF STAGES                                               20
   ALGORITHM OPTION                                             STANDARD
   ABSORBER OPTION                                              NO
   INITIALIZATION OPTION                                        STANDARD
   HYDRAULIC PARAMETER CALCULATIONS                             NO
   INSIDE LOOP CONVERGENCE METHOD                               BROYDEN
   DESIGN SPECIFICATION METHOD                                  NESTED
   MAXIMUM NO. OF OUTSIDE LOOP ITERATIONS                         25
   MAXIMUM NO. OF INSIDE LOOP ITERATIONS                          10
   MAXIMUM NUMBER OF FLASH ITERATIONS                             50
   FLASH TOLERANCE                                                 0.000100000
   OUTSIDE LOOP CONVERGENCE TOLERANCE                              0.000100000

  ****   COL-SPECS   ****

   MOLAR VAPOR DIST / TOTAL DIST                                   1.00000
   CONDENSER DUTY (W/O SUBCOOL)        WATT                  -10,000.0
   REBOILER DUTY                       WATT                   48,000.0

  ****    PROFILES   ****

   P-SPEC          STAGE   1  PRES, BAR                          27.5000

   TEMP-EST        STAGE   1  TEMP, C                          -140.000
                          20                                   -100.000
```

```
BLOCK:  B1        MODEL: RADFRAC (CONTINUED)

                                   *******************
                                   ****  RESULTS  ****
                                   *******************

    TOP STAGE TEMPERATURE              C                               -129.855
    BOTTOM STAGE TEMPERATURE           C                                -99.5663
    TOP STAGE LIQUID FLOW              KMOL/HR                            7.09941
    BOTTOM STAGE LIQUID FLOW           KMOL/HR                           49.4413
    TOP STAGE VAPOR FLOW               KMOL/HR                            8.72550
    BOTTOM STAGE VAPOR FLOW            KMOL/HR                           34.1620
    MOLAR REFLUX RATIO                                                    0.81364
    MOLAR BOILUP RATIO                                                    0.69096
    CONDENSER DUTY (W/O SUBCOOL)       WATT                          -10,000.0
    REBOILER DUTY                      WATT                           48,000.0

   ****   MAXIMUM FINAL RELATIVE ERRORS    ****

    DEW POINT                           0.39666E-06  STAGE= 17
    BUBBLE POINT                        0.15760E-05  STAGE=  1
    COMPONENT MASS BALANCE              0.31802E-05  STAGE= 18 COMP=C3H8
    ENERGY BALANCE                      0.16001E-05  STAGE= 18


   ****    PROFILES   ****


                                                  ENTHALPY
STAGE TEMPERATURE   PRESSURE                      J/KMOL                 HEAT DUTY
        C           BAR                      LIQUID         VAPOR          WATT

   1  -129.85       27.500           -0.55925E+08 -0.27438E+08   -.10000+05
   2  -122.05       27.526           -0.65604E+08 -0.37943E+08
   3  -119.39       27.553           -0.68338E+08 -0.41975E+08
   4  -118.61       27.579           -0.69077E+08 -0.43180E+08
   9  -118.21       27.711           -0.69297E+08 -0.43661E+08
  10  -118.19       27.737           -0.69284E+08 -0.43665E+08   -4114.8801
  11  -116.20       27.763           -0.71136E+08 -0.46879E+08
  15  -115.14       27.868           -0.72296E+08 -0.48348E+08
  16  -114.19       27.895           -0.75567E+08 -0.48209E+08
  17  -110.24       27.921           -0.78641E+08 -0.55041E+08
  18  -106.08       27.947           -0.81824E+08 -0.62530E+08
  19  -103.10       27.974           -0.83960E+08 -0.68167E+08
  20  -99.566       28.000           -0.87555E+08 -0.73699E+08    .48000+05
```

```
BLOCK:  B1        MODEL: RADFRAC (CONTINUED)

STAGE      FLOW RATE                         FEED RATE                      PRODUCT RATE
            KMOL/HR                           KMOL/HR                         KMOL/HR
       LIQUID      VAPOR          LIQUID    VAPOR     MIXED          LIQUID    VAPOR
  1  7.099        8.725                                                          8.7255
  2  6.892        15.82
  3  6.891        15.62
  4  6.899        15.62
  9  6.929        15.65
 10  9.839        15.65
 11  9.876        18.56
 15  9.634        18.61
 16  80.33        18.36           53.2227
 17  81.66        35.83
 18  82.28        37.16                      4.7977
 19  83.60        32.98            0.1463
 20  49.44        34.16                                              49.4412

                         ****   X-PROFILE         ****
   STAGE      CO2         N2           O2          CH4          C2H6         C3H8
      1   .28392E-14  .39630       .27270E-03  .60343       .30099E-16  .23713E-30
      2   .23121E-13  .26825       .22047E-03  .73153       .35671E-15  .22652E-28
      3   .15616E-12  .23158       .19241E-03  .76823       .35348E-14  .17699E-26
      4   .10090E-11  .22161       .18076E-03  .77821       .33554E-13  .13073E-24
      9   .10362E-07  .21848       .17421E-03  .78135       .23529E-08  .24924E-15
     10   .65340E-07  .21861       .17424E-03  .78122       .21773E-07  .17685E-13
     11   .44759E-06  .19356       .16051E-03  .80628       .21807E-06  .13050E-11
     15   .84628E-03  .18208       .14869E-03  .81502       .18682E-02  .30687E-04
     16   .60938E-02  .17052       .14377E-03  .79984       .19422E-01  .24745E-02
     17   .60840E-02  .12811       .13904E-03  .84243       .19307E-01  .24383E-02
     18   .65877E-02  .86742E-01  .12267E-03  .88169       .20853E-01  .25208E-02
     19   .68450E-02  .58520E-01  .10541E-03  .90871       .21539E-01  .26619E-02
     20   .10562E-01  .31532E-01  .76209E-04  .91655       .34092E-01  .44497E-02

                         ****   X-PROFILE         ****
   STAGE     C4H10       C5H12        C6H14
      1   .11184E-43  .11568E-57  .77387E-71
      2   .83900E-41  .74753E-54  .42004E-66
      3   .49260E-38  .35933E-50  .16126E-61
      4   .26924E-35  .15816E-46  .55776E-57
      9   .10862E-21  .20546E-28  .20664E-34
     10   .56217E-19  .84326E-25  .65656E-30
     11   .29110E-16  .33224E-21  .19228E-25
     15   .15505E-05  .55107E-07  .90558E-08
     16   .92175E-03  .26145E-03  .33239E-03
     17   .90702E-03  .25721E-03  .32698E-03
     18   .90847E-03  .25563E-03  .32459E-03
     19   .98548E-03  .27919E-03  .35487E-03
     20   .16630E-02  .47194E-03  .60004E-03
```

```
BLOCK:  B1       MODEL: RADFRAC (CONTINUED)

                         ****   Y-PROFILE        ****
STAGE     CO2         N2           O2           CH4           C2H6         C3H8
  1   .11852E-15  .71250       .29900E-03   .28720       .83764E-18   .71229E-33
  2   .13391E-14  .57064       .28720E-03   .42907       .13965E-16   .10677E-30
  3   .10269E-13  .51645       .26435E-03   .48328       .15788E-15   .99969E-29
  4   .68973E-13  .50029       .25197E-03   .49946       .15602E-14   .78099E-27
  9   .72585E-09  .49389       .24379E-03   .50587       .11228E-09   .15488E-17
 10   .45865E-08  .49384       .24377E-03   .50592       .10414E-08   .11032E-15
 11   .34629E-07  .45075       .23288E-03   .54902       .11539E-07   .93729E-14
 15   .68212E-04  .43132       .21961E-03   .56829       .10331E-03   .23425E-06
 16   .44407E-03  .43417       .22013E-03   .56417       .98031E-03   .16103E-04
 17   .54418E-03  .34312       .22768E-03   .65488       .12032E-02   .21382E-04
 18   .72125E-03  .24375       .21428E-03   .75368       .16025E-02   .29789E-04
 19   .86438E-03  .16913       .19186E-03   .82785       .19204E-02   .38967E-04
 20   .14649E-02  .97580E-01   .14768E-03   .89736       .33712E-02   .74429E-04

                         ****   Y-PROFILE        ****
STAGE     C4H10       C5H12        C6H14
  1   .38374E-47  .41010E-62   .29080E-76
  2   .50193E-44  .51897E-58   .34718E-71
  3   .37025E-41  .32988E-54   .18536E-66
  4   .21736E-38  .15856E-50   .71157E-62
  9   .92400E-25  .22002E-32   .28541E-39
 10   .48079E-22  .90938E-29   .91462E-35
 11   .29794E-19  .44691E-25   .34797E-30
 15   .17144E-08  .81523E-11   .18350E-12
 16   .81362E-06  .28917E-07   .47519E-08
 17   .11739E-05  .45639E-07   .81839E-08
 18   .17262E-05  .72961E-07   .14282E-07
 19   .24715E-05  .11249E-06   .23536E-07
 20   .49054E-05  .23113E-06   .50088E-07

                         ****   K-VALUES         ****
STAGE     CO2         N2           O2           CH4           C2H6         C3H8
  1   .41743E-01  1.7979       1.0965       .47595       .27829E-01   .30037E-02
  2   .57918E-01  2.1273       1.3027       .58654       .39149E-01   .47136E-02
  3   .65762E-01  2.2301       1.3738       .62909       .44666E-01   .56482E-02
  4   .68356E-01  2.2575       1.3939       .64180       .46499E-01   .59744E-02
  9   .70047E-01  2.2606       1.3994       .64743       .47721E-01   .62138E-02
 10   .70195E-01  2.2590       1.3990       .64760       .47830E-01   .62379E-02
 11   .77369E-01  2.3288       1.4508       .68093       .52916E-01   .71826E-02
 15   .80601E-01  2.3688       1.4770       .69726       .55297E-01   .76335E-02
 16   .72873E-01  2.5462       1.5311       .70535       .50474E-01   .65075E-02
 17   .89443E-01  2.6784       1.6376       .77737       .62319E-01   .87691E-02
 18   .10949      2.8101       1.7468       .85482       .76849E-01   .11817E-01
 19   .12628      2.8901       1.8201       .91102       .89159E-01   .14639E-01
 20   .13869      3.0947       1.9378       .97906       .98885E-01   .16727E-01
```

```
BLOCK:  B1        MODEL: RADFRAC (CONTINUED)

                             ****  K-VALUES          ****
  STAGE       C4H10       C5H12       C6H14
     1     .34312E-03  .35452E-04  .37576E-05
     2     .59825E-03  .69425E-04  .82654E-05
     3     .75163E-03  .91806E-04  .11495E-04
     4     .80734E-03  .10025E-03  .12758E-04
     9     .85064E-03  .10709E-03  .13812E-04
    10     .85524E-03  .10784E-03  .13931E-04
    11     .10235E-02  .13452E-03  .18096E-04
    15     .11057E-02  .14793E-03  .20263E-04
    16     .88268E-03  .11060E-03  .14296E-04
    17     .12942E-02  .17744E-03  .25028E-04
    18     .19001E-02  .28541E-03  .44000E-04
    19     .25079E-02  .40292E-03  .66322E-04
    20     .29497E-02  .48975E-03  .83475E-04




                    ********************************
                    ***** HYDRAULIC PARAMETERS *****
                    ********************************


      *** DEFINITIONS ***

       FLOW PARAM = (ML/MV)*SQRT(RHOV/RHOL)
       QR = QV*SQRT(RHOV/(RHOL-RHOV))
         WHERE:
         ML IS THE MASS FLOW OF LIQUID FROM THE STAGE
         MV IS THE MASS FLOW OF VAPOR TO THE STAGE
         RHOL IS THE MASS DENSITY OF LIQUID FROM THE STAGE
         RHOV IS THE MASS DENSITY OF VAPOR TO THE STAGE
         QV IS THE VOLUMETRIC FLOW RATE OF VAPOR TO THE STAGE


            MASS FLOW                   VOLUME FLOW                 DENSITY
             KG/HR                        CUM/SEC                   KG/CUM
STAGE LIQUID FROM   VAPOR TO   LIQUID FROM  VAPOR TO   LIQUID FROM  VAPOR TO
   1   147.60       362.05     0.10053E-03 0.13814E-02  407.87        72.799
   2   132.72       347.16     0.99822E-04 0.13854E-02  369.33        69.606
   3   129.67       344.11     0.10099E-03 0.13899E-02  356.68        68.771
   4   129.00       343.45     0.10150E-03 0.13907E-02  353.03        68.599
   9   129.30       343.74     0.10225E-03 0.13859E-02  351.27        68.897
  10   183.62       398.06     0.14523E-03 0.16588E-02  351.19        66.656
  11   181.35       395.79     0.14729E-03 0.16652E-02  342.01        66.024
  15   176.06       390.50     0.14412E-03 0.16722E-02  339.34        64.868
  16   1500.1       723.28     0.11702E-02 0.33123E-02  356.09        60.657
  17   1483.2       706.32     0.12173E-02 0.34756E-02  338.44        56.451
  18   1456.8       679.98     0.12568E-02 0.36895E-02  322.00        51.195
  19   1454.3       591.14     0.13014E-02 0.32576E-02  310.41        50.407
  20   863.18       591.14     0.77289E-03 0.32576E-02  310.23        50.407
```

```
BLOCK:  B1        MODEL: RADFRAC (CONTINUED)


                 VISCOSITY              SURFACE TENSION  FLOW PARAM      QR
                 N-SEC/SQM               N/M                              CUM/SEC
STAGE LIQUID FROM  VAPOR TO              LIQUID FROM
  1   0.53785E-04 0.97746E-05          0.39674E-02     0.17224         0.64392E-03
  2   0.51695E-04 0.96473E-05          0.38635E-02     0.16597         0.66765E-03
  3   0.50622E-04 0.96104E-05          0.37277E-02     0.16547         0.67931E-03
  4   0.50274E-04 0.96025E-05          0.36792E-02     0.16558         0.68298E-03
  9   0.50004E-04 0.96156E-05          0.36450E-02     0.16659         0.68457E-03
 10   0.49975E-04 0.95074E-05          0.36418E-02     0.20096         0.80289E-03
 11   0.49088E-04 0.94743E-05          0.35058E-02     0.20132         0.81446E-03
 15   0.48911E-04 0.94903E-05          0.34757E-02     0.19712         0.81293E-03
 16   0.52459E-04 0.92400E-05          0.39383E-02     0.85601         0.15008E-02
 17   0.50270E-04 0.89465E-05          0.35748E-02     0.85761         0.15551E-02
 18   0.48240E-04 0.86754E-05          0.31911E-02     0.85428         0.16042E-02
 19   0.46760E-04 0.84854E-05          0.28887E-02     0.99139         0.14343E-02
 20   0.47201E-04 0.84854E-05          0.28468E-02     0.58860         0.14348E-02


                   ************************************
                   ***** TRAY SIZING CALCULATIONS *****
                   ************************************


   ******************
   *** SECTION  1 ***
   ******************

   STARTING STAGE NUMBER                                          2
   ENDING STAGE NUMBER                                           19
   FLOODING CALCULATION METHOD                                 GLITSCH

   DESIGN PARAMETERS
   -----------------
   PEAK CAPACITY FACTOR                                        1.00000
   SYSTEM FOAMING FACTOR                                       1.00000
   FLOODING FACTOR                                             0.80000
   MINIMUM COLUMN DIAMETER             METER                   0.30480
   MINIMUM DC AREA/COLUMN AREA                                 0.100000
   HOLE AREA/ACTIVE AREA                                       0.12000

   TRAY SPECIFICATIONS
   -------------------
   TRAY TYPE                                                   SIEVE
   NUMBER OF PASSES                                              1
   TRAY SPACING                        METER                   0.60960
```

```
BLOCK:  B1        MODEL: RADFRAC (CONTINUED)


          ***** SIZING RESULTS @ STAGE WITH MAXIMUM DIAMETER *****

    STAGE WITH MAXIMUM DIAMETER                                      19
    COLUMN DIAMETER                        METER                   0.26078
    DC AREA/COLUMN AREA                                            0.32316
    DOWNCOMER VELOCITY                     M/SEC                   0.075395
    WEIR LENGTH                            METER                   0.25023


                            **** SIZING PROFILES ****

       STAGE     DIAMETER      TOTAL AREA   ACTIVE AREA   SIDE DC AREA
                  METER          SQM           SQM           SQM
          2      0.11276      0.99863E-02  0.75198E-02   0.12332E-02
          3      0.11387      0.10183E-01  0.76372E-02   0.12729E-02
          4      0.11424      0.10250E-01  0.76758E-02   0.12872E-02
          5      0.11437      0.10274E-01  0.76882E-02   0.12926E-02
          6      0.11443      0.10284E-01  0.76930E-02   0.12954E-02
          7      0.11447      0.10291E-01  0.76957E-02   0.12975E-02
          8      0.11450      0.10297E-01  0.76979E-02   0.12995E-02
          9      0.11453      0.10303E-01  0.76999E-02   0.13013E-02
         10      0.12727      0.12721E-01  0.90384E-02   0.18414E-02
         11      0.12841      0.12950E-01  0.91574E-02   0.18962E-02
         12      0.12881      0.13032E-01  0.91990E-02   0.19164E-02
         13      0.12895      0.13060E-01  0.92126E-02   0.19238E-02
         14      0.12891      0.13051E-01  0.92082E-02   0.19214E-02
         15      0.12782      0.12833E-01  0.91114E-02   0.18605E-02
         16      0.24884      0.48632E-01  0.19509E-01   0.14561E-01
         17      0.25516      0.51134E-01  0.20124E-01   0.15504E-01
         18      0.26042      0.53265E-01  0.20597E-01   0.16334E-01
         19      0.26078      0.53414E-01  0.18890E-01   0.17261E-01
BLOCK:  B10       MODEL: HEATER
------------------------------
   INLET STREAM:             12
   OUTLET STREAM:            13
   PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                      IN                OUT          RELATIVE DIFF.
    TOTAL BALANCE
       MOLE(KMOL/HR )              4.94413           4.94413               0.
       MASS(KG/HR   )              86.3177           86.3177               0.
       ENTHALPY(WATT      )       -121453.          -109453.         -0.988036E-01
```

```
BLOCK:  B10       MODEL: HEATER (CONTINUED)

                           ***  INPUT DATA  ***
  TWO    PHASE  PQ  FLASH
  SPECIFIED PRESSURE              BAR                              2.00000
  SPECIFIED HEAT DUTY             WATT                        12,000.0
  MAXIMUM NO. ITERATIONS                                          30
  CONVERGENCE TOLERANCE                                            0.000100000

                            ***  RESULTS  ***
  OUTLET TEMPERATURE     C                                       -63.409
  OUTLET PRESSURE        BAR                                       2.0000
  VAPOR FRACTION                                                   0.99946


  V-L PHASE EQUILIBRIUM :

     COMP              F(I)          X(I)           Y(I)           K(I)
     CO2             0.10562E-01   0.53645E-02    0.10565E-01     1.9695
     N2              0.31532E-01   0.15768E-03    0.31549E-01     200.09
     O2              0.76209E-04   0.94360E-06    0.76249E-04     80.807
     CH4             0.91655       0.27068E-01    0.91703         33.879
     C2H6            0.34092E-01   0.20986E-01    0.34099E-01     1.6248
     C3H8            0.44497E-02   0.24429E-01    0.44390E-02    0.18171
     C4H10           0.16630E-02   0.75446E-01    0.16233E-02    0.21516E-01
     C5H12           0.47194E-03   0.15478        0.38883E-03    0.25121E-02
     C6H14           0.60004E-03   0.69177        0.22777E-03    0.32925E-03
BLOCK:  B13       MODEL: COMPR
-----------------------------
  INLET STREAM:           200
  OUTLET STREAM:          21
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                      IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )               8.72550          8.72550              0.
      MASS(KG/HR   )               214.441          214.441              0.
      ENTHALPY(WATT     )         -63167.8         -67115.9         0.588259E-01

                           ***  INPUT DATA  ***

   GAS PHASE CALCULATION
   NO FLASH PERFORMED
   TYPE : ISENTROPIC TURBINE
   PRESSURE RATIO                                                  0.073000
   ISENTROPIC EFFICIENCY                                           0.72000
   MECHANICAL EFFICIENCY                                           1.00000
```

```
BLOCK:  B13      MODEL: COMPR (CONTINUED)

                             ***  RESULTS  ***

   INDICATED  HORSEPOWER REQUIREMENT  WATT                  -3,948.15
   BRAKE      HORSEPOWER REQUIREMENT  WATT                  -3,948.15
   NET WORK, WATT                                            3,948.15
   ISENTROPIC HORSEPOWER REQUIREMENT  WATT                  -5,483.55
   CALCULATED OUTLET PRES  BAR                                  2.00750
   CALCULATED OUTLET TEMP  C                                 -174.215
   ISENTROPIC TEMPERATURE  C                                 -193.632
   OUTLET VAPOR FRACTION                                        1.00000

BLOCK:  B15      MODEL: HEATER
-----------------------------
  INLET STREAM:            6
  OUTLET STREAM:           7
  PROPERTY OPTION SET:     SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                     IN               OUT           RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )            44.4971          44.4971                 0.
      MASS(KG/HR   )            776.859          776.859                 0.
      ENTHALPY(WATT     )     -0.108221E+07    -0.108221E+07    -0.360261E-07

                            ***  INPUT DATA  ***
  TWO    PHASE  TQ  FLASH
  SPECIFIED TEMPERATURE           C                          -135.000
  SPECIFIED HEAT DUTY             WATT                          0.0
  MAXIMUM NO. ITERATIONS                                       30
  CONVERGENCE TOLERANCE                                         0.000100000
```

```
BLOCK:  B15       MODEL: HEATER (CONTINUED)

                             ***  RESULTS  ***
  OUTLET TEMPERATURE     C                                              -135.00
  OUTLET PRESSURE        BAR                                               5.7688
  VAPOR FRACTION                                                        0.36771


  V-L PHASE EQUILIBRIUM :

     COMP                 F(I)             X(I)             Y(I)             K(I)
     CO2                  0.10562E-01      0.16554E-01      0.26045E-03      0.15734E-01
     N2                   0.31532E-01      0.79240E-02      0.72126E-01       9.1021
     O2                   0.76209E-04      0.38588E-04      0.14090E-03       3.6514
     CH4                  0.91655          0.91053          0.92690           1.0180
     C2H6                 0.34092E-01      0.53589E-01      0.56654E-03      0.10572E-01
     C3H8                 0.44497E-02      0.70362E-02      0.22948E-05      0.32614E-03
     C4H10                0.16630E-02      0.26302E-02      0.29294E-07      0.11138E-04
     C5H12                0.47194E-03      0.74640E-03      0.24551E-09      0.32892E-06
     C6H14                0.60004E-03      0.94900E-03      0.10216E-10      0.10766E-07
BLOCK:  B16       MODEL: HEATER
------------------------------
  INLET STREAM:              11
  OUTLET STREAM:             12
  PROPERTY OPTION SET:       SYSOP3     REDLICH-KWONG-SOAVE EQUATION OF STATE

                         ***  MASS AND ENERGY BALANCE  ***
                                        IN                 OUT           RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )                 4.94413            4.94413                 0.
      MASS(KG/HR   )                 86.3177            86.3177                 0.
      ENTHALPY(WATT     )           -121453.           -121453.          -0.466853E-07

                             ***  INPUT DATA  ***
  TWO    PHASE  PQ  FLASH
  SPECIFIED PRESSURE                 BAR                                2.00000
  SPECIFIED HEAT DUTY                WATT                               0.0
  MAXIMUM NO. ITERATIONS                                               30
  CONVERGENCE TOLERANCE                                                 0.000100000
```

```
BLOCK:  B16       MODEL: HEATER (CONTINUED)

                         ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                        -152.31
  OUTLET PRESSURE       BAR                                       2.0000
  VAPOR FRACTION                                                  0.36162


  V-L PHASE EQUILIBRIUM :

     COMP                F(I)          X(I)           Y(I)           K(I)
     CO2                0.10562E-01   0.16506E-01    0.71132E-04    0.43096E-02
     N2                 0.31532E-01   0.50818E-02    0.78224E-01     15.393
     O2                 0.76209E-04   0.31878E-04    0.15447E-03     4.8456
     CH4                0.91655       0.91382        0.92139         1.0083
     C2H6               0.34092E-01   0.53311E-01    0.16485E-03    0.30922E-02
     C3H8               0.44497E-02   0.69702E-02    0.27192E-06    0.39012E-04
     C4H10              0.16630E-02   0.26051E-02    0.14760E-08    0.56660E-06
     C5H12              0.47194E-03   0.73928E-03    0.49679E-11    0.67199E-08
     C6H14              0.60004E-03   0.93994E-03    0.87963E-13    0.93583E-10
BLOCK:  B17       MODEL: HEATER
------------------------------
  INLET STREAM:           3
  OUTLET STREAM:          4
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                    ***  MASS AND ENERGY BALANCE   ***
                                     IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )              53.2227          53.2227              0.
      MASS(KG/HR   )              991.302          991.302              0.
      ENTHALPY(WATT     )     -0.119070E+07   -0.119070E+07      0.122882E-06

                        ***  INPUT DATA  ***
  TWO    PHASE  PQ  FLASH
  SPECIFIED PRESSURE                BAR                         28.0000
  SPECIFIED HEAT DUTY               WATT                         0.0
  MAXIMUM NO. ITERATIONS                                       150
  CONVERGENCE TOLERANCE                                          0.000100000
```

```
BLOCK:  B17       MODEL: HEATER (CONTINUED)

                             ***  RESULTS  ***
  OUTLET TEMPERATURE     C                                           -135.80
  OUTLET PRESSURE        BAR                                          28.000
  VAPOR FRACTION                                                       0.


  V-L PHASE EQUILIBRIUM :

     COMP                  F(I)           X(I)           Y(I)           K(I)
     CO2                0.88308E-02    0.88308E-02    0.23944E-03    0.14917E-01
     N2                 0.14317        0.14317        0.47321         1.8157
     O2                 0.11273E-03    0.11273E-03    0.17807E-03    0.86786
     CH4                0.81337        0.81337        0.52570        0.35524
     C2H6               0.28503E-01    0.28503E-01    0.66524E-03    0.12844E-01
     C3H8               0.37202E-02    0.37202E-02    0.73466E-05    0.10878E-02
     C4H10              0.13904E-02    0.13904E-02    0.25142E-06    0.99702E-04
     C5H12              0.39457E-03    0.39457E-03    0.59492E-08    0.83217E-05
     C6H14              0.50167E-03    0.50167E-03    0.70384E-09    0.77512E-06
BLOCK:  B18       MODEL: FSPLIT
------------------------------
  INLET STREAM:          5
  OUTLET STREAMS:        6          9
  PROPERTY OPTION SET:   SYSOP3     REDLICH-KWONG-SOAVE EQUATION OF STATE

                        ***  MASS AND ENERGY BALANCE  ***
                                     IN               OUT         RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )              49.4413          49.4413               0.
      MASS(KG/HR   )              863.177          863.177               0.
      ENTHALPY(WATT    )      -0.120245E+07    -0.120245E+07             0.

                            ***  INPUT DATA  ***

 FRACTION OF FLOW                  STRM=6        FRAC=          0.90000

                             ***  RESULTS  ***

 STREAM= 6              SPLIT=            0.90000     KEY=  0
         9                                0.100000          0
```

```
BLOCK:  B19      MODEL: HEATER
------------------------------
  INLET STREAM:             21
  OUTLET STREAM:            22
  OUTLET HEAT STREAM:       MID
  PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                    IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )              8.72550         8.72550               0.
      MASS(KG/HR   )              214.441         214.441               0.
      ENTHALPY(WATT     )        -67115.9        -67115.9         0.216818E-15

                           ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE             C                       -120.000
  SPECIFIED PRESSURE                BAR                        2.00000
  MAXIMUM NO. ITERATIONS                                     30
  CONVERGENCE TOLERANCE                                        0.000100000

                            ***  RESULTS  ***
  OUTLET TEMPERATURE     C                                     -120.00
  OUTLET PRESSURE        BAR                                     2.0000
  HEAT DUTY              WATT                                    4114.8
  VAPOR FRACTION                                                 1.0000


  V-L PHASE EQUILIBRIUM :

     COMP               F(I)           X(I)            Y(I)             K(I)
     N2                0.71250        0.51936         0.71250          17.232
     O2                0.29900E-03    0.26697E-03     0.29900E-03      14.660
     CH4               0.28720        0.48038         0.28720          9.0474
BLOCK:  B20      MODEL: HEATER
------------------------------
  INLET STREAM:             17
  OUTLET STREAM:            17A
  PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                    IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )              4.94413         4.94413               0.
      MASS(KG/HR   )              86.3177         86.3177               0.
      ENTHALPY(WATT     )        -102771.        -106120.         0.315597E-01
```

```
BLOCK:  B20       MODEL: HEATER (CONTINUED)

                          ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE           C                         20.0000
  PRESSURE DROP                   BAR                        0.0
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                      0.000100000

                           ***  RESULTS  ***
  OUTLET TEMPERATURE     C                                   20.000
  OUTLET PRESSURE        BAR                                 28.500
  HEAT DUTY              WATT                               -3349.1
  VAPOR FRACTION                                             1.0000


  V-L PHASE EQUILIBRIUM :

     COMP                  F(I)           X(I)           Y(I)           K(I)
     CO2                0.10562E-01    0.15453E-01    0.10562E-01     2.6225
     N2                 0.31532E-01    0.22066E-01    0.31532E-01     4.9435
     O2                 0.76209E-04    0.59481E-04    0.76209E-04     4.4068
     CH4                0.91655        0.87061        0.91655         3.7314
     C2H6               0.34092E-01    0.64950E-01    0.34092E-01     2.3021
     C3H8               0.44497E-02    0.11412E-01    0.44497E-02     1.5833
     C4H10              0.16630E-02    0.66148E-02    0.16630E-02     1.0931
     C5H12              0.47194E-03    0.29329E-02    0.47194E-03    0.75275
     C6H14              0.60004E-03    0.59004E-02    0.60004E-03    0.51630
BLOCK:  B21       MODEL: HEATER
------------------------------
  INLET STREAM:             16
  OUTLET STREAM:            17
  PROPERTY OPTION SET:      SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                      ***  MASS AND ENERGY BALANCE  ***
                                  IN               OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )            4.94413          4.94413               0.
      MASS(KG/HR   )            86.3177          86.3177               0.
      ENTHALPY(WATT     )      -106307.         -102771.         -0.332650E-01

                          ***  INPUT DATA  ***
  TWO    PHASE  TP  FLASH
  SPECIFIED TEMPERATURE           C                         80.0000
  SPECIFIED PRESSURE              BAR                       28.5000
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                      0.000100000
```

```
BLOCK:  B21       MODEL: HEATER (CONTINUED)

                           ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                           80.000
  OUTLET PRESSURE       BAR                                         28.500
  HEAT DUTY             WATT                                        3536.3
  VAPOR FRACTION                                                    1.0000


  V-L PHASE EQUILIBRIUM :

     COMP                 F(I)          X(I)          Y(I)          K(I)
     CO2               0.10562E-01   0.13622E-01   0.10562E-01    4.4383
     N2                0.31532E-01   0.23812E-01   0.31532E-01    7.2088
     O2                0.76209E-04   0.63865E-04   0.76209E-04    6.4840
     CH4               0.91655       0.88024       0.91655        5.7685
     C2H6              0.34092E-01   0.51552E-01   0.34092E-01    4.0815
     C3H8              0.44497E-02   0.12974E-01   0.44497E-02    3.1739
     C4H10             0.16630E-02   0.13403E-01   0.16630E-02    2.4767
     C5H12             0.47194E-03   0.16043E-02   0.47194E-03    1.9447
     C6H14             0.60004E-03   0.27289E-02   0.60004E-03    1.5297
BLOCK:  B5        MODEL: HEATX
-----------------------------
  HOT SIDE:
  ---------
  INLET STREAM:           17A
  OUTLET STREAM:          18
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

  COLD SIDE:
  ----------
  INLET STREAM:           15
  OUTLET STREAM:          16
  PROPERTY OPTION SET:    SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                    IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )              9.88825         9.88826        -0.558420E-06
      MASS(KG/HR   )              172.635         172.635        -0.380306E-06
      ENTHALPY(WATT     )        -218448.        -218448.         0.691928E-06

                           ***  INPUT DATA  ***

  FLASH SPECS FOR HOT SIDE:
  TWO    PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                        30
  CONVERGENCE TOLERANCE                                          0.000100000
```

```
BLOCK:  B5       MODEL: HEATX (CONTINUED)

  FLASH SPECS FOR COLD SIDE:
  TWO    PHASE      FLASH
  MAXIMUM NO. ITERATIONS                                    30
  CONVERGENCE TOLERANCE                                      0.000100000


   COUNTERCURRENT  HEAT EXCHANGER WITH SPECIFIED COLD OUTLET TEMPERATURE
   COLD STREAM OUTLET TEMPERATURE (C    )                              2.00000
   HOT STREAM PRESSURE DROP (BAR       )                               1.50000
   COLD STREAM PRESSURE DROP (BAR      )                               0.0

   HEAT TRANSFER COEFFICIENTS  (WATT/SQM-K        ):
   HOT STREAM PHASE     COLD STREAM PHASE
   LIQUID               LIQUID                                       850.000
   BOILING LIQUID       LIQUID                                       850.000
   VAPOR                LIQUID                                       850.000
   LIQUID               BOILING LIQUID                               850.000
   BOILING LIQUID       BOILING LIQUID                               850.000
   VAPOR                BOILING LIQUID                               850.000
   LIQUID               VAPOR                                        850.000
   BOILING LIQUID       VAPOR                                        850.000
   VAPOR                VAPOR                                        850.000

                          ***  RESULTS  ***
   HOT STREAM INLET TEMPERATURE (C    )                               20.0000
   HOT STREAM OUTLET TEMPERATURE (C    )                             -79.8053
   COLD STREAM INLET TEMPERATURE (C    )                            -116.718
   COLD STREAM OUTLET TEMPERATURE (C    )                              2.00000
   EXCHANGER HEAT DUTY (WATT     )                                 6,021.03
   HEAT TRANSFER AREA (SQM      )                                      0.27696
```

```
BLOCK:  B5       MODEL: HEATX (CONTINUED)


   AREA CALCULATION RESULTS:

   SECTION  CONDITIONS    AREA                HEAT DUTY
            (HOT-COLD)    (SQM      )         (WATT     )
      1        V-B          0.14972           2,719.20
      2        B-V          0.0                 -11.6519
      3        V-B          0.12725           3,313.48

   SECTION   TEMPERATURE LEAVING SECTION
             HOT STREAM           COLD STREAM
             (C        )          (C        )
      1         -29.7179               2.00000
      2         -29.5048             -54.8480
      3         -79.8053             -54.6177



          ------------------------------------------------------------
          |                   |                   |                   |
17A       |      VAP          |       BOIL        |        VAP        | 18
------>   |                   |                   |                   |------>
  20.0    |              -29.7|              -29.5|                   | -79.8
          |                   |                   |                   |
16        |     BOIL          |       VAP         |       BOIL        | 15
<------   |                   |                   |                   |<------
   2.0    |              -54.8|              -54.6|                   |-116.7
          |                   |                   |                   |
          ------------------------------------------------------------



BLOCK:  B9       MODEL: HEATER
------------------------------
  INLET STREAM:              2
  OUTLET STREAM:             3
  PROPERTY OPTION SET:       SYSOP3    REDLICH-KWONG-SOAVE EQUATION OF STATE

                       ***  MASS AND ENERGY BALANCE  ***
                                     IN              OUT          RELATIVE DIFF.
   TOTAL BALANCE
      MOLE(KMOL/HR )              53.2227         53.2227               0.
      MASS(KG/HR   )              991.302         991.302               0.
      ENTHALPY(WATT     )     -0.115869E+07   -0.119070E+07     0.268826E-01

                           ***  INPUT DATA  ***
  TWO    PHASE  PQ  FLASH
  SPECIFIED PRESSURE                 BAR                            54.0000
  SPECIFIED HEAT DUTY                WATT                       -32,000.0
  MAXIMUM NO. ITERATIONS                                            500
  CONVERGENCE TOLERANCE                                               0.000100000
```

```
BLOCK:  B9         MODEL: HEATER (CONTINUED)

                              ***  RESULTS  ***
  OUTLET TEMPERATURE    C                                            -136.23
  OUTLET PRESSURE       BAR                                           54.000
  VAPOR FRACTION                                                          0.


  V-L PHASE EQUILIBRIUM :

     COMP                 F(I)          X(I)          Y(I)          K(I)
     CO2                0.88308E-02   0.88308E-02   0.25583E-03   0.86622E-02
     N2                 0.14317       0.14317       0.46231       0.98334
     O2                 0.11273E-03   0.11273E-03   0.17133E-03   0.46192
     CH4                0.81337       0.81337       0.53647       0.19954
     C2H6               0.28503E-01   0.28503E-01   0.77945E-03   0.81502E-02
     C3H8               0.37202E-02   0.37202E-02   0.98983E-05   0.78333E-03
     C4H10              0.13904E-02   0.13904E-02   0.38949E-06   0.81491E-04
     C5H12              0.39457E-03   0.39457E-03   0.10718E-07   0.78025E-05
     C6H14              0.50167E-03   0.50167E-03   0.14999E-08   0.84790E-06
```

```
1 10 11 12 13
-------------

STREAM ID                 1           10          11          12          13
FROM :                    ----        B4          B3          B16         B10
TO   :                    B2          B3          B16         B10         B3

SUBSTREAM: MIXED
PHASE:                    VAPOR       LIQUID      LIQUID      MIXED       MIXED
COMPONENTS: KMOL/HR
  CO2                     0.4700  5.2222-02   5.2222-02   5.2222-02   5.2222-02
  N2                      7.6200      0.1559      0.1559      0.1559      0.1559
  O2                   6.0000-03  3.7678-04   3.7678-04   3.7678-04   3.7678-04
  CH4                    43.2900      4.5315      4.5315      4.5315      4.5315
  C2H6                    1.5170      0.1685      0.1685      0.1685      0.1685
  C3H8                    0.1980  2.2000-02   2.2000-02   2.2000-02   2.2000-02
  C4H10                7.4000-02  8.2222-03   8.2222-03   8.2222-03   8.2222-03
  C5H12                2.1000-02  2.3333-03   2.3333-03   2.3333-03   2.3333-03
  C6H14                2.6700-02  2.9667-03   2.9667-03   2.9667-03   2.9667-03
TOTAL FLOW:
  KMOL/HR                53.2227      4.9441      4.9441      4.9441      4.9441
  KG/HR                 991.3019     86.3177     86.3177     86.3177     86.3177
  CUM/SEC              6.0091-03  7.4045-05   6.9072-05   2.4058-03   1.1823-02
STATE VARIABLES:
  TEMP   C               15.0000  -103.0662   -110.0662   -152.3090    -63.4090
  PRES   BAR             54.0000    28.0000     28.0000      2.0000      2.0000
  VFRAC                   1.0000     0.0         0.0          0.3616      0.9994
  LFRAC                   0.0        1.0000      1.0000       0.6383  5.3832-04
  SFRAC                   0.0        0.0         0.0          0.0         0.0
ENTHALPY:
  J/KMOL              -6.8837+07 -8.7868+07 -8.8434+07 -8.8434+07 -7.9697+07
  J/KG                -3.6959+06 -5.0329+06 -5.0654+06 -5.0654+06 -4.5649+06
  WATT                -1.0177+06 -1.2068+05 -1.2145+05 -1.2145+05 -1.0945+05
ENTROPY:
  J/KMOL-K            -1.0411+05 -1.6176+05 -1.6516+05 -1.6063+05 -9.6987+04
  J/KG-K              -5589.8717 -9265.1222 -9459.8357 -9200.4041 -5555.2636
DENSITY:
  KMOL/CUM                2.4603    18.5476     19.8832      0.5708      0.1161
  KG/CUM                 45.8244   323.8169    347.1337      9.9665      2.0279
AVG MW                   18.6255    17.4586     17.4586     17.4586     17.4586
```

```
14 15 16 17 17A
---------------

STREAM ID                  14          15          16          17          17A
FROM :                     B3          B4          B5          B21         B20
TO   :                     B4          B5          B21         B20         B5

SUBSTREAM: MIXED
PHASE:                    MIXED       MIXED       VAPOR       VAPOR       VAPOR
COMPONENTS: KMOL/HR
  CO2                   5.2222-02   5.2222-02   5.2222-02   5.2222-02   5.2222-02
  N2                       0.1559      0.1559      0.1559      0.1559      0.1559
  O2                    3.7678-04   3.7678-04   3.7678-04   3.7678-04   3.7678-04
  CH4                      4.5315      4.5315      4.5315      4.5315      4.5315
  C2H6                     0.1685      0.1685      0.1685      0.1685      0.1685
  C3H8                  2.2000-02   2.2000-02   2.2000-02   2.2000-02   2.2000-02
  C4H10                 8.2222-03   8.2222-03   8.2222-03   8.2222-03   8.2222-03
  C5H12                 2.3333-03   2.3333-03   2.3333-03   2.3333-03   2.3333-03
  C6H14                 2.9667-03   2.9667-03   2.9667-03   2.9667-03   2.9667-03
TOTAL FLOW:
  KMOL/HR                  4.9441      4.9441      4.9441      4.9441      4.9441
  KG/HR                   86.3177     86.3177     86.3177     86.3177     86.3177
  CUM/SEC               8.8695-03   8.5600-03   1.5633-02   1.3862-03   1.1130-03
STATE VARIABLES:
  TEMP   C              -112.1358   -116.7183      2.0000     80.0000     20.0000
  PRES   BAR               2.0000      2.0000      2.0000     28.5000     28.5000
  VFRAC                    0.9897      0.9851      1.0000      1.0000      1.0000
  LFRAC                 1.0210-02   1.4872-02      0.0         0.0         0.0
  SFRAC                    0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL               -8.1558+07  -8.1790+07  -7.7406+07  -7.4831+07  -7.7270+07
  J/KG                 -4.6715+06  -4.6848+06  -4.4337+06  -4.2862+06  -4.4259+06
  WATT                 -1.1201+05  -1.1233+05  -1.0631+05  -1.0277+05  -1.0612+05
ENTROPY:
  J/KMOL-K             -1.0714+05  -1.0860+05  -8.7480+04  -1.0106+05  -1.0862+05
  J/KG-K               -6136.9183  -6220.6520  -5010.6757  -5788.4810  -6221.6141
DENSITY:
  KMOL/CUM                 0.1548      0.1604   8.7853-02      0.9907      1.2339
  KG/CUM                   2.7033      2.8010      1.5338     17.2970     21.5432
AVG MW                    17.4586     17.4586     17.4586     17.4586     17.4586
```

```
18 19 2 200 21
--------------

STREAM ID                  18          19          2           200         21
FROM :                     B5          B1          B2          B3          B13
TO   :                     B1          B3          B9          B13         B19

SUBSTREAM: MIXED
PHASE:                     MIXED       VAPOR       LIQUID      VAPOR       VAPOR
COMPONENTS: KMOL/HR
  CO2                   5.2222-02   1.0341-15      0.4700   1.0341-15   1.0341-15
  N2                       0.1558      6.2169      7.6200      6.2169      6.2169
  O2                    3.7678-04   2.6089-03   6.0000-03   2.6089-03   2.6089-03
  CH4                      4.5315      2.5059     43.2900      2.5059      2.5059
  C2H6                     0.1685   7.3088-18      1.5170   7.3088-18   7.3088-18
  C3H8                  2.2000-02   6.2150-33      0.1980   6.2150-33   6.2150-33
  C4H10                 8.2222-03      0.0      7.4000-02      0.0         0.0
  C5H12                 2.3333-03      0.0      2.1000-02      0.0         0.0
  C6H14                 2.9667-03      0.0      2.6700-02      0.0         0.0
TOTAL FLOW:
  KMOL/HR                  4.9441      8.7255     53.2227      8.7255      8.7255
  KG/HR                   86.3177    214.4412    991.3019    214.4412    214.4412
  CUM/SEC               6.0795-04   7.1321-04   7.9051-04   1.0851-03   9.4043-03
STATE VARIABLES:
  TEMP   C               -79.8052   -129.8547   -105.0000    -99.8547   -174.2148
  PRES   BAR              27.0000     27.5000     54.0000     27.5000      2.0075
  VFRAC                    0.9697      1.0000      0.0         1.0000      1.0000
  LFRAC                 3.0212-02      0.0         1.0000      0.0         0.0
  SFRAC                    0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL               -8.1654+07  -2.7438+07  -7.8374+07  -2.6062+07  -2.7691+07
  J/KG                 -4.6770+06  -1.1164+06  -4.2079+06  -1.0604+06  -1.1267+06
  WATT                 -1.1214+05  -6.6502+04  -1.1587+06  -6.3168+04  -6.7116+04
ENTROPY:
  J/KMOL-K             -1.2682+05  -7.3989+04  -1.4997+05  -6.5218+04  -5.8085+04
  J/KG-K               -7263.8423  -3010.5654  -8051.6661  -2653.6850  -2363.4266
DENSITY:
  KMOL/CUM                 2.2590      3.3983     18.7020      2.2336      0.2577
  KG/CUM                  39.4392     83.5195    348.3353     54.8945      6.3340
AVG MW                    17.4586     24.5763     18.6255     24.5763     24.5763
```

```
22 22A 23 3 4
-------------

STREAM ID                 22          22A         23          3           4
FROM :                    B19         B4          B2          B9          B17
TO   :                    B4          B2          ----        B17         B1

SUBSTREAM: MIXED
PHASE:                    VAPOR       VAPOR       VAPOR       LIQUID      LIQUID
COMPONENTS: KMOL/HR
  CO2                   1.0341-15   1.0341-15   1.0341-15      0.4700      0.4700
  N2                       6.2169      6.2169      6.2169      7.6200      7.6200
  O2                    2.6089-03   2.6089-03   2.6089-03   6.0000-03   6.0000-03
  CH4                      2.5059      2.5059      2.5059     43.2900     43.2900
  C2H6                  7.3088-18   7.3088-18   7.3088-18      1.5170      1.5170
  C3H8                  6.2150-33   6.2150-33   6.2150-33      0.1980      0.1980
  C4H10                    0.0         0.0         0.0      7.4000-02   7.4000-02
  C5H12                    0.0         0.0         0.0      2.1000-02   2.1000-02
  C6H14                    0.0         0.0         0.0      2.6700-02   2.6700-02
TOTAL FLOW:
  KMOL/HR                  8.7255      8.7255      8.7255     53.2227     53.2227
  KG/HR                  214.4412    214.4412    214.4412    991.3019    991.3019
  CUM/SEC               1.5198-02   1.6236-02   2.9011-02   6.2850-04   6.4006-04
STATE VARIABLES:
  TEMP    C             -120.0000   -110.0000     15.0000   -136.2263   -135.7970
  PRES    BAR              2.0000      2.0000      2.0000     54.0000     28.0000
  VFRAC                    1.0000      1.0000      1.0000    0.0         0.0
  LFRAC                 0.0         0.0         0.0            1.0000      1.0000
  SFRAC                 0.0         0.0         0.0         0.0         0.0
ENTHALPY:
  J/KMOL               -2.5993+07  -2.5685+07  -2.1840+07  -8.0539+07  -8.0539+07
  J/KG                 -1.0577+06  -1.0451+06  -8.8866+05  -4.3241+06  -4.3241+06
  WATT                 -6.3001+04  -6.2253+04  -5.2935+04  -1.1907+06  -1.1907+06
ENTROPY:
  J/KMOL-K             -4.4354+04  -4.2401+04  -2.4910+04  -1.6415+05  -1.6333+05
  J/KG-K               -1804.7275  -1725.2827  -1013.5797  -8812.9866  -8769.3321
DENSITY:
  KMOL/CUM                 0.1594      0.1492   8.3547-02     23.5228     23.0978
  KG/CUM                   3.9193      3.6689      2.0532    438.1255    430.2106
AVG MW                    24.5763     24.5763     24.5763     18.6255     18.6255
```

```
5 6 7 8 9
---------

STREAM ID                5           6           7            8            9
FROM :                   B1          B18         B15          B2           B18
TO   :                   B18         B15         B2           ----         B4

SUBSTREAM: MIXED
PHASE:                   LIQUID      LIQUID      MIXED        VAPOR        LIQUID
COMPONENTS: KMOL/HR
  CO2                     0.5222      0.4700      0.4700       0.4700     5.2222-02
  N2                      1.5589      1.4030      1.4030       1.4030       0.1559
  O2                    3.7678-03   3.3911-03   3.3911-03   3.3911-03   3.7678-04
  CH4                    45.3155     40.7839     40.7839      40.7839       4.5315
  C2H6                    1.6855      1.5170      1.5170       1.5170       0.1685
  C3H8                    0.2200      0.1980      0.1980       0.1980     2.2000-02
  C4H10                 8.2222-02   7.4000-02   7.4000-02   7.4000-02   8.2222-03
  C5H12                 2.3333-02   2.1000-02   2.1000-02   2.1000-02   2.3333-03
  C6H14                 2.9667-02   2.6700-02   2.6700-02   2.6700-02   2.9667-03
TOTAL FLOW:
  KMOL/HR                49.4412     44.4971     44.4971      44.4971       4.9441
  KG/HR                 863.1770    776.8593    776.8593     776.8593      86.3177
  CUM/SEC               7.7289-04   6.9560-04   8.4152-03   5.1299-02   7.7289-05
STATE VARIABLES:
  TEMP    C             -99.5662    -99.5662   -135.0000      18.0845     -99.5662
  PRES    BAR            28.0000     28.0000      5.7688       5.7688      28.0000
  VFRAC                   0.0         0.0         0.3677       1.0000       0.0
  LFRAC                   1.0000      1.0000      0.6322       0.0          1.0000
  SFRAC                   0.0         0.0         0.0          0.0          0.0
ENTHALPY:
  J/KMOL               -8.7555+07  -8.7555+07  -8.7555+07  -7.6902+07  -8.7555+07
  J/KG                 -5.0150+06  -5.0150+06  -5.0150+06  -4.4048+06  -5.0150+06
  WATT                 -1.2025+06  -1.0822+06  -1.0822+06  -9.5053+05  -1.2025+05
ENTROPY:
  J/KMOL-K             -1.5994+05  -1.5994+05  -1.5687+05  -9.4438+04  -1.5994+05
  J/KG-K               -9160.8578  -9160.8578  -8985.3131  -5409.2686  -9160.8578
DENSITY:
  KMOL/CUM               17.7692     17.7692      1.4688       0.2409      17.7692
  KG/CUM                310.2261    310.2261     25.6433       4.2066     310.2261
AVG MW                   17.4586     17.4586     17.4586      17.4586      17.4586
```

```
MID
---

STREAM ID                   MID
FROM :                      B19
TO   :                      B1
CLASS:                      HEAT

STREAM ATTRIBUTES:
HEAT
Q         WATT           -4114.8363
```

APPENDIX 9

The factors and coefficients for the investment cost calculation of the design process

The dimension of C_i is 10^3 x US \$. The last column of the tables is the PCE.

Table A9.1. The furnace.

Code	F_m	F_p	F_t	Q (kW)	C_{fuo}	C_{fu}
H-2101	1.6	1	1.5	4170	335.8	857.5

Table A9.2. The pressure vessels.

Code	F_m	F_p	l (m)	d (m)	a	b	C_{pvo}	C_{pv}
V-2101	1	1.4	4.10	0.66	1500	1100	3.81	5.67
V-2102	1	1.4	3.60	1.00	1500	1100	5.46	8.14
V-2103	1	1.4	3.40	1.05	890	705	3.47	5.17
V-2104	3.7	1	5.24	0.70	1294	1141	4.91	19.33
V-2107	3.7	1.2	2.55	0.65	1500	1100	2.68	12.67
V-2108	3.7	1.2	2.30	0.61	1500	1100	2.34	11.05
V-2109	3.7	1	2.60	0.51	1500	1100	2.07	8.15
V-2110	1	1	4.80	2.00	1500	1100	14.53	15.47
V-2111	1	1	1.20	0.70	1500	1100	1.91	2.03
V-2112	1	1.4	3.60	1.00	1500	1100	5.46	8.14
V-2113	3.7	1.2	1.85	0.45	1500	1100	1.47	6.94
V-2114	3.7	1.2	1.85	0.35	1500	1100	1.11	5.26
V-2115	1	1.2	4.50	0.66	1500	1100	4.09	5.22
V-2116	1	1.2	2.35	0.61	1500	1100	2.37	3.03
V-2117	1	1.6	2.35	0.51	1500	1100	1.94	3.30
V-2119	1	1.2	2.00	0.41	1500	1100	1.37	1.76

Table A9.3. The columns without internals.

Code	F_m	F_p	l (m)	d (m)	a	b	C_{pvo}	C_{pv}
V-2105	1	1.2	21.56	0.76	1294	1141	18.86	24.09
V-2106	2.3	1.1	19.90	0.90	1294	1141	21.37	57.55
V-2118	1	1.6	4.48	1.10	1500	1100	7.13	12.14
T-21	3.7	1.6	14.70	0.80	1294	1141	14.13	89.03
T-22	3.7	1.2	10.54	0.40	1294	1141	4.86	22.97
T-23	3.7	1.2	6.02	0.40	1294	1141	2.98	14.07
T-24	3.7	1.2	5.55	0.40	1294	1141	2.78	13.14

Table A9.4. The trays.

Code	N_{tr}	F_{nt}	F_m	F_{tt}	d (m)	C_{tr}	C_{int}
V-2105	1	3	1	1	0.76	0.16	0.50
V-2106	4	2.5	1.7	1	0.90	0.18	3.28
V-2118	1	3	1	1	1.10	0.22	0.70
T-21	20	1	1.7	1	0.80	0.16	5.91
T-22	25	1	1.7	2.9	0.40	0.10	13.44
T-23	11	1.5	1.7	2.9	0.40	0.10	8.87
T-24	11	1.5	1.7	2.9	0.40	0.10	8.87

Table A9.5. The packings.

Code	$V_{packing}$ (m^3)	C_{po}	N_{db}	C_{do}	C_{pd}
V-2105	6.0	15.00	3	4.10	19.10
V-2106	5.7	14.18	3	5.70	19.88

$V_{packing}$ is the volume of the packing, C_{po} is the price of the packing (Pall rings), N_{db} the number of distributors, C_{do} the price of the distibutors and C_{pd} the total price.

Table A9.6. The compressors.

Code	F_m	P (kW)	a	b	C_{como}	C_{com}
K-2103	1	200	6.628	0.968	76.57	102.60
K-2104	1	300	6.628	0.968	113.40	151.90
K-2105	1	140	6.628	0.968	54.21	72.62

Table A9.7. The drivers.

Code	F_t	F_{red}	C_{emo}	C_{em}
K-2103	1.4	1	11.91	19.23
K-2104	1.4	1	16.54	26.70
K-2105	1.4	1	8.77	14.16

Table A9.8. The heat exchangers.

Code	F_t	F_p	A (m^2)	a	b	C_{heo}	C_{he}
H-2102	0.8	1.25	4.6	7.085	0.656	3.23	3.43
H-2103	0.8	1.1	22.7	6.587	0.9955	16.24	15.21
H-2104	0.8	1.25	9.1	6.587	0.9955	6.54	6.96
H-2105	0.8	1.25	9.1	7.085	0.656	5.08	5.41
H-2106	0.8	1.3	18.2	7.085	0.656	8.01	8.87
H-2107	1	1.3	23.9	7.085	0.656	9.58	13.25
H-2108	0.85	1	50.0	7.085	0.656	15.54	14.06
H-2109A	0.85	1.1	35.2	7.085	0.656	12.35	12.29
H-2109B	0.85	1.1	35.2	6.587	0.9955	25.14	25.01
H-2110	0.85	1.1	83.3	6.587	0.9955	59.25	58.96
H-2111	0.85	1.1	51.0	6.587	0.9955	36.36	36.18
H-2112	0.85	1	28.4	6.587	0.9955	20.30	18.36
H-2113	0.8	1.1	14.9	7.085	0.656	7.02	6.58
H-2114	0.85	1.1	9.3	7.085	0.656	5.16	5.13
H-2115	0.85	1.3	15.5	7.085	0.656	7.21	8.48
H-2116	0.85	1.25	6.5	7.085	0.656	4.08	4.61
H-2117	0.85	1.1	7.5	7.085	0.656	4.48	4.46
H-2118	0.8	1.1	16.8	7.085	0.656	7.60	7.12
H-2119	0.8	1.1	7.2	7.085	0.656	4.36	4.08
H-2120	0.85	1	6.6	7.085	0.656	4.12	3.72
E-21	0.8	1.3	10.0*	7.439	0.8861	13.09	14.48
E-22	1.4	1.3	18.0	7.439	0.8861	22.03	42.66
E-23L	1.4	1.3	62.2	8.6063	0.601	65.42	126.69
E-23U	1.4	1.3	116.7	8.6063	0.601	95.49	184.92
E-24	1.4	1.1	4.3	7.439	0.8861	6.19	10.15
E-25	1.4	1.1	4.3	7.439	0.8861	6.19	10.15
E-27	1.4	1.1	4.3	7.439	0.8861	6.19	10.15

* The transfer area of the heat exchanger E-21 is an estimation.

APPENDIX 10

H_2-PSA design

The basic parameters for the design of the H_2-PSA system are in following table:

Table A10.1 : Basic data for H_2-PSA system

Feedgas (ChemCad)	adsorbent (zeolite 5A)	PSA system
$\omega_o = 0.68$ kg/s $\rho_o = 17.1$ kg/m^3 $\mu = 1.416 * 10^{-5}$	$D_p = 0.016$ m $\varepsilon = 0.42$ $\rho_a = 786$ kg/m^3	$P_{ads} = 27$ bar $P_{des} = 1$ bar $t_c = 600$ sec

With the equations 10.4...10.7 and the basic data above, the minimal column diameter is calculated:

v_s(max) = 1.02 m/s
A(min) = 0.082 m_2
d(min) = 0.32 m

Table A10.2 : PSA-feedgas

component	feedgas (mol/s)
H_2	27.17
CO	0.00
CO_2	11.83
N_2	4.76
CH_4	0.513

According to the adsorption- and desorption pressure, cycle time (table A10.1) and the amount of adsorbed component in equilibrium, the column height is determined with equation 10.8. Taking a column diameter greater than the minimum diameter thinking about the pressure drop (A = 0.65 m_2 ,d = 0.90 m) the length of the H_2-PSA beds is:

L = 1.6 m

With equation 10.9 the pressure drop over these beds is:

$\delta P = 0.12$ bar

An estimation of the practical work of compression is made by calculating the energy necessary for compressing (efficiency = 0.75) the feed from desorption pressure to adsorption pressure: $P_{total} = 1.0$ MW

CO-VSA design

The basic parameters for the design of the CO-VSA system are in following table:

Table A10.3 : basic data for CO-VSA system

Feedgas (ChemCad)	adsorbent (CO-selective)	VSA system
ω_o = 1.14 kg/s ρ_o = 11.78 kg/m^3 μ = 1.597 * 10^{-5}	D_p = 0.016 m ε = 0.42 ρ_a = 800 kg/m^3	P_{ads} = 1 bar P_{des} = 0.04 bar t_c = 600 sec

With the equations 10.4 .. 10.7 and the basic data above, the minimal column diameter is calculated:

v_s(max) = 0.88 m/s
A(min) = 0.12 m_2
d(min) = 0.37 m

Table A10.4 : CO-VSA feedgas

component	feedgas (mol/s)
H_2	27.17
CO	16.00
CO_2	11.83
N_2	4.76
CH_4	0.513

According to the adsorption- and desorption pressure, cycle time (table A10.3) and the amount of adsorbed component in equilibrium, the column height is determined with equation 10.8. Taking a column diameter greater than the minimum diameter thinking about the pressure drop (A = 0.5 m_2 ,d = 0.80 m) the length of the CO-VSA beds is:

L = 1.37 m

With equation 10.9 the pressure drop over these beds and the total pressure drop are:

δP = 0.11 bar $\qquad$ $\delta P_{total} = \delta P_{psa} + \delta P_{vsa}$ = 0.23 bar

An estimation of the practical work of vacuum treatment is made by calculating the energy necessary (efficiency = 0.75) to change the feed from adsorption pressure to desorption pressure:

P_{total} = 0.3 MW

CO-VSA and H_2-PSA investment cost

Table A10.5: H_2 PSA equipment cost(PCE)

investment cost for H_2 PSA	prices in fl. (Webci)
5 columns (d=0.90, L=1.6) 18 valves (pneumatic) compressor (1 MW ,acc.Olujić) controlsystem (64*in/output) Zeolite 5A (22 m^3)	175000.- 54000.- 600000.- 168000.- 120000.-
Purchased Cost Equipment(PCE):	1117000.-

Table A10.6: H_2-PSA system investment cost

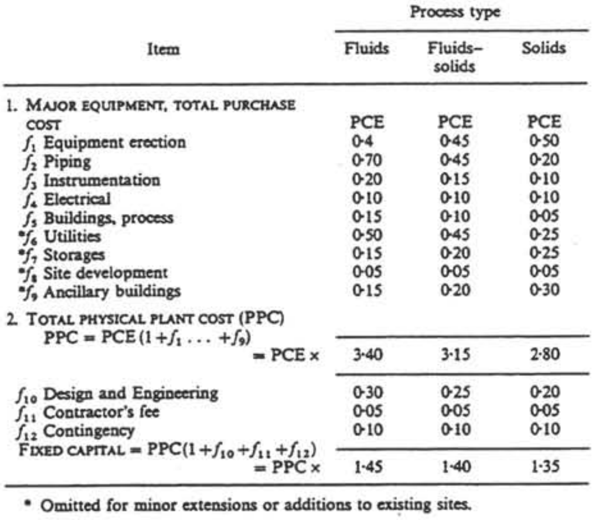
H_2-PSA system	f_a	f_b	PCE	PPC	FC
	3.25	1.45	$1.12*10^6$	$3.63*10^6$	$5.26*10^6$

Table A10.7 : CO-VSA equipment cost(PCE)

investment cost for CO VSA	prices in fl. (Webci)
5 columns (d=0.8, L=1.40) 18 valves (pneumatic) vacuum-pump (0.3 MW) controlsystem (64*in/output) CO-selective adsorbent (20 m^3)	185000.- 54000.- 314000.- 168000.- 156000.-
Purchased Cost Equipment(PCE):	877000.-

Table A10.8: CO-VSA system investment cost

CO-VSA system	f_a	f_b	PCE	PPC	FC
	3.25	1.45	877000.-	$2.85*10^6$	$4.13*10^6$



Item	Process type		
	Fluids	Fluids–solids	Solids
1. MAJOR EQUIPMENT, TOTAL PURCHASE COST	PCE	PCE	PCE
f_1 Equipment erection	0·4	0·45	0·50
f_2 Piping	0·70	0·45	0·20
f_3 Instrumentation	0·20	0·15	0·10
f_4 Electrical	0·10	0·10	0·10
f_5 Buildings, process	0·15	0·10	0·05
*f_6 Utilities	0·50	0·45	0·25
*f_7 Storages	0·15	0·20	0·25
*f_8 Site development	0·05	0·05	0·05
*f_9 Ancillary buildings	0·15	0·20	0·30
2. TOTAL PHYSICAL PLANT COST (PPC) $PPC = PCE(1+f_1 \ldots +f_9)$ $= PCE \times$	3·40	3·15	2·80
f_{10} Design and Engineering	0·30	0·25	0·20
f_{11} Contractor's fee	0·05	0·05	0·05
f_{12} Contingency	0·10	0·10	0·10
FIXED CAPITAL $= PPC(1+f_{10}+f_{11}+f_{12})$ $= PPC \times$	1·45	1·40	1·35

* Omitted for minor extensions or additions to existing sites.

Fig A10.1 : factor for factoring method

Table A10.9 : H_2 PSA + CO VSA equipment cost(PCE)

investment cost for H_2 PSA + CO VSA	prices in fl. (Webci)
5 columns (d=0.8, L=1.40)	175000.-
5 columns (d=0.90, L=1.6)	185000.-
36 valves (pneumatic)	108000.-
compressor (1 MW ,acc.Olujić)	600000.-
vacuumpump (0.3 MW)	314000.-
controlsystem (64*in/output)	168000.-
CO selective adsorbent (20 m^3)	156000.-
Zeolite 5A (22 m^3)	120000.-
Purchased Cost Equipment(PCE):	1826000.-

Table A10.10 : H_2-PSA + CO VSA system investment cost

H_2-PSA system	f_a	f_b	PCE	PPC	FC
	3.25	1.45	$1.83*10^6$	$5.93*10^6$	$8.61*10^6$

COSORB® cost calculations

Requirements	Steam-natural gas reformer CO_2 recycle
CO [kg/h]	1500
COSORB unit investment [MM $]	7.3
Feed required [kmol/hr] dry	989.2
Utilities	
Power (kWh)	1,102
Steam (M kg/h)	9.9
Cooling Water (M kg/h)	140
Toluene (kg/h)	20

Table A10.11 : Investment, feedgas, and utility requirements

Costs	Steam-natural gas reformer CO_2 recycle
	¢/kg CO
Utilities & Chemicals	
Power @ 4.5 ¢/kWh	1.06
Steam @ 9.0 $/Mkg	0.95
Cooling Water @ 15 ¢/gal	0.06
Toluene @ 1.50 $/gal	0.08
Catalyst & Chemicals	0.10
Total Variable Cost	2.25
Fixed cost	
Operating manpower	0.22
Maintenace @ 8% investment/yr	0.73
Insurance & Taxes	0.18
Depreciation @ 10 yr Straight life	0.93
Total Fixed Cost	2.06
Investment	
Cost at 30% of investment yr	2.80
Total Recovery Cost	7.11

Table A10.12 : CO Recovery costs

```
PROGRAM COSORBER    [ © I. Ketelaars, 1993];

     Uses  Crt, Iwan, Iwan2, Dos, IwanScr;

     CONST
           Nmax = 400;
           R = 8.314E-2;                                   { bar*M3/kmol*K }
           TcCO = 132.9;          TcCH4 = 190.6;
           TcCO2 = 304.2;         TcN2 = 126.2;
           TcH2 = 33.2;           TcAr = 150.8;
           TcTol = 591.7;                                  { K }
           PcCO = 35.0;           PcCH4 = 46.0;
           PcCO2 = 73.8;          PcN2 = 33.9;
           PcH2 = 13.0;           PcAr = 48.7;
           PcTol = 41.1;                                   { Bar }
           MCuAlCl4 = 232.3;  Mtol =  92.14;
           MCO  =  28.01;         MCH4 =  16.04;
           MH2  =  2.016;         MN2  =  28.01;
           MCO2 =  44.01;         MAr  =  39.948;          { kg/kmol }


     VAR
           x1, x2, y1, y2, Value, komma, it                    : Byte;
           a, Teller1, Teller2, Step, N                        : Word;
           k1, k2, k3, k4, h, Z, Ze, at, Eff,
           Kog, hg_a, Gb, GN2, GCO1,
           PTol, GCH4, GH2, GAr, GCO2, LCu,
           aw, xCu, P, dp, Tgest,
           Enh, Sig_l, F, Hv1, Hv0, Ro_l,
           Lab_g, Visc_l, sigc, Visc_Tol,
           Ro_g, Visc_g, Keq, corr, kg_CO,
           kl_CO, Hos, Hv, Dg_CO, He, Le,
           Dl_CO, Dg_Tol, Dg, kg_Tol, TlTemp,
           YTol2, L2, Tg2, Tl2, yCO2, TotError,
           KeyError, yN2, yCH4, yAr, yH2, Mavr_g,
           CpTol, CpCO2, CpCO, CpH2, CpCH4, CpN2,
           Cpb, CpAr, Mavr_l, Prm, Trm,
           Tcm, Pcm, epsy, epst, epsg                          : Real;
           Y                                                   : ARRAY[0..1] OF REAL;
           iri                                                 : ARRAY[1..8] OF Byte;
           YCO, YTol, Tg, Tl, XCO, XTol,
           YCOe, YTole, L, G, Ra, Lo,
           Cpg, Cpq, yb                                    : ARRAY[0..Nmax] OF REAL;
           Open, Initer, siap, First,
           NoInput, SaveProf, Nooit                            : Boolean;
```

```
(**************************************************************************)

   PROCEDURE Get_Fract;    { - }    { Gas fraction of component i }
      BEGIN
        yN2  := GN2/G[i];
       yAr  := GAr/G[i];
       yCH4 := GCH4/G[i];
       yH2  := GH2/G[i];
       yCO2 := GCO2/G[i];
       yb[i]   := Gb/G[i];
     END;

(**************************************************************************)

   PROCEDURE Get_Mavrg;   { kg/kmol }    { Average MolWeight of Gas }
     BEGIN
       yb[i] :=      yN2 + yCH4 + yAr + yH2 + yCO2;
       Mavr_g  :=  yN2*MN2  +  yCH4*MCH4  +  YCO[i]*yb[i]*MCO  +  yAr*MAr  +
                   yH2*MH2 + yCO2*MCO2 + yTol[i]*yb[i]*Mtol;
     END;

(**************************************************************************)

   PROCEDURE Get_Mavrl;    { kg/kmol }    { Average MolWeight of Liquid }
     BEGIN
       Mavr_l := (XCO[i]/Lo[i])*MCuAlCl4 + XTol[i]*MTol + XCO[i]*MCO;
     END;

(**************************************************************************)

   PROCEDURE Get_Critical;    { K, bar }    { Critical Temperature and pressure }
     BEGIN
       Tcm  :=  TcCO*YCO[i]*yb[i]  +  TcCH4*yCH4  +  TcN2*yN2  +  TcH2*yH2  +
                   TcAr*yAr + TcCO2*yCO2;  { K }
       Pcm := PcCo*YCO[i]*yb[i] + PcCH4*yCH4 + PcN2*yN2 + PcH2*yH2 + PcAr*yAr
                   + PcCO2*yCO2;  { Bar }
       Trm := Tg[i]/Tcm;  Prm := P/Pcm;
     END;

(**************************************************************************)

   PROCEDURE Get_Rol;    { kg/m3 }    { Liquid Density }
     BEGIN
       Ro_l :=  1000*((1.5562/(Ra[i]+1) + 0.8810 ) - (0.0002614/(Ra[i]+1)
              + 0.0009207)*(Tl[i] - 273.15) - Lo[i]*0.06/Ra[i]);
     END;
```

```
(****************************************************************************)

   PROCEDURE Get_Rog;    { kg/ m3 }    { Gas Density }
     VAR  V1, V2, aRK, bRK :     Real;

     BEGIN
       Get_Critical;

     { Redlich & Kwong Equation }

         aRK := (0.42748*R*R*Raise(Tcm,2.5))/Pcm;
         bRK := (0.08664*R*Tcm)/Pcm;

         V2 := R*Tg[i]/P;

         REPEAT
           V1 := V2;
           V2 := R*Tg[i]/P + bRK - (aRK*(V1-bRK))/(Raise(Tg[i],0.5)*
                 P*V1*(V1+bRK));
         UNTIL Abs(V2-V1) < 1E-6;
         Ro_g := Mavr_g/V2
     END;

(****************************************************************************)

   PROCEDURE Get_Viscl;    { mNs/M2 = cp }    { Liquid Viscosity }

     CONST
            C2 = -5.08093E-2;    D2 = 12.2693E-2;
            E2 = -6.78159E-2;    F2 = -9.6315E-2;
            G2 = 8.026396E-2;

      VAR   A2, B2   : Real;

     BEGIN
       A2 := -4.122269 - 2.34034*EXP(C2*Raise(Ra[i],3) + D2*Raise(Ra[i],2) + E2*Ra[i]);
       B2 := 1051.795 + 2026.852*EXP(F2*Raise(Ra[i],2) + G2*Ra[i]);
       Visc_l := EXP( A2 + B2/Tl[i]);
     END;

(****************************************************************************)

   PROCEDURE Get_Viscg;    { mNs/M2 = cp }    { Gas Viscosity }
     BEGIN
       Visc_g := 0.0172 + (Tg[i] - Tg[0] )*1E-4;
     END;
```

```
(**************************************************************************)

   PROCEDURE Get_DgCO;    { m2/s }    { Gas Diffusivity of CO }
     BEGIN
       Dg_CO := (1.013E-7*Raise(Tg[i],1.75)*
               Raise((1/MCO+1/Mavr_g),0.5))/
              (P*Raise(Raise(18.9,1/3) + Raise(10.5,1/3),2));
     END;

(**************************************************************************)

   PROCEDURE Get_DlCO;    { m2/s }    { Liquid Diffusivity of CO }
     BEGIN
       Dl_CO := (1.173E-13*Raise(Mavr_l,0.5)*Tl[i])/
              (Visc_l*Raise(0.0307,0.6));
     END;

(**************************************************************************)

   PROCEDURE Get_DgTol;    { m2/s }    { Gas Diffusitivity of Toluene }
      BEGIN
       Dg_Tol := (1.013E-7*Raise(Tg[i],1.75)*
                Raise((1/MTol+1/Mavr_g),0.5))/
               (P*Raise(Raise(18.9,1/3) + Raise(10.5,1/3),2));
     END;
```

```
(****************************************************************************)

  PROCEDURE Get_CPg;    { kJ/kmol*K }    { Specific heat of gas }

      FUNCTION Cp(a,b,c,d : Real) : Real;
        BEGIN
          Cp := a + b*Tg[i] + c*Raise(Tg[i],2) + d*Raise(Tg[i],3);
        END;

    BEGIN
      CpCo  := Cp(30.869,-1.285E-2,2.789E-5,-1.271E-8);
      CpTol := Cp(-24.355,5.124E-1,-2.765E-4,4.911E-8);
      CpH2  := Cp(27.143,9.273E-3,-1.38E-5,7.645E-9);
      CpCH4 := Cp(19.251,5.212E-2,1.197E-5,-1.131E-8);
      CpN2  := Cp(31.15,-1.356E-2,2.679E-5,-1.168E-8);
      CpAr  := Cp(20.804,-3.211E-5,5.166E-8,0);


      CpB         :=  yN2*CpN2/yb[i]  +  yH2*CpH2/yb[i]  +  yAr*CpAr/yb[i]  +
                      yCH4*CpCH4/yb[i];

      Cpg[i]   := (CpB*yb[i] + YCO[i]*yb[i]*CpCO + YTol[i]*yb[i]*CpTol)*0.986;

    END;

(****************************************************************************)

  PROCEDURE Get_Cpl;    { KJ/Kmol*K}    { Specific heat of liquid }
     BEGIN
       Cpq[i]   := ((36.6809*(Ra[i]-1) + 65.2886)/(92.14*(Ra[i]-1) + 324.48) +
                    0.000637*(Tl[i] - 273.15) + 0.0263*Lo[i])*Mavr_l*4.183;
     END;

(****************************************************************************)

  PROCEDURE Get_aw;    { M2/M3 }    { Wetted interfacial area }
     VAR Lster  : REAL;

    BEGIN
      Lster := L[i]*Mavr_l/F;    { kg/s*M2 }
      aw := at*(1 - EXP(-1.45*
            Raise(sigc/sig_l,0.75)*
            Raise(Lster/(at*Visc_l*1E-3),0.1)*
            Raise(Raise(Lster,2)*at/(Raise(Ro_l,2)*9.831),-0.05)*
            Raise(Raise(Lster,2)/(Ro_l*sig_l*1E-3*at),0.2)));
    END;
```

```
(***************************************************************************)

  PROCEDURE Get_Sigl; { mN/M = Dyne/cm = mJ/M2 } { Liquid Surfase Tension }
    BEGIN
      Sig_l :=  30.62 + 3.075/Ra[i] +
            (-0.1103 + 0.1267/Ra[i])*(Tl[i]-273.15);
     END;

(***************************************************************************)

  PROCEDURE Get_Labg;    { kW/m*K) }    { Coefficient of heat conductivity }
    BEGIN
      Lab_g := (Visc_g*(Cpg[i]/Mavr_g + 10.4/Mavr_g))/1000;
    END;

(***************************************************************************)

  PROCEDURE Get_kgCO;    { kmol/m2*s*bar }
                    { Mass-transfer coefficient CO in vapor phase }
    BEGIN
      kg_CO  := 5.23*at*
              Raise((G[i]*Mavr_g/F)/(at*Visc_g*1E-3),0.7)*
              Raise(Visc_g*1E-3/(Ro_g*Dg_CO),1/3)*
              Raise(at*dp,-2)*Dg_CO/(R*Tg[i]);
    END;

(***************************************************************************)

  PROCEDURE Get_klCO;    { kmol/m2*s*(kmol/m3) = m/sm-2 }
                    { Mass-transfer coefficient CO in vapor phase }
    BEGIN
      kl_CO :=  0.0051*
              Raise(((L[i]*Mavr_l/F)/(aw*Visc_l*1E-3)),2/3)*
              Raise(Visc_l*1E-3/(Ro_l*Dl_CO),-1/2)*
              Raise(at*dp,0.4)*Raise(Ro_l/(Visc_l*1E-3*9.8319),-1/3);
    END;

(***************************************************************************)

  PROCEDURE Get_Kog;    { 1/sm-2 }
                    { Overall Mass-transfer coefficient CO of gas }
    BEGIN
      Kog := eff/(1/kg_CO + He/(kl_CO*Enh));
    END;
```

```
(******************************************************************************)

  PROCEDURE Get_kgTol;   { m/sm-2 }
                      { Mass-transfer coefficient Toluene in vapor phase }
    BEGIN
      kg_Tol := kg_CO*Raise((Dg_Tol/Dg_CO),0.5);
    END;

(******************************************************************************)

  PROCEDURE Get_hga;   { KJ/Kmol/K }   { heat transfer coefficient of gas }

    BEGIN
      corr := Gb*(CpCO*(YCO[i+1] - YCO[i]) + CpTol*(YTol[i+1] - YTol[i]));
      Le   := Lab_g*Mavr_g/(Ro_g*Cpg[i]*Dg_CO);
      hg_a := Kg_CO*at*Cpg[i]*Raise(Le,2/3);
      hg_a := -corr/(1 - Exp(corr/hg_a));
    END;

(******************************************************************************)

  PROCEDURE Get_Keq;   { m3/kmol }   { Equilibrium constant }
    BEGIN
      Keq := 74*EXP(-67*(1/Tl[i] - 3E-3));
    END;

(******************************************************************************)

  PROCEDURE Get_Enh;   { - }   { Enhancement factor }
    BEGIN
      Enh := 1 + (Keq*(LCu/L[i])/( 1 + Keq*(YCOe[i]*yb[i])));
    END;

(******************************************************************************)

  PROCEDURE Get_Henry;   { bar*m3/kmol }   { Henry''s Law constant }
    BEGIN
      He := 5.8e-3*(EXP(14.3686 - (530.22/(Tl[i]-13.15)))*1E-5*133.32);
    END;

(******************************************************************************)

  PROCEDURE Get_YCOe;   { - }   { Equilibrium fraction of CO in gas phase }
    BEGIN
      YCOe[i] := He*XCO[i]/(P*yb[i]);
    END;
```

```
(****************************************************************************)

  PROCEDURE Get_YTole; { - } { Equilibrium fraction of Toluene in gas phase  }

    CONST   D6 = -0.056757;
            E6 = -0.0011087;
            F6 = 23.00;
            G6 = -7000.0;

    VAR     CF, Pc, Ps  : REAL;

    BEGIN
      CF := EXP((D6 + E6*(Tl[i]-293.15))*Raise(Ra[i]-1,2));
      Pc := EXP(F6 + G6/Tl[i]);
      Ps := (Ptol*1E5/133.32)*(Ra[i]-CF)/Ra[i] + Pc*CF/Ra[i];
      YTole[i] := 2.15*Ps*XTol[i]*133.32*1E-5/(P*yb[i]);
    END;

(****************************************************************************)

  PROCEDURE Get_Enthalpie;      { KJ/Kmol }
                               { Latent heat of evaporation or condensation }
                               { Heat of reaction (include heat of solution ) }

    CONST
          ANTAtol = 16.0137;
          ANTBtol = 3096.52;
          ANTCtol = -53.67;

    VAR    dz, hv1, hv2  : REAL;


    BEGIN
      Hos := 78.3E3;
      Ptol := 133.32E-5*EXP(ANTAtol - ANTBtol/(Tl[i] + ANTCtol));
      dz  := Raise(1-(Ptol/PcTol)/Raise(Tg[i]/TcTol,3),0.5);
      Hv  := 8.5*ANTBtol*Raise(Tg[i],2)*dz/Raise(Tg[i] + ANTCtol,2);
    END;

(****************************************************************************)

  PROCEDURE Get_RaLo;   { - }   { Ratio Tol/Cu & Ratio CO/Cu }
    BEGIN
      Ra[i]     := (L[i]*XTol[i])/LCu;          { Ratio Tol/Cu }
      Lo[i]     := (L[i]*XCO[i])/LCu;           { Ratio CO/Cu }
    END;
```

```
(****************************************************************************)

  PROCEDURE Get_FysData;
    BEGIN
      Get_RaLo;         { Ratio Tol/Cu }
                        { Ratio CO/Cu }
      Get_Fract;        { Liquid fraction CO }
                        { Liquid fraction Tol }
                        { Gas fraction CO }
                        { Gas fraction Tol }
                        { Gas fraction Inert }
      Get_Mavrg;        { Average MolWeight of Gas }
      Get_Viscg;        { Gas Viscosity }
      Get_Rog;          { Gas Density }
      Get_DgCO;         { Gas Diffusivity of CO }
      Get_Mavrl;        { Average MolWeight of Liquid }
      Get_Viscl;        { Liquid Viscosity }
      Get_Rol;          { Liquid Density }
      Get_DlCO;         { Liquid Diffusivity of CO }
      Get_Sigl;         { Liquid Surfase Tension }
      Get_aw;           { Wetted interfacial area }
      Get_Henry;        { Henry''s Law constant }
      Get_Keq;          { Equilibrium constant }
      Get_Enthalpie;    { Latent heat of evaporation or condensation }
                        { Heat of reaction (include heat of solution ) }
      Get_YCOe;         { Equilibrium fraction of CO in gas phase }
      Get_YTole;        { Equilibrium fraction of Toluene in gas phase  }
      Get_Enh;          { Enhancement factor }
      Get_kgCO;         { Mass-transfer coefficient CO in vapor phase }
      Get_klCO;         { Mass-transfer coefficient CO in liquid phase }
      Get_Kog;          { Overall Mass-transfer coefficient CO of gas }
      Get_DgTol;        { Gas Diffusitivity of Toluene }
      Get_kgTol;        { Mass-transfer coefficient Toluene in vapor phase }
      Get_Cpg;          { Specific heat of gas }
      Get_Cpl;          { Specific heat of liquid }
      Get_Labg;         { Coefficient of heat conductivity }
      Y[0] := YCO[i];

    END;
```

```
(****************************************************************************)

   PROCEDURE SetValue;   { Change iteration key value }
     BEGIN
       Case Value OF

       1 : BEGIN
            IF Abs((G[N] - G[N-1])/G[N]) < epsg THEN Set_Key_Value(2) ELSE
            G[N] := (Abs(G[N-1]+G[N]))/2;
          END;
       2 : BEGIN
            IF Abs((Tg[N] - Tg[N-1])/Tg[N]) < epst THEN
            BEGIN
              IF Abs((G[N] - G[N-1])/G[N]) < epsg THEN Set_Key_Value(3) ELSE
              Set_Key_Value(1);
            END ELSE Tg[N] := (Abs(Tg[N] + Tg[N-1]))/2;
          END;
       3 : BEGIN
            IF Abs((YCO[N] - YCO[N-1])/YCO[N]) < epsy THEN
            BEGIN
              IF Abs((G[N] - G[N-1])/G[N]) < epsg THEN
              BEGIN
                IF Abs((Tg[N] - Tg[N-1])/Tg[N]) < epst THEN EndCalculations
                  ELSE Set_Key_Value(2);
              END ELSE Set_Key_Value(1);
            END ELSE YCO[N]:= (Abs(YCO[N] + YCO[N-1]))/2;
          END;
       END;
     END;

(****************************************************************************)

   PROCEDURE MasBalance;
     BEGIN

{ Inert Bal } G[i+1] := Gb*(YTol[i+1] + 1 + YCO[i+1]);
{ Flow Bal  } L[i+1] := G[i+1] + L[i] - G[i];
{ CO Bal    } XCO[i+1] := (Gb*(YCO[i+1] - YCO[i]) + L[i]*XCO[i])/L[i+1];
{ Tol Bal   } XTol[i+1] := (Gb*(YTol[i+1] - YTol[i]) + L[i]*XTol[i])/L[i+1];

     END;
```

```
(****************************************************************************)

    PROCEDURE RungeKutta;


       FUNCTION FunctionRK(V : REAL ) : REAL;

       BEGIN
           CASE a OF

  1 : FunctionRK := (-Kog*at*P*F*(V-YCOe[i]))/Gb;
  2 : FunctionRK := (-kg_Tol*at*P*F*(V-YTole[i]))/Gb;
  3 : FunctionRK := (-hg_a*F*(V-Tl[i])/(Gb*Cpg[i]/yb[i]));



           END;

       END; { FunctionRK }


    BEGIN

       CASE a OF

       1..3  : BEGIN

                 k1 := h*FunctionRK( Y[0]); Writeln('k1 = ',k1);
                 k2 := h*FunctionRK( Y[0] + k1/2 ); Writeln('k2 = ',k2);
                 k3 := h*FunctionRK( Y[0] + k2/2 ); Writeln('k3 = ',k3);
                 k4 := h*FunctionRK( Y[0] + k3 ); Writeln('k4 = ',k4); Writeln;

                 Y[1] := Y[0] + (1/6)*( k1 + 2*k2  + 2*k3 + k4);

               END;

       4     : Y[1] :=   (Y[0]*L[i] + (G[i+1]*Cpg[i]*Tg[i+1] - G[i]*cpg[i]*Tg[i] +
                        Hos*Gb*(YCO[i+1] - YCO[i]) +
                        Hv*Gb*(YTol[i+1] - YTol[i]))/Cpq[i])/L[i+1];

       END;
    END; {RungeKutta}
```

```
(********************************************************************************)

   PROCEDURE Equation1;
          BEGIN
            YCO[i+1] := Y[1];
            a :=  2;
            Y[0] := YTol[i];
          END;


(********************************************************************************)


   PROCEDURE Equation2;
          BEGIN
            YTol[i+1] := Y[1];
            Get_hga;
            a := 3;
            Y[0] := Tg[i];
          END;


(********************************************************************************)


   PROCEDURE Equation3;
          BEGIN
            Tg[i+1] := Y[1];
            a := 4;
            Y[0] := Tl[i];
          END;


(********************************************************************************)


   PROCEDURE Equation4;
          BEGIN
            Tl[i+1] := Y[1];
            a := 1;
          END;
```

```
(*******************************************************************************)

   PROCEDURE InitMasBal;  { kmol/s }
      BEGIN


 { FlowBal   }  L[0]    := L[N] + G[0] - G[N];
 { CO Bal    }  XCO[0]  := (L[N]*XCO[N] + Gb*(YCO[0] - YCO[N]))/L[0];
 { Inert Bal }  YTol[N] := G[N]/Gb - YCO[N] - 1;
 { Tol Bal   }  XTol[0] := (L[N]*XTol[N] + Gb*(YTol[0] - YTol[N]))/L[0];

          i := N;
          Get_Fract;
          Get_RaLo;
          Get_Mavrl;
          Get_Mavrg;
          Get_Cpl;
          Get_Cpg;
          Get_Enthalpie;
          Hv1 := Hv;
          i := 0;
          Get_Fract;
          Get_RaLo;
          Get_Mavrl;
          Get_Mavrg;
          Get_Cpg;
          Get_Enthalpie;
          Hv0 := Hv;
      END;

(*******************************************************************************)

   PROCEDURE InitHeatBalance;
      BEGIN
        TlTemp := Tg[0];
        REPEAT
          Tl[0] := (TlTemp + Tl[0])/2;
          Get_Cpl;
          Get_Enthalpie;

 { Heat Bal}  TlTemp   := (G[0]*Cpg[0]*Tg[0] - G[N]*Cpg[N]*Tg[N] +
                        L[N]*Cpq[N]*Tl[N] - (YTol[N]*Hv1 - YTol[0]*Hv0)*Gb -
                       (YCO[N] - YCO[0])*Gb*Hos)/(L[0]*Cpq[0]);

        UNTIL Abs(TlTemp - Tl[0]) < 1E-3;
      END;
```

```
(*****************************************************************************)

   PROCEDURE Init;
      BEGIN
        F := 0.7;                          { m2 }
        Z := 0;                            { m }
        Ze := 8;                           { m }
        a := 1;                            { - }
        h := 0.04;                         { m }
        P := 25;                           { Bar }
        dp   :=  0.038;                    { m }
        sigc :=  75;                       { mN/M }
        at   :=  130;                      { m2/m3 }


        { GasStream }

        Tg[0] := 40 + 273.15;
        YTol[0]  := 0;                     { yTol/yInert }
        GN2      := 67.23/3600;            { Kmol/s }
        GCH4     := 1.22/3600;             { Kmol/s }
        GH2      := 174.58/3600;           { Kmol/s }
        GAr      := 0.91/3600;             { Kmol/s }
        GCO2     := 0;
        GCO1     := 35.37/3600;            { Kmol/s }
        Gb       := GN2 + GCH4 + GH2 + GAr;    { Kmol/s }
        G[0]     := GCO1 + Gb;             { Kmol/s }
        YCO[0]   := GCO1/Gb;               { - }


        { LiquidStream }

        XCu {Top} := 0.2774;               { - }
        L[N]      := 204.28/3600;          { Kmol/s }
        LCu       := L[N]*XCu;             { Kmol/s }
        XCO[N]    := 0.0028;               { - }
        Tl[N]     := 40 + 273.15;          { K }
        XTol[N]   := 1 - XCu - XCO[N];     { - }


        { Guesses }

        G[N] := 240.82/3600; { = ong Gb } { Kmol/s }
        YCO[N] := 0.00024;                 { yCO/yInert }
        Tg[N] := 43 + 273.15;              { K }
      END;
```

```
(************************************************************************************)

    PROCEDURE CalculateTower;
       BEGIN
         REPEAT
           InitMasBal;
           InitHeatBalance;
           REPEAT
             Get_FysData; { at Height i in the Tower }
             RungeKutta; Equation1;
             RungeKutta; Equation2;
             MasBalance;
             RungeKutta; Equation3;
             RungeKutta; Equation4;
             i := i + 1;
             Z := Z + h;
             IF KeyPressed THEN Key;
           UNTIL (i = N-1) OR (ch = 'y');
           IF ch <> 'y' THEN
           BEGIN
             Get_Fract;
             SetValue;
           END;
         UNTIL siap;
       END; { CalculateTower }



(************************************************************************************)
(************************************************************************************)


BEGIN { HoofdProgramma }
  Init;
  REPEAT
    CalculateTower;
  UNTIL Nooit;
END. { Simulation }
```

APPENDIX 12. WORKING WITH ASPEN PLUS.

Creating an input file with ModelManager.

First you have to start ModelManager; the procedure to do this depends on the host-computer which is used. When this is done ModelManager displays a field on which the flowsheet is to be drawn; on the right of the screen a menu is displayed containing all models to be chosen from. These models are given below along with a description.

Model	Description
FEED	Incoming material-, heat- or work-stream
PROD	Outgoing material-, heat- or work-stream
MIXER	Mixes two or more streams
FSPLIT	Splits a stream into two or more of the same composition
SEP	Splits a stream into two with specified composition
SEP2	Same as SEP, but with specified T & P
HEATER	Simple heater or cooler
FLASH2	Two phase flash
FLASH3	Three phase flash
HEATX	Heatexchanger
MHEATX	Multistream heatexchanger
DSTWU	Shortcut distillation; Win-Underwood-Gilliland method
DISTL	Shortcut distillation; Edmister method
SCFRAC	Shortcut distillation for complex situation
RADFRAC	Rigorous distillation column
MULTIFRAC	Interlinked multistage fractionation units
RATEFRAC	Rate-based non-equilibrium distillation
ABSORBR	Rigorous absorber/stripper
EXTRACT	Liquid-liquid
RSTOIC	Stoichiometric reactor
RYIELD	Reactor with given yield distribution
REQUIL	Reactor with chemical/thermodynamic equilibrium
RGIBBS	Reactor which minimizes Gibbs energy

Block Unit	Description
RCSTR	Continuous stirred tank reactor
RPLUG	Plug-flow reactor
RBATCH	Batch or fed-batch reactor
PUMP	Pump
COMPR	Compressor or turbine/expander
MCOMPR	Multistage compressor or turbine
MULT	Multiplies a stream by a given factor
DUPL	Duplicates a stream any number of times
CLCHNG	Changes stream class
SSPLIT	Substream-splitter
CRUSHER	Crusher
SCREEN	Solids/solids separator
FABFL	Fabric filter
CYCLONE	Cyclone
VSCRUB	Venturi scrubber
ESP	Electrostatic precipitator
HYCYC	Hydrocyclone
CFUGE	Centrifuge filter
FILTEC	Continuous rotary vacuum filter
SWASH	Single stage solids washer
CCD	Countercurrent decanter / multistage solids washer
USER	User-defined block
USER2	Same as USER

On top of the screen there are a number of pull-down menus which represent the basic functions of Aspen; these are FILE (opening or creating files), FLOWSHEET (mainly options on how to display the flowsheet), MODIFY (renaming blocks and streams etc.), VIEW (zoom in/out on the flowsheet), FORMS (entering and reviewing all input and results), RUN (generating input files and running the simulation), PFD (generating process flow diagrams), SETTINGS (settings for the program, e.g. autosave-level).

To create a new file, open the file menu and select new. Then select the models to be used on the flowsheet from the model menu on the right of the screen, by clicking on it with the left mouse button. Put it on the right place in the flowsheet and click the left button again to place it there; interconnecting the blocks by streams is done by selecting the block (clicking on it with the left button) and then pressing the right button to display the menu of in- and outlet streams. You choose the desired stream, and click the left mouse-button on the block where the stream is to go to or come from. When all this is done, open the forms-menu and select 'next input'; Aspen then asks for all required data regarding the blocks and streams and gives a prompt when sufficient data is entered. Then open the run-menu and select 'generate' to create an Aspen input file; after this, 'submit' runs the simulation. If all results are read into ModelManager open 'forms' to display the results.
On the following pages you will find an example of in Aspen input file.

```
DESCRIPTION "
        This is the flowsheet used by the G-group feb. 1993 to
        simulate the GE-Plastics CO-plant II "

DATABANKS ASPENPCD

PROP-SOURCES ASPENPCD

COMPONENTS
    H2 H2 H2 /
    CO CO CO /
    CO2 CO2 CO2 /
    N2 N2 N2 /
    O2 O2 O2 /
    CH4 CH4 CH4 /
    C2H6 C2H6 C2H6 /
    C3H8 C3H8 C3H8 /
    C4H10 C4H10-1 C4H10 /
    C5H12 C5H12-1 C5H12 /
    C6H14 C6H14-1 C6H14 /
    MEA C2H7NO MEA /
    H2O H2O H2O /
    AR AR AR

FLOWSHEET S
    BLOCK H2-MIX IN=201 202 OUT=202B
    BLOCK H2104 IN=3 202B OUT=4 203
    BLOCK V2101 IN=203 OUT=142
    BLOCK CO2-MIX IN=204 146 OUT=204B
    BLOCK H2O-MIX IN=204B 205 150 OUT=206
    BLOCK H2103 IN=2 206 OUT=3 207
    BLOCK H2101 IN=207 OUT=208
    BLOCK H2107 IN=208 G OUT=208B H
    BLOCK H20-MIX2 IN=208B 260 OUT=208C
    BLOCK M2102 IN=208C 253 OUT=209
    BLOCK H2102 IN=1 A OUT=2 B
    BLOCK H2105A IN=4 C OUT=5 D
    BLOCK H2105B IN=5 E OUT=6 F
    BLOCK H2106 IN=6 251 OUT=7 251B
    BLOCK DRUMMIX IN=B D F H OUT=STMFD
    BLOCK V2103 IN=STMFD 251B OUT=STM LIQ
    BLOCK SPLIT IN=LIQ OUT=A C E G
    BLOCK BURNER IN=BIN OUT=1
    BLOCK B1 IN=228 OUT=140 202 150

FLOWSHEET SI
    BLOCK H2110A IN=209 OUT=209B
    BLOCK V2107 IN=209B OUT=210 264
    BLOCK H2111 IN=210 OUT=210B
    BLOCK V2108 IN=210B OUT=211 265
```

```
    BLOCK COND-MIX IN=264 265 OUT=266
    BLOCK V2105 IN=281 211 OUT=212 282
    BLOCK V2106 IN=285 282B OUT=213 281C
    BLOCK H2108 IN=281B OUT=281A
    BLOCK H2109A IN=281C OUT=281B
    BLOCK H2109B IN=282 OUT=282B

FLOWSHEET SII
    BLOCK V2116 IN=212 OUT=218 MEASUMP
    BLOCK K2104 IN=218 OUT=218B
    BLOCK H2115 IN=218B OUT=218C
    BLOCK V2117 IN=218C OUT=219 270
    BLOCK V2118 IN=219 OUT=220 OUT

FLOWSHEET SIII
    BLOCK H2112 IN=213 OUT=213B
    BLOCK V2109 IN=213B 284 OUT=215 285
    BLOCK VENTTANK IN=215 OUT=215B 214
    BLOCK CO-MIX IN=215B 227 OUT=216
    BLOCK K2103-1 IN=216 OUT=216B
    BLOCK H2113 IN=216B OUT=216C
    BLOCK V2113 IN=216C OUT=216D 268
    BLOCK K2103-3 IN=216D OUT=216E
    BLOCK H2114 IN=216E OUT=216F
    BLOCK V2114 IN=216F OUT=204 269
    BLOCK CONDMIX2 IN=269 268 OUT=284

FLOWSHEET SIIII
    BLOCK E21 IN=220 L22 L49 L48 225 OUT=L35 L2 224 228  &
          227
    BLOCK SPLIT1 IN=L35 OUT=L38 L36 L39
    BLOCK E24 IN=L38 OUT=L41
    BLOCK V41 IN=L41 OUT=L42
    BLOCK T22MIX IN=L42 L43 L11 OUT=L44
    BLOCK E22B IN=L36 OUT=L37
    BLOCK V37 IN=L37 OUT=L43
    BLOCK V39 IN=L39 OUT=L40
    BLOCK T24 IN=L40 L30 OUT=L31 L11
    BLOCK E22 IN=L2 OUT=L3
    BLOCK T21 IN=L3 LG OUT=LB L6
    BLOCK CO1 IN=LF OUT=LC LD
    BLOCK MIX1 IN=LB LE OUT=LF
    BLOCK CO2 IN=LC OUT=L4 LE
    BLOCK E23A IN=L4 OUT=L22
    BLOCK T23 IN=L28 OUT=L29 L8
    BLOCK V6 IN=L6 OUT=L28
    BLOCK V8 IN=L8 OUT=L33
    BLOCK T22 IN=L33 L46 OUT=L49 L47
    BLOCK MIX2 IN=L13 L7 L10 OUT=L48
    BLOCK V47 IN=L47 OUT=L13
    BLOCK E25-27 IN=L44 OUT=L46
    BLOCK V29 IN=L29 OUT=L7
    BLOCK V31 IN=L31 OUT=L10
    BLOCK SPLIT2 IN=LD OUT=L9 LG
    BLOCK V9 IN=L9 OUT=L30
```

```
FLOWSHEET SIIIII
    BLOCK K2105-1 IN=224 OUT=224A
    BLOCK H2118 IN=224A OUT=224B
    BLOCK K2105-2 IN=224B OUT=224C
    BLOCK CO-SPLIT IN=224D OUT=226 225
    BLOCK H2119 IN=224C OUT=224D
    BLOCK B2 IN=142 144 OUT=143
    BLOCK B3 IN=147 OUT=146
    BLOCK B5 IN=143 OUT=147

PROPERTIES SYSOP3
    PROPERTIES AMINES

STREAM 144
    SUBSTREAM MIXED TEMP=220 PRES=23.2
    MASS-FLOW H2O 450

STREAM 201
    SUBSTREAM MIXED TEMP=15 PRES=21
    MASS-FLOW CO 0.31 / N2 203.8 / CH4 660 / C2H6 43.4 /  &
        C3H8 8.3 / C4H10 4.1 / C5H12 1.44 / C6H14 2.05

STREAM 202
    SUBSTREAM MIXED TEMP=120 PRES=21.8
    MASS-FLOW H2 10.7 / CO 2.5 / N2 2.2

STREAM 205
    SUBSTREAM MIXED TEMP=220 PRES=23.2
    MASS-FLOW CO2 610 / H2O 1800

STREAM 227
    SUBSTREAM MIXED TEMP=31 PRES=2.0 NPHASE=1
    MASS-FLOW H2 5.8 / CO 197.3 / N2 29.4 / CH4 68.6

STREAM 251
    SUBSTREAM MIXED TEMP=104 PRES=27
    MASS-FLOW H2O 5400

STREAM 253
    SUBSTREAM MIXED TEMP=104 PRES=27
    MASS-FLOW H2O 550

STREAM 260
    SUBSTREAM MIXED TEMP=208 PRES=18.3
    MASS-FLOW H2O 1900

STREAM 281
    SUBSTREAM MIXED TEMP=40 PRES=14.7 NPHASE=1 PHASE=L
    MASS-FLOW CO2 390 / MEA 4921.1 / H2O 12915

STREAM BIN
    SUBSTREAM MIXED TEMP=40 PRES=2 NPHASE=1
    MASS-FLOW H2 245.6 / CO 64.5 / N2 7301.5 / O2 2284 /  &
        CH4 0.39 / AR 124.7
```

```
BLOCK B2 MIXER
    PARAM PRES=18.5

BLOCK CO-MIX MIXER
    PARAM PRES=1.5 NPHASE=1

BLOCK CO2-MIX MIXER
    PARAM PRES=16.2

BLOCK COND-MIX MIXER
    PARAM PRES=3.5 NPHASE=1 PHASE=L

BLOCK CONDMIX2 MIXER
    PARAM PRES=1.5 NPHASE=1 PHASE=L

BLOCK DRUMMIX MIXER
    PARAM PRES=0

BLOCK H2-MIX MIXER
    PARAM PRES=21

BLOCK H20-MIX2 MIXER
    PARAM PRES=11

BLOCK H2O-MIX MIXER
    PARAM PRES=15.6
    BLOCK-OPTION FREE-WATER=NO

BLOCK M2102 MIXER
    PARAM PRES=11

BLOCK MIX1 MIXER
    PARAM PRES=0

BLOCK MIX2 MIXER
    PARAM PRES=0

BLOCK T22MIX MIXER
    PARAM PRES=0

BLOCK B1 FSPLIT
    MASS-FLOW 202 10.7 1 / 150 80 2
    DEF-KEY KEYNO=1 SUBSTREAM=MIXED COMPS=H2
    DEF-KEY KEYNO=2 SUBSTREAM=MIXED COMPS=H2

BLOCK CO-SPLIT FSPLIT
    FRAC 225 0.16347

BLOCK SPLIT FSPLIT
    PARAM PRES=0
    FRAC A 0.10 / C 0.10 / G 0.65

BLOCK SPLIT1 FSPLIT
    FRAC L38 0.546 / L36 0.156

BLOCK SPLIT2 FSPLIT
    FRAC L9 0.2564
```

```
BLOCK V2118 SEP
    FRAC STREAM=220 SUBSTREAM=MIXED COMPS=H2 CO CO2 N2 O2  &
        CH4 C2H6 C3H8 C4H10 C5H12 C6H14 MEA H2O AR FRACS= &
        0.994 0.994 0 0.994 0 0.994 0 0 0 0 0 0 0 0

BLOCK VENTTANK SEP
    FRAC STREAM=214 SUBSTREAM=MIXED COMPS=H2 CO CO2 N2 O2  &
        CH4 C2H6 C3H8 C4H10 C5H12 C6H14 MEA H2O FRACS=0 0  &
        0.04761905 0.04832633 0 0 0 0 0 0 0 1 0.04761950

BLOCK B5 HEATER
    PARAM TEMP=500 PRES=18.2

BLOCK E22 HEATER
    PARAM PRES=-0.1 DELT=-7.2

BLOCK E22B HEATER
    PARAM PRES=-0.1 DELT=-5.7

BLOCK E23A HEATER
    PARAM TEMP=-176.1 PRES=3.9

BLOCK E24 HEATER
    PARAM PRES=-0.1 DELT=-2.5

BLOCK E25-27 HEATER
    PARAM TEMP=-184.5 PRES=-0.175 NPHASE=1 PHASE=L

BLOCK H2108 HEATER


    PARAM TEMP=40 PRES=14.7 NPHASE=1 PHASE=L

BLOCK H2109A HEATER
    PARAM TEMP=88 PRES=0 NPHASE=1 PHASE=L

BLOCK H2109B HEATER
    PARAM TEMP=104 PRES=0

BLOCK H2110A HEATER
    PARAM TEMP=132 PRES=10.7

BLOCK H2111 HEATER
    PARAM TEMP=40 PRES=10.4

BLOCK H2112 HEATER
    PARAM TEMP=40 PRES=1.5

BLOCK H2113 HEATER
    PARAM TEMP=40 PRES=-0.2

BLOCK H2114 HEATER
    PARAM TEMP=40 PRES=16.2

BLOCK H2115 HEATER
    PARAM TEMP=35 PRES=-0.1
```

```
BLOCK H2118 HEATER
    PARAM TEMP=30 PRES=-0.2

BLOCK H2119 HEATER
    PARAM TEMP=35 PRES=-0.2

BLOCK V2101 HEATER
    PARAM TEMP=500 PRES=18.2
    BLOCK-OPTION FREE-WATER=NO

BLOCK V29 HEATER
    PARAM PRES=-3.1 DUTY=0

BLOCK V31 HEATER
    PARAM PRES=-5.3 DUTY=0

BLOCK V37 HEATER
    PARAM PRES=-6.6 DUTY=0

BLOCK V39 HEATER
    PARAM PRES=-1.25 DUTY=0

BLOCK V41 HEATER
    PARAM PRES=-6.6 DUTY=0

BLOCK V47 HEATER
    PARAM PRES=-0.1 DUTY=0

BLOCK V6 HEATER
    PARAM PRES=-21.83 DUTY=0

BLOCK V8 HEATER
    PARAM PRES=-3.017 DUTY=0

BLOCK V9 HEATER
    PARAM PRES=-19.497 DUTY=0

BLOCK CO1 FLASH2
    PARAM TEMP=-171.5 PRES=27.347


BLOCK CO2 FLASH2
    PARAM TEMP=-201.5 PRES=27.3

BLOCK V2103 FLASH2
    PARAM TEMP=221 VFRAC=0.0421

BLOCK V2107 FLASH2
    PARAM TEMP=40 PRES=10.7

BLOCK V2108 FLASH2
    PARAM TEMP=40 PRES=10.4

BLOCK V2109 FLASH2
    PARAM TEMP=40 PRES=1.5
```

```
BLOCK V2113 FLASH2
    PARAM TEMP=40 PRES=9.6

BLOCK V2114 FLASH2
    PARAM TEMP=40 PRES=16.2

BLOCK V2116 FLASH2
    PARAM TEMP=40 PRES=10.3

BLOCK V2117 FLASH2
    PARAM TEMP=35 PRES=28.3

BLOCK H2102 HEATX
    PARAM VFRAC-COLD=0.048
    FEEDS HOT=1 COLD=A
    PRODUCTS HOT=2 COLD=B
    HEAT-TR-COEF U=97.2 <KCAL/HR-SQM-K>

BLOCK H2103 HEATX
    PARAM T-COLD=487 TYPE=COCURRENT PRES-COLD=-0.5
    FEEDS HOT=2 COLD=206
    PRODUCTS HOT=3 COLD=207
    HEAT-TR-COEF U=63.2 <KCAL/HR-SQM-K>

BLOCK H2104 HEATX
    PARAM T-COLD=550 TYPE=COCURRENT PRES-COLD=-0.3
    FEEDS HOT=3 COLD=202B
    PRODUCTS HOT=4 COLD=203
    HEAT-TR-COEF U=54.7 <KCAL/HR-SQM-K>

BLOCK H2105A HEATX
    PARAM VFRAC-COLD=0.048
    FEEDS HOT=4 COLD=C
    PRODUCTS HOT=5 COLD=D
    HEAT-TR-COEF U=152 <KCAL/HR-SQM-K>

BLOCK H2105B HEATX
    PARAM VFRAC-COLD=0.048
    FEEDS HOT=5 COLD=E
    PRODUCTS HOT=6 COLD=F
    HEAT-TR-COEF U=250 <KCAL/HR-SQM-K>

BLOCK H2106 HEATX
    PARAM T-COLD=180 PRES-COLD=-0.2
    FEEDS HOT=6 COLD=251
    PRODUCTS HOT=7 COLD=251B
    HEAT-TR-COEF U=258 <KCAL/HR-SQM-K>

BLOCK H2107 HEATX
    PARAM VFRAC-COLD=0.048
    FEEDS HOT=208 COLD=G
```

```
    PRODUCTS HOT=208B COLD=H
    HEAT-TR-COEF U=275 <KCAL/HR-SQM-K>

BLOCK E21 MHEATX
    HOT-SIDE IN=220 OUT=L2 DELT=-192.6 PRES=-0.2 MAXIT=250
    COLD-SIDE IN=L22 OUT=228 PRES=-0.4 MAXIT=250
    COLD-SIDE IN=L49 OUT=224 DELT=205.5 PRES=-0.2 MAXIT=250
    COLD-SIDE IN=L48 OUT=227 DELT=197.9 PRES=-0.2 MAXIT=250
    HOT-SIDE IN=225 OUT=L35 DELT=-190.1 PRES=-0.2 MAXIT=250

BLOCK T21 RADFRAC
    PARAM NSTAGE=20
    FEEDS L3 21 / LG 1 ON-STAGE
    PRODUCTS LB 1 V / L6 20 L
    P-SPEC 1 27.3
    COL-SPECS Q1=0 QN=0 MASS-RDV=1
    T-EST 1 -173.6 / 20 -172

BLOCK T22 RADFRAC
    PARAM NSTAGE=12
    FEEDS L33 9 / L46 1
    PRODUCTS L49 1 V / L47 12 L
    P-SPEC 1 2.25
    COL-SPECS Q1=0 MASS-RDV=1 MOLE-BR=5.7

BLOCK T23 RADFRAC
    PARAM NSTAGE=4
    FEEDS L28 1
    PRODUCTS L8 4 L / L29 1 V
    P-SPEC 1 5.4
    COL-SPECS Q1=-6000 MASS-RDV=1 MOLE-RR=6.55

BLOCK T24 RADFRAC
    PARAM NSTAGE=5
    FEEDS L40 6 / L30 1
    PRODUCTS L11 5 L / L31 1 V
    P-SPEC 1 7.6
    COL-SPECS QN=0 MASS-RDV=1 MASS-RR=10.35496

BLOCK V2105 RADFRAC
    PARAM NSTAGE=20 EFF=MURPHREE
    FEEDS 281 1 ON-STAGE / 211 20 ON-STAGE
    PRODUCTS 212 1 V / 282 20 L
    P-SPEC 1 10.3 / 20 10.4
    COL-SPECS Q1=0 QN=0 MASS-RDV=1
    COMP-EFF 10 CO2 0.2
    T-EST 1 40 / 20 72
    SPEC 1 MASS-FLOW 0.5 PHASE=V COMPS=CO2 STREAMS=212
    VARY 1 MURPHREE 0 0.5 STAGE1=1 STAGE2=20 COMPS=CO2
    PROPERTIES AMINES
```

```
BLOCK V2106 RADFRAC
    PARAM NSTAGE=18
    FEEDS 285 1 / 282B 5
    PRODUCTS 213 1 V / 281C 18 L
    P-SPEC 1 1.7
    COL-SPECS Q1=0 QN=2.85E6 MASS-RDV=1
    T-EST 16 120 / 1 102
    SPEC 1 MASS-FLOW 1250 PHASE=V COMPS=CO2 STREAMS=213
    VARY 1 QN 1E4 1E8
    PROPERTIES AMINES

BLOCK B3 RGIBBS
    PARAM TEMP=450 PRES=15

BLOCK BURNER RGIBBS


    PARAM TEMP=1005 PRES=-0.5 NPHASE=1 MAXIT=100

BLOCK H2101 RGIBBS
    PARAM TEMP=860 PRES=11.5 NREAC=9
    STOIC 1 CH4 -1 / H2O -1 / CO 1 / H2 3
    STOIC 2 H2 -1 / CO2 -1 / CO 1 / H2O 1
    STOIC 3 C2H6 -1 / H2 -1 / CH4 2
    STOIC 4 C3H8 -1 / H2 -2 / CH4 3
    STOIC 5 C4H10 -1 / H2 -3 / CH4 4
    STOIC 6 C5H12 -1 / H2 -4 / CH4 5
    STOIC 7 C6H14 -1 / H2 -5 / CH4 6
    STOIC 8 O2 -1 / CO -2 / CO2 2
    STOIC 9 N2 -1 / C4H10 -1 / H2O -2 / MEA 2
    TAPP-SPEC 1 -20 / 8 -860 / 9 2000

BLOCK K2103-1 COMPR
    PARAM TYPE=POLYTROPIC PRES=9.6 TEMP=145

BLOCK K2103-3 COMPR
    PARAM TYPE=POLYTROPIC PRES=15.4 TEMP=145

BLOCK K2104 COMPR
    PARAM TYPE=POLYTROPIC PRES=28.5 TEMP=145

BLOCK K2105-1 COMPR
    PARAM TYPE=POLYTROPIC PRES=6 TEMP=100

BLOCK K2105-2 COMPR
    PARAM TYPE=POLYTROPIC PRES=9.6 TEMP=90

DESIGN-SPEC PRE
    DEFINE PRE BLOCK-VAR BLOCK=B3 VARIABLE=QCALC SENTENCE=PARAM
    SPEC "PRE" TO "0"
    TOL-SPEC "0.1"
    VARY BLOCK-VAR BLOCK=B3 VARIABLE=TEMP SENTENCE=PARAM
    LIMITS "250" "800"

CONV-OPTIONS
    WEGSTEIN MAXIT=150
```