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APPENDIX A

SAMPLE CALCULATIONS

Table A.1 Topping unit – Mass, Exergy and Cumulative Exergy Balance

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
Crude oil	189,356.00	2,618,714.380	79.640	2,756,541.452	80.345
Wild gasoline	618.00	8,542.069	0.260	9,291.979	0.271
Fuel gas	467.20	7,930.802	0.241	9,481.633	0.278
Fuel oil	1,855.52	26,024.726	0.791	27,961.506	0.815
Air	35,707.78	1.500	0.000	1.500	0.000
Hot oil	45,574.00	626,485.907	19.053	626,485.907	18.260
BFW	2,547.34	73.378	0.002	73.378	0.002
Electricity		405.960	0.012	1,053.505	0.031
Sum	276,125.84	3,288,178.722	100.00	3,430,890.860	100.00
Useful Effluents/Stream					
Off gas	1,187.00	16,043.500	0.488	17,237.469	0.502
LPG to Deet.	920.00	12,380.687	0.377	13,302.067	0.388
Whole Naphtha	28,904.00	411,119.624	12.503	441,715.453	12.875
Kerosene	27,510.00	377,124.733	11.469	405,190.637	11.810
Diesel to GOHDU	55,801.00	769,896.235	23.414	827,192.486	24.110
Diesel to Plant 3	1,473.00	20,278.816	0.617	21,787.980	0.635
Light gas oil	856.00	11,846.253	0.360	12,727.860	0.371
Heavy gas oil	8,105.00	112,263.920	3.414	120,618.684	3.516
Residue oil	65,218.00	873,334.330	26.560	938,328.521	27.349
Flue gas	38,030.502	7,759.695	0.236	7,759.695	0.226
Hot oil	45,574.000	624,942.107	19.006	624,942.107	18.215
Cooling water		87.900	0.003	87.900	0.003
Loss					
Condensate water	2,547.34	37.157	0.001	0.000	0.000
others		51,063.764	1.553	0.000	0.000
Sum	276,125.84	3,288,178.722	100.00	3,430,890.860	100.00

Section 1 – Topping Unit

Total Exergy of the useful products :

$$\sum B_1 = B_{offgas} + B_{lpg} + B_{naph} + B_{ker\ o} + B_{do\_go} + B_{do\_3}$$
$$B_{lg\ o} + B_{hgo} + B_{rc}$$
$$= 16,043.500 + 12,380.687 + 411,119.624 +$$
$$377,124.733 + 769,896.235 + 20,278.816 +$$
$$11,846.253 + 112,263.920 + 873,334.330$$
$$= 2,604,288.099 \quad kW$$

Cumulative Exergy entering Section 1 :

$$\sum C_1 = C_{crude} + C_{gaso} + C_{fg} + C_{fo} + C_{air} + C_{hotoil} +$$
$$C_{bfw} + C_{elec}$$
$$= 2,756,541.452 + 9,291.979 + 9,481.633 +$$
$$27,961.506 + 1.500 + 626,485.907 + 73.378 +$$
$$1,053.505$$
$$= 3,430,90.860 \quad kW$$

Cumulative Exergy of the Off Gas :

$$C_{offgas} = \frac{B_{offgas}}{\sum B_1} \times \{\sum C_1 - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$
$$= \frac{16,043.500}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 -$$
$$624,942.107 - 37.157\}$$
$$= 17,237.469 \quad kW$$

Cumulative Exergy of the LPG :

$$C_{lpg} = \frac{B_{lpg}}{\sum B_1} \times \{\sum C_1 - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$
$$= \frac{12,380.687}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 -$$
$$624,942.107 - 37.157\}$$
$$= 13,302.067 \quad kW$$

Cumulative Exergy of the Whole Naphtha :

$$C_{naph} = \frac{B_{naph}}{\sum B_i} \times \{\sum C_i - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$

$$= \frac{411,119.624}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 - 624,942.107 - 37.157\}$$

$$= 441,715.45\ 3 \quad kW$$

Cumulative Exergy of the Kerosene :

$$C_{kero} = \frac{B_{kero}}{\sum B_i} \times \{\sum C_i - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$

$$= \frac{377,124.733}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 - 624,942.107 - 37.157\}$$

$$= 405,190.63\ 7 \quad kW$$

Cumulative Exergy of the Diesel to GOHDU :

$$C_{do\_go} = \frac{B_{do\_go}}{\sum B_i} \times \{\sum C_i - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$

$$= \frac{769,896.235}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 - 624,942.107 - 37.157\}$$

$$= 827,192.48\ 6 \quad kW$$

Cumulative Exergy of the Diesel to Plant 3 :

$$C_{do\_3} = \frac{B_{do\_3}}{\sum B_i} \times \{\sum C_i - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$

$$= \frac{20,278.816}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 - 624,942.107 - 37.157\}$$

$$= 21,787.980 \quad kW$$

Cumulative Exergy of the Light Gas Oil :

$$C_{lgo} = \frac{B_{lgo}}{\sum B_i} \times \{\sum C_i - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$

$$= \frac{11,846.253}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 - 624,942.107 - 37.157\}$$

$$= 12,727.860 \quad kW$$

Cumulative Exergy of the Heavy Gas Oil :

$$C_{hgo} = \frac{B_{hgo}}{\sum B_i} \times \{\sum C_i - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$

$$= \frac{112,263.920}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 - 624,942.107 - 37.157\}$$

$$= 120,618.68\ 4 \quad kW$$

Cumulative Exergy of the Reduced Crude :

$$C_{rc} = \frac{B_{rc}}{\sum B_i} \times \{\sum C_i - C_{fluegas} - C_{hotoil} - C_{condensate}\}$$

$$= \frac{873,334.330}{2,604,288.099} \times \{3,430,890.860 - 7,759.695 - 624,942.107 - 37.157\}$$

$$= 938,328.52\ 1 \quad kW$$

Table A.2 Deethanizer Unit – Mass, Exergy and Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
LPG from TPU	920.00	12,380.687	46.424	13,302.067	43.170
LPG from CRU	1,044.00	14,066.412	52.745	16,986.286	55.126
LP-steam	520.00	176.630	0.662	408.821	1.327
Electricity		44.756	0.168	116.146	0.377
Sum	2,484.00	26,668.485	100.00	30,813.320	100.00
Useful Effluents/Stream					
Off gas	78.00	1,074.926	4.031	1,249.485	4.055
LPG to LPGU	1,886.00	25,426.274	95.342	29,555.274	95.917
Condensate water	520.00	7.861	0.029	7.861	0.026
Cooling water		0.700	0.003	0.700	0.002
Loss					
Others		158.723	0.595	0.000	0.000
Sum	2,484.00	26,668.485	100.00	30,813.320	100.00

Section 2 – Deethanizer Unit

Total Exergy of the useful products :

$$\sum B_2 = B_{offgas} + B_{lpg}$$

$$= 1{,}074.926 + 25{,}426.274$$

$$= 26{,}501.201 \quad kW$$

Cumulative Exergy entering Section 2 :

$$\sum C_c = C_{lpg\_tpu} + C_{lpg\_cru} + C_{lp-steam} + C_{elec}$$

$$= 13{,}302.966 + 17{,}027.777 + 176.630 + 44.756$$

$$= 30{,}813.320 \quad kW$$

Cumulative Exergy of the Off Gas :

$$C_{offgas} = \frac{B_{offgas}}{\sum B_2} \times \{\sum C_2 - C_{cond}\}$$

$$= \frac{1{,}074.926}{26{,}501.201} \times \{30{,}813.320 - 7.861\}$$

$$= 1{,}249.485 \quad kW$$

Cumulative Exergy of the LPG to LPGU :

$$C_{lpg} = \frac{B_{lpg}}{\sum B_2} \times \{\sum C_2 - C_{cond}\}$$

$$= \frac{25{,}426.274}{26{,}501.201} \times \{30{,}813.320 - 7.861\}$$

$$= 29{,}555.274 \qquad kW$$

Table A.3 LPG Treating unit – Mass, Exergy and Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
LPG from Deet.	1,886.00	25,426.274	32.181	29,555.274	32.179
LPG from Plant 3	3,960.00	53,580.535	67.815	62,281.535	67.811
Air	5.19	0.000	0.000	0.000	0.000
LP-steam	4.00	1.359	0.002	3.145	0.003
Electricity		2.100	0.003	5.450	0.006
Sum	5,855.19	79,010.268	100.00	91,845.404	100.00
Useful Effluents/Stream					
Vent gas & Disulfide	233.19	3,133.002	3.965	3,648.344	3.972
LPG Product	5,618.00	75,738.855	95.860	88,197.000	96.028
Condensate water	4.00	0.060	0.000	0.060	0.000
Losses					
Others		138.350	0.175	0.000	0.000
Sum	5,855.19	79,010.268	100.00	91,845.404	100.00

Section 3 – LPG Treating Unit

Total Exergy of the useful products :

$$\sum B_3 = B_{vent\ \&\ disulf} + B_{lpg}$$
$$= 75{,}738.855 + 3{,}133.002$$
$$= 78{,}871.857 \quad kW$$

Cumulative Exergy entering Section 3 :

$$\sum C_3 = C_{lpg\_deet} + C_{lpg\_3} + C_{air} + C_{lp-steam} + C_{elec}$$
$$= 29{,}555.274 + 62{,}281.535 + 0.000 +$$
$$3.145 + 5.450$$
$$= 91{,}845.404 \quad kW$$

Cumulative Exergy of the Vent Gas & Disulfide :

$$C_{vent\ \&\ disulf} = \frac{B_{vent\ \&\ disulf}}{\sum B_3} \times \{\sum C_3 - C_{cond}\}$$
$$= \frac{3{,}133.002}{78{,}871.857} \times \{91{,}845.404 - 0.060\}$$
$$= 3{,}648.344 \quad kW$$

Cumulative Exergy of the LPG product :

$$C_{lpg} = \frac{B_{lpg}}{\sum B_3} \times \{\sum C_3 - C_{cond}\}$$

$$= \frac{75{,}738.855}{78{,}871.857} \times \{91{,}845.404 - 0.060\}$$

$$= 88{,}197.000 \quad kW$$

Table A.4 Naphtha Pretreating Unit – Mass, Exergy, Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
Naphtha from TPU	28,904.00	411,119.624	50.687	441,715.453	49.952
Naphtha from Plant 3	23,770.00	337,957.156	41.667	363,108.179	41.062
Hydrogen from CRU	2,482.00	45,174.679	5.570	54,551.937	6.169
Fuel gas	130.87	2,222.800	0.274	2,657.459	0.301
Fuel oil	669.06	9,384.522	1.157	10,082.925	1.140
Air	12,030.18	0.000	0.000	0.000	0.000
HP-steam	11,600.00	4,998.456	0.616	11,569.241	1.308
Electricity		230.100	0.028	597.132	0.068
Sum	79,586.11	811,087.338	100.00	884,282.325	100.00
Useful Effluents/Stream					
Off gas from D201	1,818.00	33,169.057	4.089	38,323.453	4.334
Off gas from D202	1,279.00	17,388.785	2.144	20,090.963	2.272
Off gas from D203	66.00	893.374	0.110	1,032.203	0.117
Treat light naphtha to Plant 3	8,181.00	108,806.572	13.415	125,714.864	14.217
Treat light naphtha to Isomerization unit	19,649.00	261,304.199	32.217	301,910.273	34.142
Treat Heavy naphtha	24,163.00	339,378.528	41.842	392,117.174	44.343
Flue gas	12,830.11	2,592.064	0.320	2,592.064	0.293
Condensate water	11,600.00	2,494.932	0.308	2,494.932	0.282
Cooling water		6.400	0.001	6.400	0.001
Loss					
Others		45,053.425	5.555	0.000	0.000
Sum	79,586.11	811,087.338	100.00	884,282.325	100.00

Section 4 – Naphtha Pre-treating Unit

Total Exergy of the useful products :

$$\sum B_4 = B_{offgas\,(D201,D202,D203)} + B_{llp\_3} + B_{llp\_iso} + B_{lhn}$$
$$= 33{,}169.057 + 17{,}388.785 + 893.374 + 108{,}806.572 + 261{,}304.199 + 339{,}378.528$$
$$= 760{,}940.517 \quad kW$$

Cumulative Exergy entering Section 4 :

$$\sum C_4 = C_{h_2} + C_{naph} + C_{naph\_3} + C_{fg} + C_{fo} + C_{air} + C_{hp-steam} + C_{elec}$$

$$= 54{,}551.937 + 441{,}715.453 + 363{,}108.179 + 2{,}657.459 + 10{,}082.925 + 0.000 + 11{,}569.241 + 597.132$$

$$= 884{,}282.325 \quad kW$$

Cumulative Exergy of the Off Gas (D201) :

$$C_{offgas\ D201} = \frac{B_{offgas\ D201}}{\sum B_4} \times \{\sum C_4 - C_{fluegas} - C_{cond}\}$$

$$= \frac{33{,}169.057}{760{,}940.517} \times \{884{,}282.325 - 2{,}592.064 - 2{,}494.932\}$$

$$= 38{,}323.453 \quad kW$$

Cumulative Exergy of the Off Gas (D202) :

$$C_{offgas\ D202} = \frac{B_{offgas\ D202}}{\sum B_4} \times \{\sum C_4 - C_{fluegas} - C_{cond}\}$$

$$= \frac{17{,}388.785}{760{,}940.517} \times \{884{,}282.325 - 2{,}592.064 - 2{,}494.932\}$$

$$= 20{,}090.963 \quad kW$$

Cumulative Exergy of the Off Gas (D203) :

$$C_{offgas,D203} = \frac{B_{offgas,D203}}{\sum B_4} \times \{\sum C_4 - C_{fluegas} - C_{cond}\}$$

$$= \frac{893.374}{760{,}940.517} \times \{884{,}282.325 - 2{,}592.064 - 2{,}494.932\}$$

$$= 1{,}032.203 \quad kW$$

Cumulative Exergy of the Treated Light Naphtha to Plant 3 :

$$C_{tln\_3} = \frac{B_{tln\_3}}{\sum B_4} \times \{\sum C_4 - C_{fluegas} - C_{cond}\}$$

$$= \frac{108{,}806.572}{760{,}940.517} \times \{884{,}282.325 - 2{,}592.064 - 2{,}494.932\}$$

$$= 125{,}714.864 \quad kW$$

Cumulative Exergy of the Treated Light Naphtha to Isomerization Unit :

$$C_{lhn\_Iso} = \frac{B_{lhn\_Iso}}{\sum B_4} \times \{\sum C_4 - C_{fluegas} - C_{cond}\}$$

$$= \frac{261{,}304.199}{760{,}940.517} \times \{884{,}282.325 - 2{,}592.064 - 2{,}494.932\}$$

$$= 301{,}910.273 \quad kW$$

Cumulative Exergy of the Treated Heavy Naphtha :

$$C_{lhn} = \frac{B_{lhn}}{\sum B_4} \times \{\sum C_4 - C_{fluegas} - C_{cond}\}$$

$$= \frac{339{,}378.528}{760{,}940.517} \times \{884{,}282.325 - 2{,}592.064 - 2{,}494.932\}$$

$$= 392{,}117.174 \quad kW$$

Table A.5 Isomerization unit – Mass, Exergy and Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
Treated light naphtha	19,649.00	261,304.199	96.393	301,910.273	95.696
Hydrogen from plant 3	453.00	8,248.202	3.043	9,960.345	3.157
HP-stream	2,900.00	1,249.575	0.461	2,892.219	0.917
Electricity		280.100	0.103	726.886	0.230
Sum	23,002.00	271,082.076	100.00	315,489.724	100.00
Useful Effluents/Stream					
Off gas	853.00	11,836.634	4.366	13,902.523	4.407
Isomerate product	19,249.00	256,237.485	94.524	300,959.517	95.394
Condensate water	2,900.00	623.719	0.230	623.719	0.198
Cooling water		3.965	0.001	3.965	0.001
Loss					
Others		2,380.274	0.878	0.000	0.000
Sum.	23,002.00	271,082.076	100.00	315,489.724	100.00

Section 5 – Isomerization Unit

Total Exergy of the useful products :

$$\sum B_5 = B_{offgas} + B_{Isomerate}$$
$$= 256{,}237.485 + 11{,}836.634$$
$$= 268{,}074.119 \quad kW$$

Cumulative Exergy entering Section 5 :

$$\sum C_5 = C_{rln} + C_{h_2} + C_{hp-steam} + C_{elec}$$
$$= 301{,}910.273 + 9{,}960.345 + 2{,}892.219 + 726.886$$
$$= 315{,}489.724 \quad kW$$

Cumulative Exergy of the Off Gas :

$$C_{offgas} = \frac{B_{offgas}}{\sum B_5} \times \{\sum C_5 - C_{cond}\}$$
$$= \frac{11{,}836.634}{268{,}074.11\ 9} \times \{315{,}489.724 - 623.719\}$$
$$= 13{,}902.523 \quad kW$$

Cumulative Exergy of the Isomerate :

$$C_{Isomerate} = \frac{B_{Isomerate}}{\sum B_s} \times \{\sum C_s - C_{cond}\}$$

$$= \frac{256{,}237.485}{268{,}074.119} \times \{315{,}489.724 - 623.719\}$$

$$= 300{,}959.517 \quad kW$$

Table A.6 Catalytic Cracking Unit – Mass, Exergy and Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
Treated heavy naphtha	24,163.00	339,378.528	34.594	392,117.174	37.698
Hydrogen from plant 3	288.00	5,223.321	0.532	6,307.457	0.606
Fuel gas	515.59	8,757.578	0.893	10,470.081	1.007
Air	9,954.39	0.000	0.000	0.000	0.000
Hot oil	45,574.00	624,942.107	63.702	624,942.107	60.081
BFW	2,180.00	54.315	0.006	54.315	0.005
HP-steam	5,900.00	2,542.324	0.259	5,884.370	0.556
Electricity		147.702	0.015	383.300	0.037
Sum	88,574.98	981,045.785	100.00	1,040,158.804	100.00
Useful Effluents/Stream					
Off gas	2,279.00	33,691.222	3.434	40,684.770	3.911
Hydrogen	2,482.00	45,174.679	4.605	54,551.937	5.245
LPG to Deet.	1,044.00	14,066.412	1.434	16,986.286	1.633
Reformate product	18,646.00	242,287.200	24.697	292,580.627	28.128
Flue gas	10,469.98	1,924.870	0.196	1,924.870	0.185
Hot oil	45,574.00	626,485.907	63.859	626,485.907	60.230
HP-steam	1,769.90	939.395	0.096	2,174.288	0.209
LP-steam	5,900.00	2,051.324	0.209	4,747.919	0.456
Cooling water		22.200	0.002	22.200	0.002
Loss					
Others		14,402.575	1.468	0.000	0.000
Sum	88,574.98	981,045.785	100.00	1,040,158.804	100.00

Section 6 – Catalytic Reforming Unit

Total Exergy of the useful products :

$$\sum B_6 = B_{offgas} + B_{h_2} + B_{lpg} + B_{rdformate}$$
$$= 242,287.200 + 45,174.679 + 14,066.412 + 33,691.222$$
$$= 335,219.514 \quad kW$$

Cumulative Exergy entering Section 6 :

$$\sum C_6 = C_{thn} + C_{h_2} + C_{fg} + C_{air} + C_{hotoil} + C_{bfw} + C_{hp-steam} + C_{elec}$$

$$= 392{,}117.174 + 6{,}307.457 + 10{,}470.081 + 0.000 + 624{,}942.107 + 54.315 + 5{,}884.370 + 383.300$$

$$= 1{,}040{,}158.804 \quad kW$$

Cumulative Exergy of the Off Gas :

$$C_{offgas} = \frac{B_{offgas}}{\sum B_6} \times \{\sum C_6 - C_{fluegas} - C_{hotoil} - C_{hp-steam} - C_{lp-steam}\}$$

$$= \frac{33{,}691.222}{335{,}219.514} \times \{1{,}040{,}158.804 - 1{,}924.870 - 626{,}485.907 - 2{,}174.288 - 4{,}747.919 - 22.200\}$$

$$= 40{,}684.770 \quad kW$$

Cumulative Exergy of the Hydrogen :

$$C_{h_2} = \frac{B_{h_2}}{\sum B_6} \times \{\sum C_6 - C_{fluegas} - C_{hotoil} - C_{hp-steam} - C_{lp-steam}\}$$

$$= \frac{45{,}174.679}{335{,}219.514} \times \{1{,}040{,}158.804 - 1{,}924.870 - 626{,}485.907 - 2{,}174.288 - 4{,}747.919 - 22.200\}$$

$$= 54{,}551.937 \quad kW$$

Cumulative Exergy of the LPG :

$$C_{lpg} = \frac{B_{lpg}}{\sum B_6} \times \{\sum C_6 - C_{fluegas} - C_{hotoil} - C_{hp-steam} - C_{lp-steam}\}$$

$$= \frac{14{,}066.412}{335{,}219.514} \times \{1{,}040{,}158.804 - 1{,}924.870 - 626{,}485.907 - 2{,}174.288 - 4{,}747.919 - 22.200\}$$

$$= 16{,}986.286 \quad kW$$

Cumulative Exergy of the Reformate :

$$C_{reformate} = \frac{B_{reformate}}{\sum B_6} \times \{\sum C_6 - C_{fluegas} - C_{hotoil} - C_{hp-steam} - C_{lp-steam}\}$$

$$= \frac{242{,}287.200}{335{,}219.514} \times \{1{,}040{,}158.804 - 1{,}924.870 - 626{,}485.907 - 2{,}174.288 - 4{,}747.919 - 22.200\}$$

$$= 292{,}580.627 \quad kW$$

Table A.7 Gas Oil Hydrodesulfurization Unit – Mass, Exergy and Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
Hydrogen from NPU	854.00	15,508.858	1.255	17,918.899	1.347
Gas oil from Plant 3	22,994.00	318,377.215	25.769	342,071.084	25.717
Diesel oil from TPU	55,801.00	769,896.235	62.315	827,192.486	62.189
Light gas oil	856.00	11,846.253	0.959	12,727.860	0.957
Heavy gas oil	8,105.00	112,263.920	9.087	120,618.684	9.068
Fuel gas	357.11	6,065.650	0.491	7,251.760	0.545
Fuel oil	70.89	994.352	0.080	1,068.353	0.080
Air	8,235.26	0.000	0.000	0.000	0.000
Process water	2,506.40	34.903	0.003	34.903	0.003
BFW	1,368.04	34.485	0.003	34.485	0.003
Electricity		469.000	0.038	1,217.100	0.092
Sum	101,147.70	1,235,490.871	100.00	1,330,135.614	100.00
Useful Effluents/Stream					
Off gas from D3702	444.00	8,302.421	0.672	9,031.292	0.679
Off gas from D3703	178.00	2,603.655	0.211	2,832.231	0.213
Wild gasoline	618.00	8,542.069	0.691	9,291.979	0.699
Diesel oil product to Tank	31,365.00	431,525.763	34.927	469,409.506	35.290
Diesel oil product to Plant 3	56,005.00	770,527.669	62.366	838,172.465	63.014
Flue gas	8,663.26	1,345.513	0.109	1,345.513	0.101
Condensate water	2,506.402	46.529	0.004	46.529	0.003
Cooling water		6.100	0.000	6.100	0.000
Loss					
Sour water	1,368.036	19.857	0.002	0.000	0.000
Others		12,571.395	1.018	0.000	0.000
Sum	101,147.70	1,235,490.871	100.00	1,330,135.614	100.00

Section 7 – Gas Oil Hydrodesulfurization Unit

Total Exergy of the useful products :

$$\sum B_7 = B_{offgas\,(D3702,D3703)} + B_{w\_gaso} + B_{diesel\_tank} + B_{diesel\_3}$$

$$= 8{,}302.421 + 2{,}603.655 + 8{,}542.069 + 431{,}525.763 + 770{,}527.669$$

$$= 1{,}221{,}501.577 \quad kW$$

Cumulative Exergy entering Section 7 :

$$\sum C_7 = C_{h_2} + C_{gasoil\_3} + C_{do\_go} + C_{lgo} + C_{hgo} + C_{fg} + C_{fo} + C_{air} + C_{water} + C_{ofw} + C_{elec}$$

$$= 17{,}918.899 + 342{,}071.084 + 12{,}727.860 + 120{,}618.684 + 827{,}192.486 + 7{,}251.760 + 1{,}068.353 + 0.000 + 34.903 + 34.485 + 1{,}217.100$$

$$= 1{,}330{,}135.614 \quad kW$$

Cumulative Exergy of the Off Gas (D3702) :

$$C_{offgas(D3702)} = \frac{B_{offgas(D3702)}}{\sum B_7} \times \{\sum C_7 - C_{fluegas} - C_{cond} - C_{cw}\}$$

$$= \frac{8{,}302.421}{1{,}221{,}501.577} \times \{1{,}330{,}135.614 - 1{,}345.513 - 46.529 - 6.100\}$$

$$= 9{,}031.292 \quad kW$$

Cumulative Exergy of the Off Gas (D3703) :

$$C_{offgas(D3703)} = \frac{B_{offgas(D3703)}}{\sum B_7} \times \{\sum C_7 - C_{fluegas} - C_{cond} - C_{cw}\}$$

$$= \frac{2{,}603.655}{1{,}221{,}501.577} \times \{1{,}330{,}135.614 - 1{,}345.513 - 46.529 - 6.100\}$$

$$= 2{,}832.231 \quad kW$$

Cumulative Exergy of the Wild Gasoline :

$$C_{w\_gaso} = \frac{B_{w\_gaso}}{\sum B_7} \times \{\sum C_7 - C_{fluegas} - C_{cond} - C_{cw}\}$$

$$= \frac{8{,}542.069}{1{,}221{,}501.577} \times \{1{,}330{,}135.614 - 1{,}345.513 - 46.529 - 6.100\}$$

$$= 9{,}291.979 \quad kW$$

Cumulative Exergy of the Diesel Oil Product to Tank :

$$C_{diesel\_tank} = \frac{B_{diesel\_tank}}{\sum B_7} \times \{\sum C_7 - C_{fluegas} - C_{cond} - C_{cw}\}$$

$$= \frac{431{,}525.763}{1{,}221{,}501.577} \times \{1{,}330{,}135.614 - 1{,}345.513 - 46.529 - 6.100\}$$

$$= 469{,}409.506 \quad kW$$

Cumulative Exergy of the Diesel Oil Product to Plant 3 :

$$C_{diesel\_3} = \frac{B_{diesel\_3}}{\sum B_7} \times \{\sum C_7 - C_{fluegas} - C_{cond} - C_{cw}\}$$

$$= \frac{770{,}527.669}{1{,}221{,}501.577} \times \{1{,}330{,}135.614 - 1{,}345.513 - 46.529 - 6.100\}$$

$$= 838{,}172.465 \quad kW$$

Table A.8 Fuel Gas Treating Unit – Mass, Exergy, Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
Off gas	3,741.00	57,414.747	98.749	66,313.556	97.477
LP-steam	1,750.00	608.462	1.047	1,408.324	2.070
Electricity		118.609	0.204	307.802	0.452
Sum	5,491.00	58,141.819	100.00	68,029.682	100.00
Useful Effluents/Stream					
Fuel gas	2,363.00	40,321.654	69.351	48,206.365	70.861
Acid gas	282.00	1,869.144	3.215	2,234.646	3.285
Hydrocarbon	1,096.00	14,690.298	25.266	17,562.917	25.817
Condensate water	1,750.00	24.853	0.043	24.853	0.037
Cooling water		0.900	0.002	0.900	0.001
Loss					
Others		1,234.969	2.124	0.000	0.000
Sum	5,491.00	58,141.819	100.00	68,029.682	100.00

Section 8 – Fuel Gas Treating Unit

Total Exergy of the useful products :

$$\sum B_8 = B_{fuel\,gas} + B_{acidgas} + B_{hydrocarbon}$$
$$= 40{,}321.654 + 1{,}869.144 + 14{,}690.298$$
$$= 56{,}881.097 \quad kW$$

Cumulative Exergy entering Section 8 :

$$\sum C_8 = C_{offgas} + C_{lp-steam} + C_{elec}$$
$$= 66{,}313.556 + 1{,}408.324 + 307.802$$
$$= 68{,}029.682 \quad kW$$

Cumulative Exergy of the Fuel Gas :

$$C_{fuel\,gas} = \frac{B_{fuel\,gas}}{\sum B_8} \times \{\sum C_8 - C_{cond} - C_{cw}\}$$
$$= \frac{40{,}321.654}{56{,}881.097} \times \{68{,}029.682 - 24.853 - 0.900\}$$
$$= 48{,}206.365 \quad kW$$

Cumulative Exergy of the Acid Gas :

$$C_{acidgas} = \frac{B_{acidgas}}{\sum B_8} \times \{\sum C_8 - C_{cond} - C_{cw}\}$$

$$= \frac{1,869.144}{56,881.097} \times \{68,029.682 - 24.853 - 0.900\}$$

$$= 2,234.646 \quad kW$$

Cumulative Exergy of the Hydrocarbon :

$$C_{hydrocarbon} = \frac{B_{hydrocarbon}}{\sum B_8} \times \{\sum C_8 - C_{cond} - C_{cw}\}$$

$$= \frac{14,690.298}{56,881.097} \times \{68,029.682 - 24.853 - 0.900\}$$

$$= 17,562.917 \quad kW$$

Table A.9 Sulfur Recovery Unit – Mass, Exergy, Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
Acid gas from Plant 2	282.00	1,866.998	41.397	2,234.646	39.887
Acid gas from Plant 3	266.00	1,765.065	39.137	2,110.215	37.666
Fuel gas	34.50	588.450	13.048	703.518	12.557
Air	1,995.00	90.000	1.996	90.000	1.606
BFW	800.00	33.634	0.746	33.634	0.600
Electricity		165.861	3.678	430.425	7.683
Sum	3,377.50	4,510.008	100.00	5,602.439	100.00
Useful Effluents/Stream					
Liquid Sulfur	472.00	2,511.924	55.697	4,507.768	80.461
HP-steam	583.00	374.122	8.295	865.930	15.456
LP-steam	174.00	91.114	2.020	210.888	3.764
LLP-steam	43.00	7.564	0.168	17.508	0.313
Cooling water		0.345	0.008	0.345	0.006
Loss					
Stack gas	2,105.50	337.265	7.478	0.000	0.000
Others		1,187.674	26.334	0.000	0.000
Sum	3,377.50	4,510.008	100.00	5,602.439	100.00

Section 9 – Sulfur Removal Unit

Total Exergy of the useful product :

$$\sum B_9 = B_{liq\_sulfur}$$
$$= 2{,}511.924 \quad kW$$

Cumulative exergy entering Section 9 :

$$\sum C_9 = C_{acidgas\_2} + C_{acidgas\_3} + C_{fuel\ gas} + C_{air} + C_{bfw} + C_{elec}$$
$$= 2{,}234.646 + 2{,}110.215 + 703.518 + 90.000 + 33.634 + 430.425$$
$$= 5{,}602.439 \quad kW$$

Cumulative exergy of the Liquid Sulfur :

$$C_{liq\_sulfur} = \frac{B_{liq\_sulfur}}{\sum B_q} \times \{\sum C_q - C_{hp-steam} - C_{lp-steam} - C_{llp-steam} - C_{cw}\}$$

$$= \frac{2,511.924}{2,511.924} \times \{5,602.439 - 865.930 - 210.888 - 17.508 - 0.345\}$$

$$= 4,507.768 \quad kW$$

Table A.10 Energy Section – Mass, Exergy, Cumulative Exergy Balances

	Mass	Exergy		Cumulative Exergy	
	Kg/hr	kW	%	kW	%
Influents/Stream					
BFW to Boiler A&B	76,000.00	2,434.077	2.407	2,434.077	2.173
BFW to WHB	9,320.00	270.837	0.268	270.837	0.242
Sat. Steam to WHB	2,180.00	939.395	0.929	2,174.288	1.941
Fuel gas	770.90	13,094.109	12.946	15,654.601	13.973
Fuel oil	4,961.00	69.585.134	68.797	74,763.712	66.733
Air	86,610.73	0.000	0.000	0.000	0.000
Flue gas from all furnace	69,993.85	13,622.135	13.468	13,622.135	12.159
Electricity		1,200.000	1.186	3,114.115	2.780
Sum	249,836.48	101,145.687	100.00	112,033.765	100.00
Useful Effluents/Stream					
Electricity from GT 1&2		5,200.000	5.141	12,035.728	10.743
Electricity from GT 3		5,500.000	5.438	12,730.097	11.363
HP-steam to Plant 2	36,100.00	15,555.532	15.379	36,004.258	32.137
HP-steam to Plant 3	51,400.00	22,148.319	21.897	51,263.682	45.757
Loss					
Stack gas from Boiler A&B	92,342.63	9,974.630	9.862	0.000	0.000
Stack gas from WHB	69,993.85	6,753.735	6.677	0.000	0.000
Others		36,013.471	35.606	0.000	0.000
Sum	249,836.48	101,145.687	100.00	112,033.765	100.00

Section 10 – Energy Section

Total exergy of the useful products :

$$\sum B_{10} = B_{elec\,(1,2\&3)} + B_{hp-steam\,(2,3)}$$
$$= 5{,}200 + 5{,}500 + 15{,}555.532 + 22{,}148.319$$
$$= 48{,}403.851 \quad kW$$

Cumulative Exergy entering Section 10 :

$$\sum C_{10} = C_{bfw\_boiler} + C_{bfw\_whb} + C_{sat\_steam} + C_{fg} + C_{fo} + C_{air}$$
$$C_{elec} + C_{fluegas}$$
$$= 2{,}434.077 + 270.837 + 2{,}174.288 + 13{,}094.109$$
$$74{,}763.712 + 0.000 + 3{,}114.115 + 13{,}622.135$$
$$= 112{,}033.765 \quad kW$$

Cumulative exergy of the Produced Electricity (Generator 1, 2 and 3) :

$$C_{elec}^{Prod} = \frac{B_{produced\_elec}}{\sum B_{10}} \times \sum C_{10}$$

$$= \frac{10{,}700}{48{,}403.851} \times 112{,}033.765$$

$$= 24{,}765.8245 \quad kW$$

Cumulative exergy of the Process Steam :

$$C_{process\_steam} = \frac{B_{process\_steam}}{\sum B_{10}} \times \sum C_{10}$$

$$= \frac{37{,}703.851}{48{,}403.851} \times 112{,}033.765$$

$$= 87{,}267.9401 \quad kW$$

Cumulative Exergy of the Imported Electricity :

$$C_{elec}^{Imp} = \frac{\sum B_{elec\_overall} - B_{produced\_elec}}{\eta_{elec}^{Imp}}$$

$$= \frac{12{,}610 - 10{,}700}{24.00\%}$$

$$= 7{,}958.333 \quad kW$$

Overall Efficiency of Electricity Generation :

$$\eta_{avelec} = \frac{\sum B_{elec\_overall}}{C_{elec}^{Imp} + C_{elec}^{Prod}} \times 100$$

$$= \frac{12{,}610}{7{,}958.333 + 24{,}765.8245} \times 100$$

$$= 38.53 \quad \%$$

Overall Efficiency of Steam Generation :

$$\eta_{steam} = \frac{B_{process\_steam}}{C_{process\_steam}} \times 100$$

$$= \frac{37{,}703.851}{87{,}267.9401} \times 100$$

$$= 43.20 \quad \%$$

APPENDIX B

EXPERIMENTAL DATA

B.1 ELEMENTAL ANALYSIS

Experimental Equipment	:	CHOS/O ANALYSIS (PERKIN ELMER PE2400 SERIES II)
Analyzing Method	:	Pyrolysis in High-Purity Oxygen (Static-State Oxidation) Gas Chromatographically Separated by Frontal Analysis Quantitatively Detected by Thermal Conductivity Detector
Analyzer	:	Scientific and Technological Research Equipment Center, Chulalongkorn University

Table B1 Elemental analysis results

Sample name	% Carbon (C)	% Hydrogen (H)	% Nitrogen (N)
1. Crude oil	85.550	13.677	0.455
2. Wild gasoline	86.262	13.550	-
3. Whole naphtha	84.734	15.116	0.051
4. Kerosene	86.863	13.007	-
5. Diesel oil from TPU	86.603	13.257	0.026
6. Treated heavy naphtha	85.295	14.490	-
7. Reformate	86.765	12.819	0.127
8. Gas oil from TPU	85.827	12.005	0.037
9. Gas oil feed to GOHDU	86.439	13.314	0.075
10. Gas oil product from GOHDU	85.406	14.384	0.051
11. Reduced crude	86.957	11.985	0.490

B.2 GAS CHROMATOGRAPHY

Experimental Equipment : PERKIN ELMER
Auto System XL, ARNEL

Table B2 Gas composition in gas streams

Component	Off gas to FGTU	Fuel gas	Acid gas To SRU	LPG product	Off gas from TPU	LPG to Deet.
H_2	65.11	78.24	1.84	0.03	0.31	0.03
H_2S	0.07		83.75		0.17	0.04
NH_3	0.32		13.73			
Methane	8.57	7.36	0.22		4.91	0.31
Ethane	7.25	5.02	0.16	0.12	9.37	2.36
Ethylene	0.01	0.01			0.08	0.01
Propane	8.72	4.16	0.10	38.32	34.25	21.14
Propylene	0.02	0.01		0.06	0.10	0.06
i-Butane	2.68	1.37	0.03	26.92	17.98	19.72
n-Butane	5.44	2.61	0.06	34.21	29.97	53.3
Butene-1						
i-Butylene	0.03			0.08		0.70
t-Butene-2				0.02		0.01
c-Butene-2				0.01		
i-Pentane	1.48	0.59	0.02	0.22	0.86	2.08
n-Pentane	0.21	0.35			0.03	0.21
n-Hexane	0.07	0.27	0.08	0.01	0.02	0.03
n-Heptane						
n-Octane						
Total	99.98	99.99	99.99	100.00	98.05	100.00

Table B2 Gas composition in gas streams (continued)

Component	Off gas to Deet.	Off gas to LPGU	Off gas from NPU 2D-201	Off gas from NPU 2D202	Off gas from CRU	LPG from CRU
H_2	0.26	0.01	84.59	12.35	40.25	0.03
H_2S	0.04			0.02		
NH_3						
Methane	0.84		5.28	4.41	14.12	0.03
Ethane	26.14	0.11			42.29	2.14
Ethylene	0.02		2.86	13.35	0.01	
Propane	63.27	37.16	2.42	23.07	0.27	33.28
Propylene	0.26	0.08				0.07
n-Butane	4.63	28.59	1.48	11.01	0.49	33.6
i-Butane	4.00	33.21	2.21	25.06	1.39	29.66
Butene-1		0.04				0.04
i-Butylene		0.14	0.01	0.51		0.19
t-Butene-2		0.03				0.05
c-Butene-2		0.02				0.03
n-Pentane	0.50	0.61	0.82	10.07	0.82	0.79
i-Pentane			0.26	0.12	0.22	0.07
n-Hexane	0.02	0.01	0.07	0.02	0.12	0.01
n-Heptane						
n-Octane						
Total	99.98	100.01	100.00	99.99	99.98	99.99

Table B2 Gas composition in gas streams (continued)

Component	Hydrogen from CRU	Off gas from GOHDU (2D3703)	Off gas from GOHDU (2D3702)	Light Naphtha	Isomerate
H_2	82.81	56.35	81.37		
H_2S		0.55			
NH_3					
Methane	5.68	8.63	10.6		
Ethane	4.34	5.73	2.77		
Ethylene					
Propane	4.25	5.11	2.94		0.18
Propylene	0.01				
n-Butane	1.24	5.09	0.81		
i-Butane	1.43	14.58	1.30	1.45	1.82
Butene-1					
i-Butylene		0.01			
t-Butene-2		0.01			
c-Butene-2					
n-Pentane	0.19	1.99	0.16		
i-Pentane	0.04	1.12	0.03	42.36	48.6
n-Hexane	0.02	0.82	0.02	55.12	48.83
n-Heptane				0.94	0.32
n-Octane				0.13	0.24
Total	100.01	99.99	100.00	100.00	99.99

B.3 CRUDE OIL ASSAY

API Gravity : 35.0
Sulfur content: 0.829 wt%

Light Hydrocarbon Analysis

	Wt %	Vol %
Hydrogen Sulfide	0.00	0.00
Methane	0.00	0.00
Ethane	0.02	0.05
Propane	0.20	0.33
Iso-Butane	0.23	0.35
N-Butane	0.51	0.74
Iso-Pentane	0.83	1.14
N-Pentane	0.70	0.94

Table B3 Wide cut data

	Initial Cut Point (° C)	Final Cut Point (° C)	Vol. Yield on Crud (vol %)	Wt. Yield on Crude (wt %)	API Gravity
Cut A1	0.0	78.1	5.8	4.5	-
Cut A2	78.1	100.0	3.4	2.8	64.8
Cut A3	100.0	147.6	9.0	8.1	55.2
Cut A4	147.6	229.6	16.4	15.5	44.4
Cut A5	229.6	332.5	24.7	25.0	32.7
Cut A6	332.5	373.2	7.7	8.0	27.8
Cut A7	373.2	850.0	31.6	35.1	18.5

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