Design & Modeling for a Small Scale Cogeneration Plant Feasibility Study

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Overview:

With issues related to the sustainable development of the energy sector pushing actions towards improving generation efficiency, the case for small scale cogeneration has become more compelling. Cogeneration, the simultaneous generation of electric power and heat, usually in the form of steam or hot water, has long been a stalwart option for installations in hospitals and university campuses. However, on-site small-scale cogeneration is increasingly becoming a viable option for both domestic and international industrial plants. Opportune industries include pulp and paper, breweries, bottling and canneries, manufacturing, agricultural mills (sugar, rice, wood, coconut, palm oil, fertilizer), steel, chemical, cement, and aluminum.

The increased viability is due to consistently low natural gas costs and electricity prices resistant to fall in step with generation fuel prices. Moreover, gas prices are expected to remain at historic lows for some time to come in the U.S. as the country currently sits on ample reserves for the next 120 years (1) and as a result of a growing aversion to imported foreign energy sources. With traditional renewable energy technologies such as photovoltaic and wind energy consistently unable to prove financially or physically accessible to large populations of the country at any reasonable scale, natural gas, as the cleanest of all fossil fuels and more than twice as clean as coal (2), will continue to be the obvious choice for industrial on-site generation—with small scale cogeneration as an attractive long term option.

This paper describes the principal results of a pre-engineering and modeling feasibility study for a small scale cogeneration power plant performed by Maven Power, LLC of Houston, TX. The study was based on an industrial plant requiring 5.3MW of electrical power and two steam conditions for the plant processes. The objective of the study was to determine the techno-economic feasibility of on-site self generation of power and steam using a turbine-based cogeneration plant vs. purchasing utility electric power and steam generation using traditional on-site boilers.

The cogeneration power plant was based on a single Solar Taurus™60 gas turbine generator and accompanying HRSG (Heat Recovery Steam Generator). The gas turbine was modeled using the manufacturer's SoLoNOx™ DLE technology, however SCR (Selective Calalytic Reduction, NO_x reduction only, no CO catalyst reduction included) equipment was included in the modeling to ensure the plant would qualify as a minor source of emissions as defined by some regulating authorities. Modeling calculations were performed using the GT Pro software by Thermoflow, Inc.

Objectives of the study included the determination of:

1) Gas turbine, HRSG and net overall plant performance;
2) Site considerations for water usage, fuel consumption, emissions, and site spacing requirements;
3) Commercial feasibility considerations;
4) Financial implications of a future carbon cap and trade program in the U.S.

The turbine model used for the study was the Solar Taurus™60 T7900S, rated at 5.7MW ISO, operating on pipeline quality natural gas.

Baseline site conditions (annual averages) used for the study included:

T_{amb} *= 75°F*
ALT =150 ft ASL
RH = 75%
ΔP_{inlet} *= 3 in.* H_2O
$\Delta P_{exhaust+HRSG+SCR}$ *= 11.55 in.* H_2O
Plant Electrical Requirement: 5.3MWe continuous
Plant Heat Requirement: 2 separate streams of saturated steam at 750 and 100 psig.

Turbine air inlet fogging was included at 85% effectiveness with a fine mean droplet size. The SCR

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mavenpower.com/powerplantdesign.htm

equipment was included internal to the HRSG and was included in the model at an 80% NO_x reduction effectiveness.

Plant Performance:
The study yielded the following performance results[1]:

1) Net Plant Elec. Output: 5306 kW
2) Net Electrical Efficiency: 29.49%
3) Net Heat Rate: 11,569 Btu/kWh
4) CHP (Total) Efficiency: 81.93%

HRSG Performance:
The HRSG design determined from the study delivered a total of 26,000 pph of steam with two steam flows (baseline case) at the required saturated steam conditions:

1) HP (High Pressure) Steam Condition:
    a. P_{HP} = *750 psig,*
    b. T_{HP} = *513°F,*
    c. HRSG design at 90°F pinch
    d. HP flow: $\dot{m}_{HP\ Steam} = 22.9\ kpph$
2) IP (Intermediate Pressure) Steam Condition:
    a. P_{IP} = *100 psig ,*
    b. T_{IP} = *338°F,*
    c. HRSG design at 99.5°F pinch
    d. IP flow: $\dot{m}_{IP\ Steam} = 3.1\ kpph.$

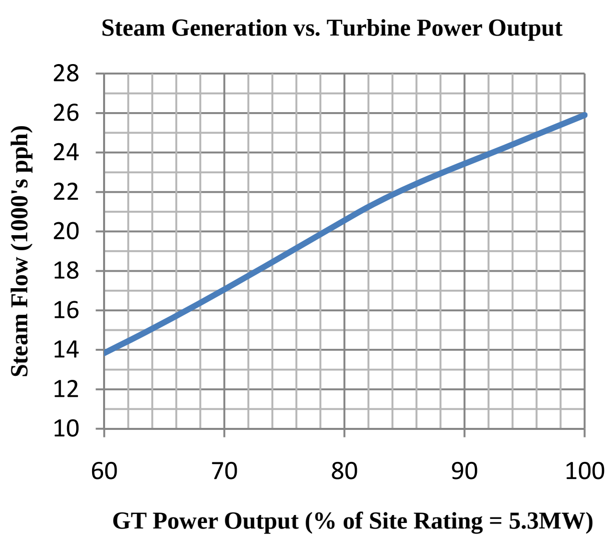


Figure 1. Steam Generation Range

An optional case of HRSG steam generation was also analyzed. Figure 1 shows the range of steam generation expected for the case of a one-stage HRSG producing a single stream of saturated steam at 300 psig:

[1] Performance based on continuous power output at 92.5% capacity factor (8100 hr/yr).

Site Considerations:
Maven Power's modeling yielded the following results as related to the base line green-field site considerations:

1) Expected water usage[2]: 3,186 gal/hr at 75°F
2) Fuel consumption: 2,982 lb/hr natural gas (59 MMBtu/hr)
3) Required Site Area[3]: 221 x 204 ft.
4) Emissions:
    a. NO_x= 4.85 tons/yr (as NO_2)
    b. CO = 29.5 tons/yr
    c. CO_2 = 31,338 tons/yr
5) Ammonia consumption (SCR):
    a. Pure (NH_3) = 7.2 tons/yr
    b. Aqueous = 24.7 tons/yr

Commercial Considerations:
Maven Power modeled the economic feasibility of this project using the following base assumptions about today's commercial climate[4]:

Baseline Case
Fuel Cost = 6.0 USD/MMBtu, natural gas
Tolling Energy Cost = 0.105 USD/kWh
Heat (Steam) Export Price = 6.0 USD/MMBtu
Water Cost = 1 USD/kgal
Capacity Factor = 92.5% (8100 hr/yr operation)
Variable Costs = 0.0075 USD/kWh
Escalation: 3-4%

Commercial results from the study for this case assuming a U.S. green-field installation with a 20 year project life yielded the following:

Time to Payback: 3.02 years
Cum. Net Cash Flow: 37.8 MMUSD

Figure 2 below shows the baseline case for time to payback vs. electricity price based on \$4-\$14 natural gas prices.

[2] Makeup Water: all process steam consumed by customer's process with none returning as boiler feedwater.
[3] Required area is reduced by a factor of 2 or more if location is an existing facility and new building/access infrastructure is not required.
[4] In addition to the given commercial assumptions, factors accounting for debt term and interest rate, taxes, and depreciation were included in the commercial analysis.

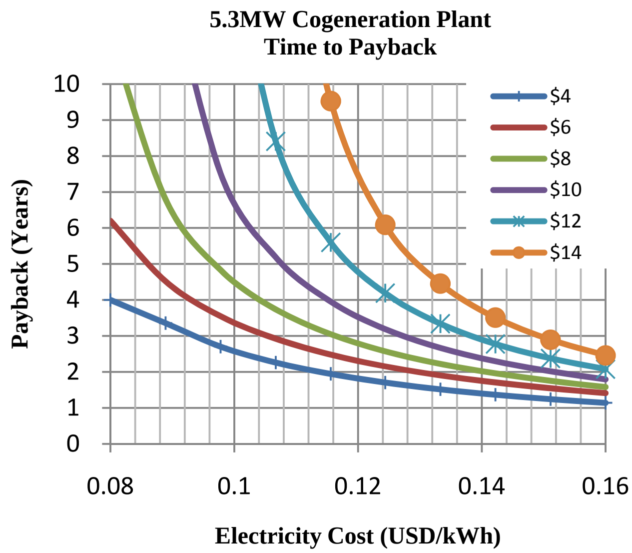


Figure 2. Project Payback vs. Electricity Price

Cap and Trade Considerations:
What are the possible implications of a federal cap and trade program on carbon dioxide emissions from a small scale cogeneration plant? At this point, several bills have been presented by the U.S. Congress, but the recently published American Power Act (APA) in June 2010, serves as a basis for estimating the impact on an industrial generating facility.

The APA, starting in 2013, would apply emissions allowances to covered entities based on the amount of CO_2 emitted by the entity in a given year. Noncompliance would be defined on a per ton basis in which the emissions of CO_2 of a covered entity in a given year exceeded those of the previous year.

For the purposes of Maven Power's model, an industrial covered entity was used which exceeded its prior year's emissions of CO_2 by 10% of the previous year's allowance. The penalty for noncompliance as stated by the APA is effectively double the current auction price of carbon credits at the time of the violation (3), but with a limit of $25 starting in 2013 and a fixed increase of 5% year on year thereafter (4).

In this cogeneration study, the baseline CO_2 emissions of the plant for the previous year were assumed at (31,338 tons/yr)/1.1 = 28,489 resulting in an excess of 31,338 – 28,489 = 2,849 tons. Hence, the penalty under the APA with credits trading at a maximum value of $25/ton, would be:

Carbon Penalty (1 year, 10% over allowance):
($25/ton) x 2 x (2,849 tons) = $142,450.

Cleary, compliance on even a small scale is highly incentivized.

Conclusion:
In the current market, given the reasonably large "spark gap" between electricity and fuel costs, and the expectation for natural gas prices to remain suppressed for the foreseeable future, small scale cogeneration in industrial applications is increasingly attractive. Moreover, even with longer term fuel price volatility an uncertainty, with short break-even payback periods as demonstrated in the Maven Power study, risk is significantly reduced to the owner or end user. Further arguing the case, is that the presented study focuses on a near worst case scenario in terms of scaling—a single turbine/HRSG configuration generating relatively small amounts of power and steam. The economics and overall risk are significantly improved by the addition of another gas turbine (2 CGT x 1 HRSG configuration) or an additional turbine with HRSG (2 CGT x 2 HRSG configuration).

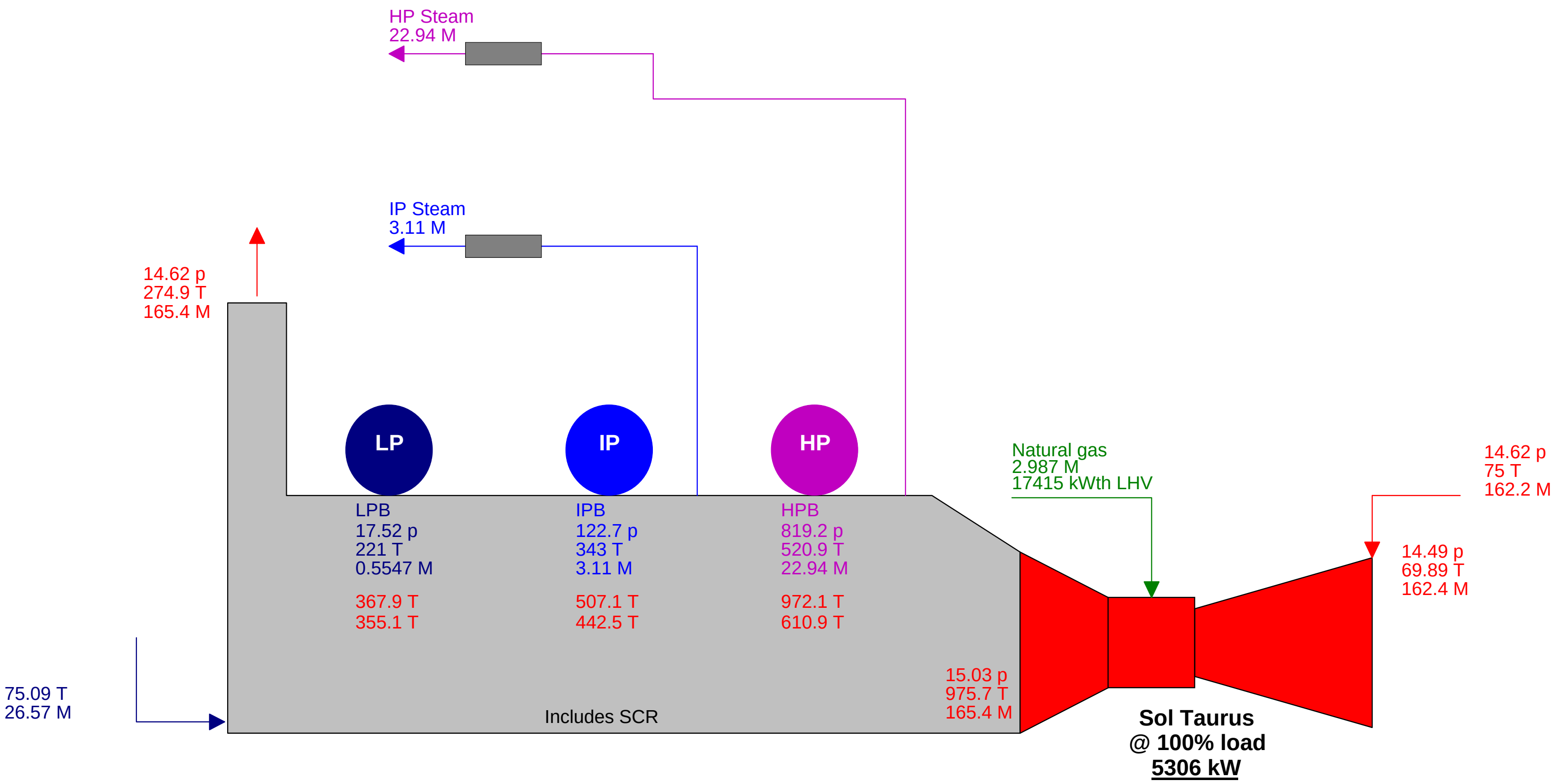
References

1. **Smead, Richard G.** *North American Natural Gas Supply Assessment.* Chicago : Navigant Consulting, Inc., 2008.
2. **U.S. Energy Information Administration.** 2008.
3. **Kerry, John and Lieberman, Joseph.** *American Power Act, 111th Congress 2D Session.* Washington, D.C. : US Congress, 2010.
4. **U.S. Environmental Protection Agency, Office of Atmoshperic Programs.** *EPA Analysis of the American Power Act in the 111th Congress.* s.l. : EPA, 2010.

GT PRO 20.0 David Oehl

Gross Power	5306 kW
Net Power	5137 kW
Aux. & Losses	169.2 kW
LHV Gross Heat Rate	11200 BTU/kWh
LHV Net Heat Rate	11569 BTU/kWh
LHV Gross Electric Eff.	30.47 %
LHV Net Electric Eff.	29.49 %
Fuel LHV Input	59427 kBTU/h
Fuel HHV Input	65792 kBTU/h
Net Process Heat	31174 kBTU/h

Ambient
14.62 P
75 T
75% RH



p [psia] T [F] M [kpph], Steam Properties: Thermoflow - STQUIK
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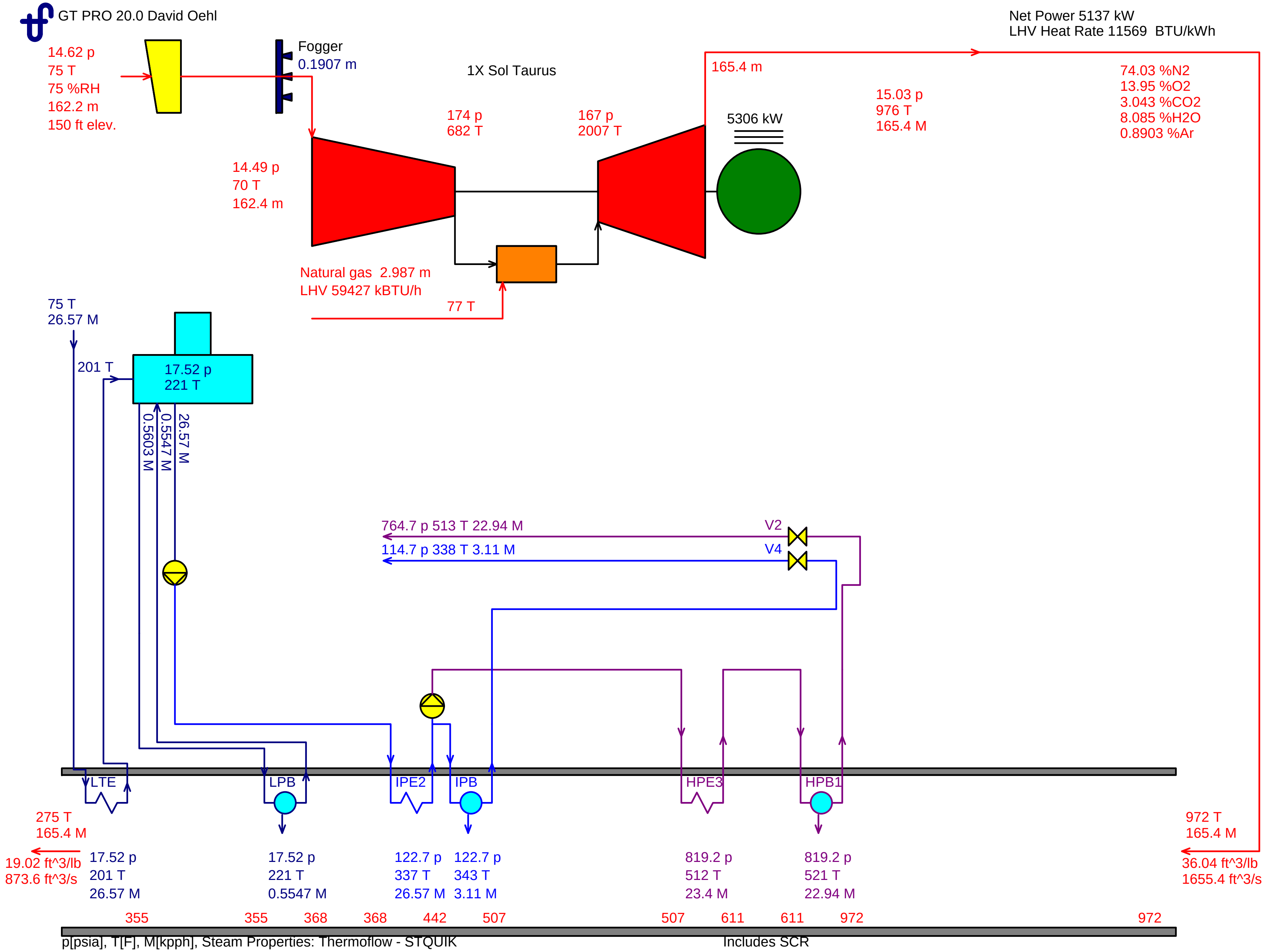

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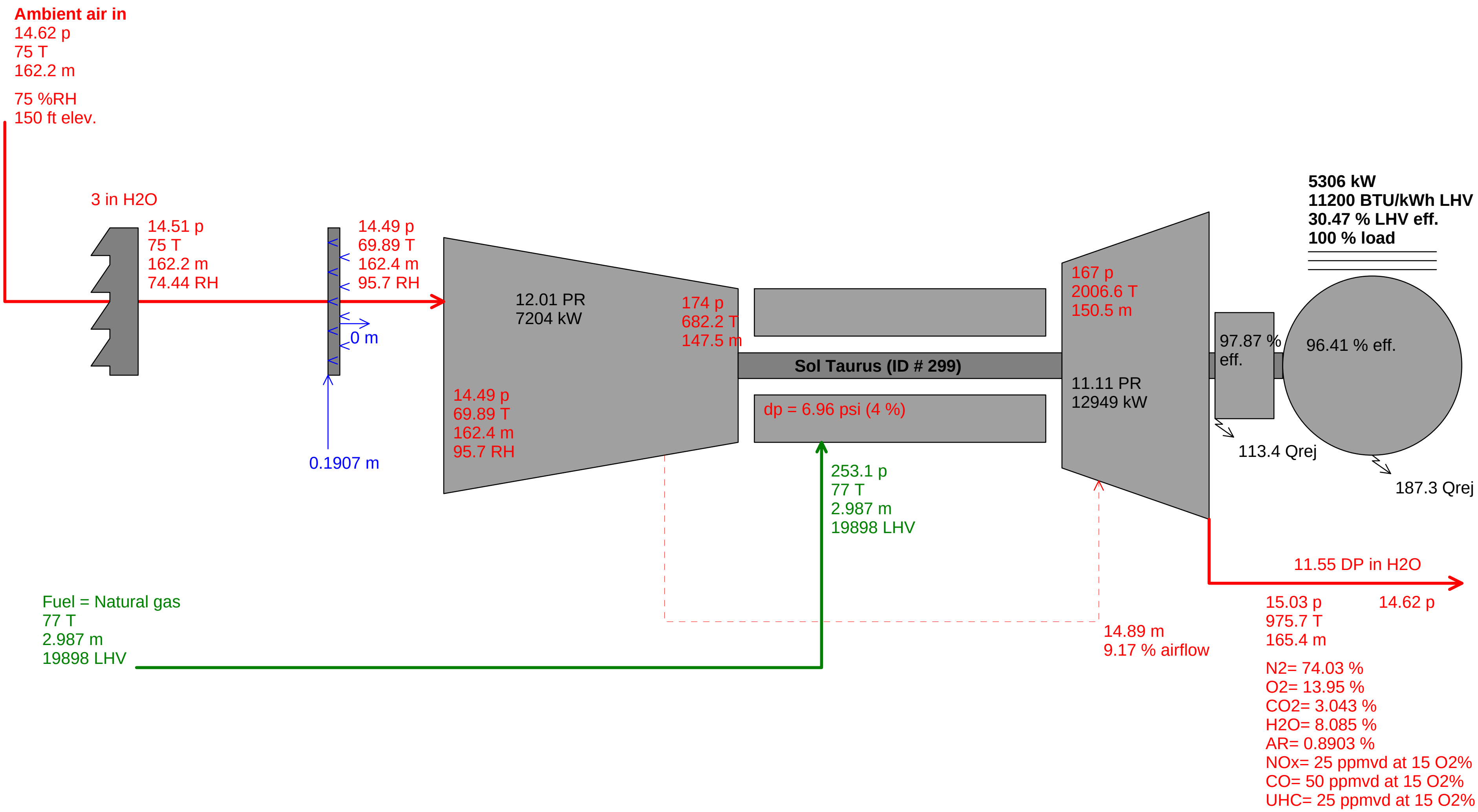
GT generator power = 5306 kW
GT Heat Rate @ gen term = 11200 BTU/kWh
GT efficiency @ gen term = 27.518% HHV   = 30.47% LHV
GT @ 100 % rating, inferred TIT control model, CC limit



p[psia], T[F], M[kpph], Q[BTU/s], Steam Properties: Thermoflow - STQUIK

GT PRO 20.0 David Oehl
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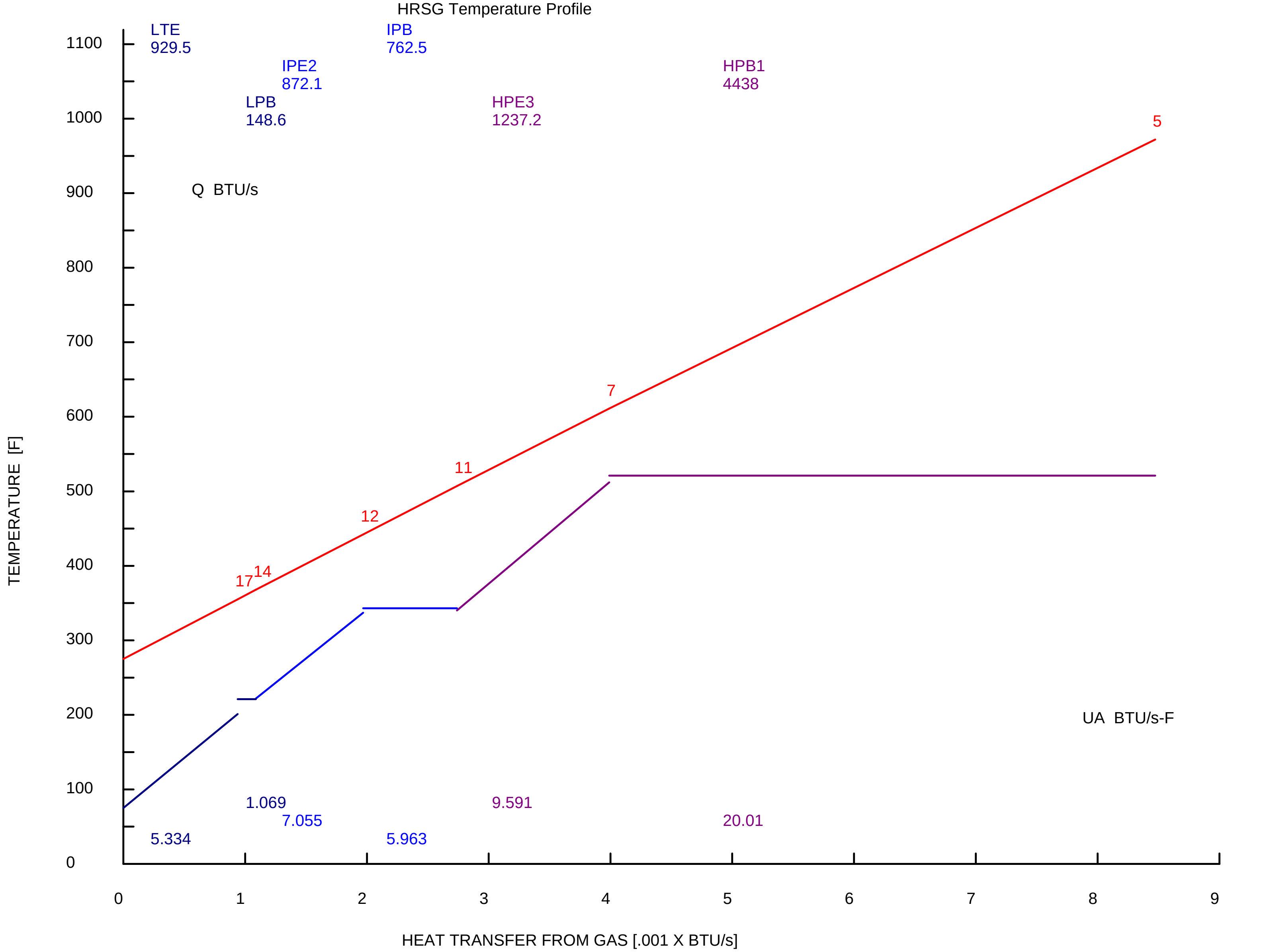
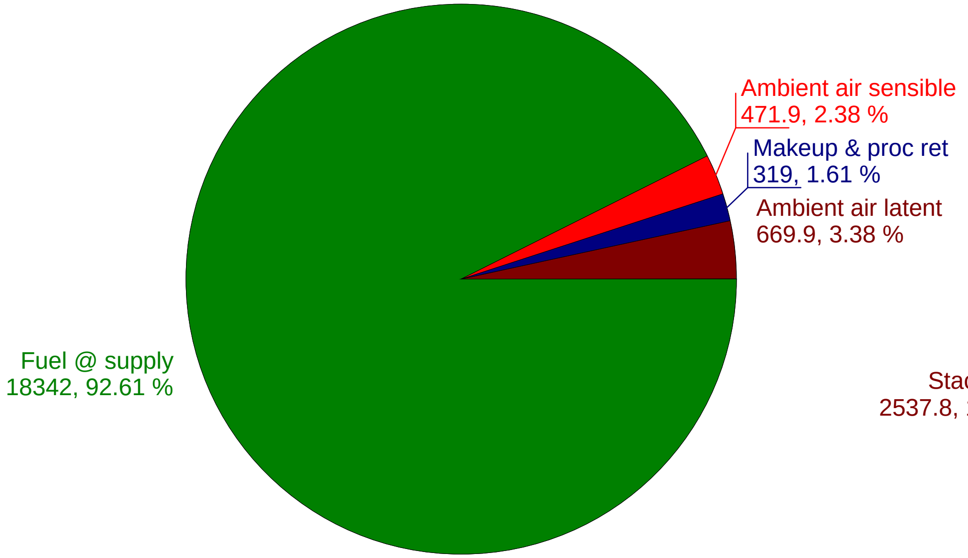

HRSG Temperature Profile
LTE
929.5
IPE2
872.1
LPB
148.6
IPB
762.5
HPE3
1237.2
HPB1
4438
Q BTU/s
UA BTU/s-F
1.069
7.055
5.334
5.963
9.591
20.01
5
7
11
12
17
14
TEMPERATURE [F]
HEAT TRANSFER FROM GAS [.001 X BTU/s]
0
100
200
300
400
500
600
700
800
900
1000
1100
1
2
3
4
5
6
7
8
9

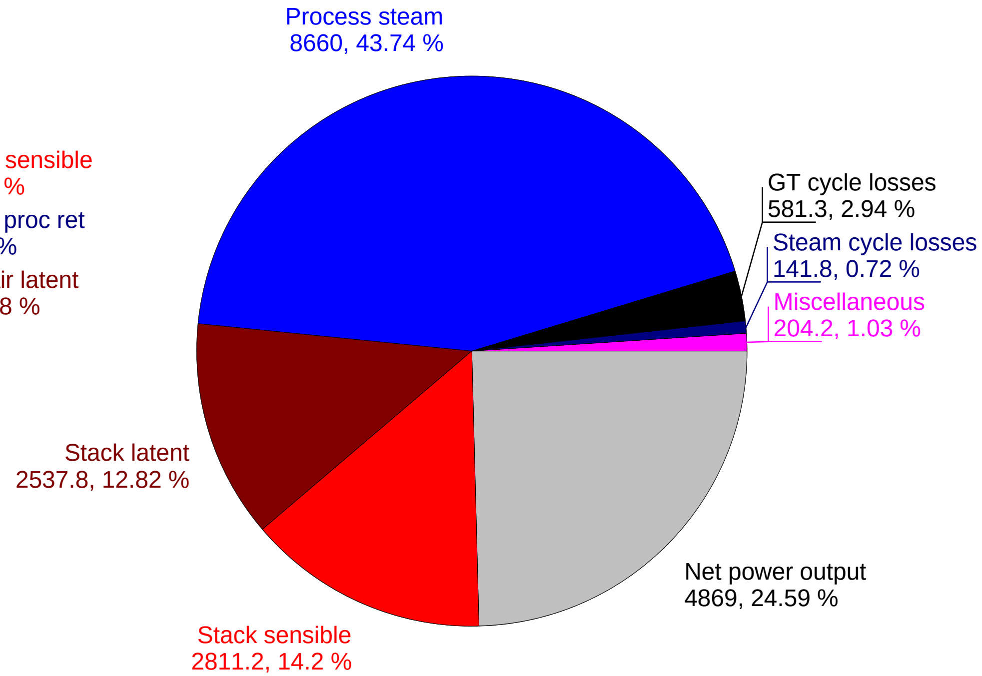
Plant Energy In [BTU/s]

Plant energy in = 19805 BTU/s
Plant fuel chemical LHV input = 16507 BTU/s, HHV = 18276 BTU/s
Plant net LHV elec. eff. = 29.49 % (100% * 4869 / 16507), Net HHV elec. eff. = 26.64 %



Plant Energy Out [BTU/s]

Plant energy out = 19796 BTU/s



Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)

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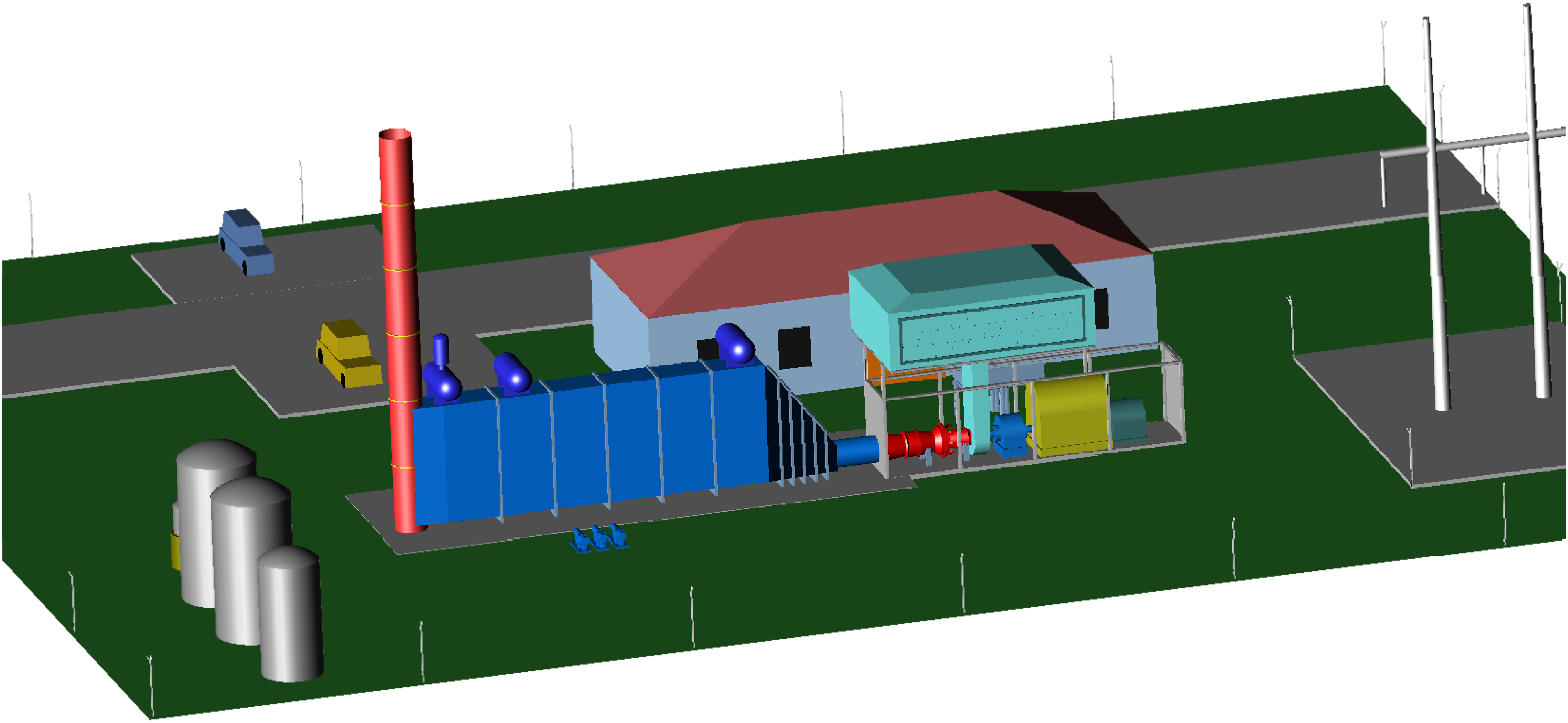

System Summary Report

GT PRO 20.0 David Oehl	
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Plant Configuration: GT & HRSG only (no ST)	
One Sol Taurus Engine, GT PRO Type 2, Subtype 2	
Steam Property Formulation: Thermoflow - STQUIK	

SYSTEM SUMMARY

	Power Output kW		LHV Heat Rate BTU/kWh		Elect. Eff. LHV%	
	@ gen. term.	net	@ gen. term.	net	@ gen. term.	net
Gas Turbine(s)	5306		11200		30.47	
Steam Turbine(s)	0					
Plant Total	5306	5137	11200	11569	30.47	29.49

PLANT EFFICIENCIES

PURPA efficiency	CHP (Total) efficiency	Power gen. eff. on	Canadian Class 43
%	%	chargeable energy, %	Heat Rate, BTU/kWh
55.72	81.95	67.66	4556

GT fuel HHV/LHV ratio =	1.107			
DB fuel HHV/LHV ratio =	1.107			
Total plant fuel HHV heat input / LHV heat input =	1.107			
Fuel HHV chemical energy input (77F/25C) =	65792	kBTU/hr	18276	BTU/s
Fuel LHV chemical energy input (77F/25C) =	59427	kBTU/hr	16507	BTU/s
Total energy input (chemical LHV + ext. addn.) =	59427	kBTU/hr	16507	BTU/s
Energy chargeable to power (93.0% LHV alt. boiler) =	25906	kBTU/hr	7196	BTU/s

GAS TURBINE PERFORMANCE - Sol Taurus

	Gross power	Gross LHV	Gross LHV Heat Rate	Exh. flow	Exh. temp.
	output, kW	efficiency, %	BTU/kWh	kpph	F
per unit	5306	30.47	11200	165	976
Total	5306			165	

Number of gas turbine unit(s) =	1			
Gas turbine load [%] =	100	%		
Fuel chemical HHV (77F/25C) per gas turbine =	65792	kBTU/hr	18276	BTU/s
Fuel chemical LHV (77F/25C) per gas turbine =	59427	kBTU/hr	16507	BTU/s

STEAM CYCLE PERFORMANCE

HRSG eff.	Gross power output	Internal gross	Overall	Net process heat output
%	kW	elect. eff., %	elect. eff., %	kBTU/hr
77.43	0	0.00	0.00	31174

Fuel chemical HHV (77F/25C) to duct burners =	0	kBTU/hr	0	BTU/s
Fuel chemical LHV (77F/25C) to duct burners =	0	kBTU/hr	0	BTU/s
DB fuel chemical LHV + HRSG inlet sens. heat =	38998	kBTU/hr	10833	BTU/s
Net process heat output as % of total output =	64.01	%		

System Summary Report

ESTIMATED PLANT AUXILIARIES (kW)		
GT fuel compressor(s)*	0	kW
GT supercharging fan(s)*	0	kW
GT electric chiller(s)*	0	kW
GT chiller/heater water pump(s)	0	kW
HRSG feedpump(s)*	37.7	kW
Condensate pump(s)*	0	kW
HRSG forced circulation pump(s)	0	kW
LTE recirculation pump(s)	0	kW
Cooling water pump(s)	0	kW
Air cooled condenser fans	0	kW
Cooling tower fans	0	kW
HVAC	2.75	kW
Lights	4.5	kW
Aux. from PEACE running motor/load list	110.2	kW
Miscellaneous gas turbine auxiliaries	11.34	kW
Miscellaneous steam cycle auxiliaries	0	kW
Miscellaneous plant auxiliaries	2.653	kW
Constant plant auxiliary load	0	kW
Gasification plant, ASU*	0	kW
Gasification plant, coal mill	0	kW
Gasification plant, AGR*	0	kW
Gasification plant, other/misc	0	kW
Desalination plant auxiliaries	0	kW
Program estimated overall plant auxiliaries	**169.2**	**kW**
Actual (user input) overall plant auxiliaries	**169.2**	**kW**
Transformer losses	0	kW
Total auxiliaries & transformer losses	**169.2**	**kW**
* Heat balance related auxiliaries		

System Summary Report

PLANT HEAT BALANCE				
Energy In	**19805**	**BTU/s**		
Ambient air sensible	471.9	BTU/s		
Ambient air latent	669.9	BTU/s		
Fuel enthalpy @ supply	18342	BTU/s		
External gas addition to combustor	0	BTU/s		
Steam and water	1.819	BTU/s		
Makeup and process return	319	BTU/s		
Energy Out	**19796**	**BTU/s**		
Net power output	4869	BTU/s		
Stack gas sensible	2811.2	BTU/s		
Stack gas latent	2537.8	BTU/s		
GT mechanical loss	115.6	BTU/s		
GT gear box loss	113.4	BTU/s		
GT generator loss	187.3	BTU/s		
GT miscellaneous losses	165.1	BTU/s		
GT ancillary heat rejected	0	BTU/s		
GT process air bleed	0	BTU/s		
Fuel compressor mech/elec loss	0	BTU/s		
Supercharging fan mech/elec loss	0	BTU/s		
Condenser	0	BTU/s		
Process steam	8660	BTU/s		
Process water	0	BTU/s		
Blowdown	71.16	BTU/s		
Heat radiated from steam cycle	141.8	BTU/s		
ST/generator mech/elec/gear loss	0	BTU/s		
Non-heat balance related auxiliaries	124.6	BTU/s		
Transformer loss	0	BTU/s		
Energy In - Energy Out	**8.381**	**BTU/s**	**0.0423**	**%**
Zero enthalpy: dry gases & liquid water @ 32 F (273.15 K)				
Gas Turbine and Steam Cycle: Energy In - Energy Out = 8.381 BTU/s				

Emissions

Emissions	lb/hr	ton/year	lb/MWhr (gross)
Gas Turbine Emissions (total for 1 units) - burning gas fuel			
NOx as NO2	5.981	24.22	1.127
CO	7.283	29.5	1.373
UHC as CH4	2.086	8.447	0.3931
SOx as SO2	0	0	0
CO2 (net)	7738	31338	1458.4
Plant Total Emissions			
NOx as NO2	1.196	4.845	0.2255
CO	7.283	29.5	1.373
UHC as CH4	2.086	8.447	0.3931
SOx as SO2	0	0	0
CO2 (net)	7738	31338	1458.4
NH3	0	0	0
Plant Total Ammonia Consumption for SCR			
Pure NH3	1.771	7.174	0.3339
Aqueous Ammonia	6.108	24.74	1.151
Note:			
Gas turbine and duct burner NOx, CO, and UHC emissions rates			
are computed from user-specified concentrations, input on the Environment topic.			
NH3 emissions are user-specified via the 'Ammonia slip' input on the SCR design menu.			
The program DOES NOT predict emissions of these compounds.			
It is the user's responsibility to input OEM-provided			
data that is consistent with equipment operation at this specific running condition.			

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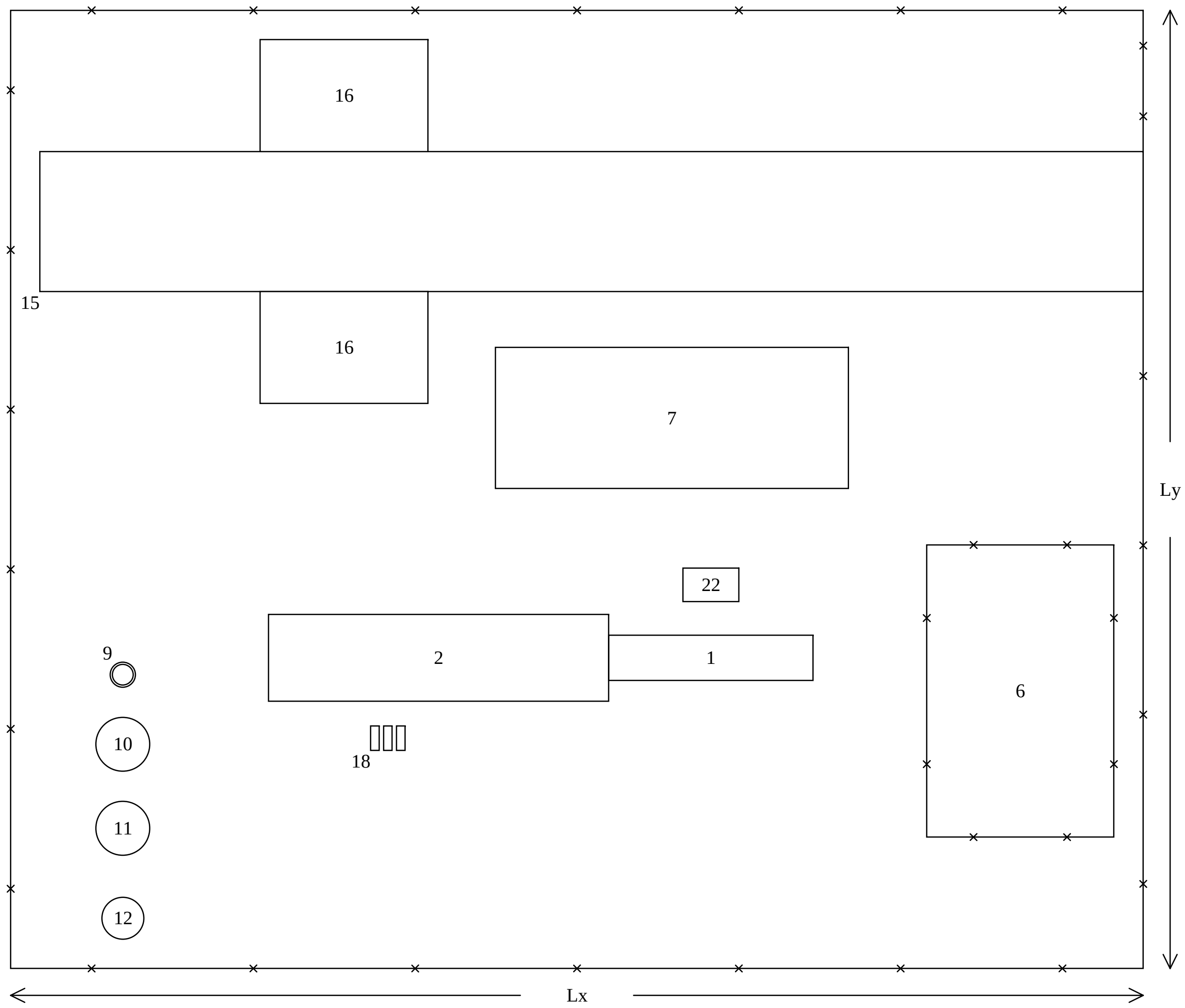

Area 0.79 acre
Lx 202 ft
Ly 171 ft

1 - Gas Turbine Package
2 - Heat Recovery Steam Generator
6 - Switchyard
7 - Administration, Shop & Warehouse
9 - Hydrous Ammonia Tank
10 - Demineralized Water Tank
11 - Raw Water Tank
12 - Neutralized Water Tank
15 - Road
16 - Parking
18 - Feed Pumps
22 - GT Fin Fan Coolers

Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	SITE PLAN
Date: 07/20/10	
Drawing No:	

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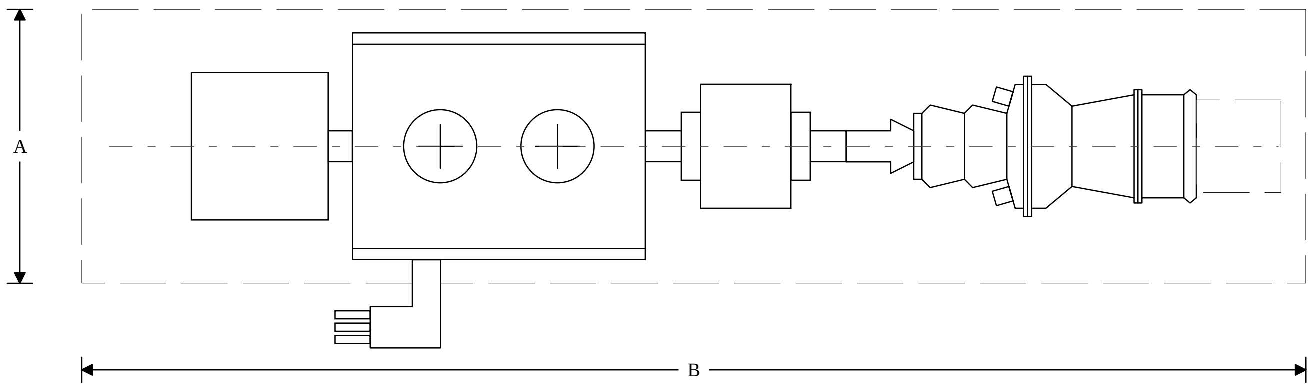

SHAPE, DIMENSIONS & SCALE ARE APPROXIMATE

A	B	C	D	E	F	G	H	I	J
8.09 ft	32 ft	-	-	-	-	-	-	-	-

Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	GAS TURBINE PACKAGE
	PLAN
Date: 07/20/10	Sol Taurus 299 (Package)
Drawing No:	

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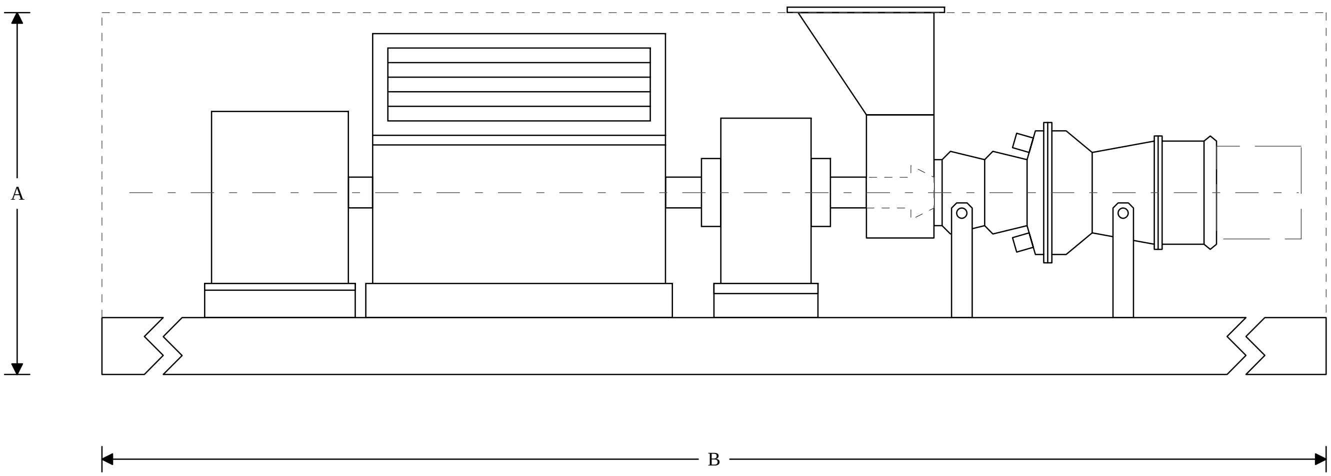
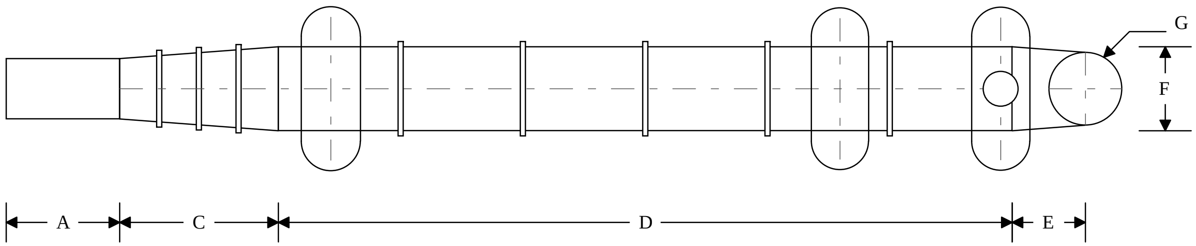


SHAPE, DIMENSIONS & SCALE ARE APPROXIMATE

A	B	C	D	E	F	G	H	I	J
10.67 ft	32 ft	-	-	-	-	-	-	-	-

Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	GAS TURBINE PACKAGE
	PLAN
Date: 07/20/10	Sol Taurus 299 (Package)
Drawing No:	

FOR QUALITATIVE INDICATION ONLY



A	B	C	D	E	F	G	H	I	J
6.174 ft	-	8.644 ft	39.96 ft	3.984 ft	4.579 ft	3.969 ft	-	-	-

Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	HEAT RECOVERY STEAM GENERATOR PLAN
Date: 07/20/10	
Drawing No:	

PEACE/GT PRO 20.0 David Oehl
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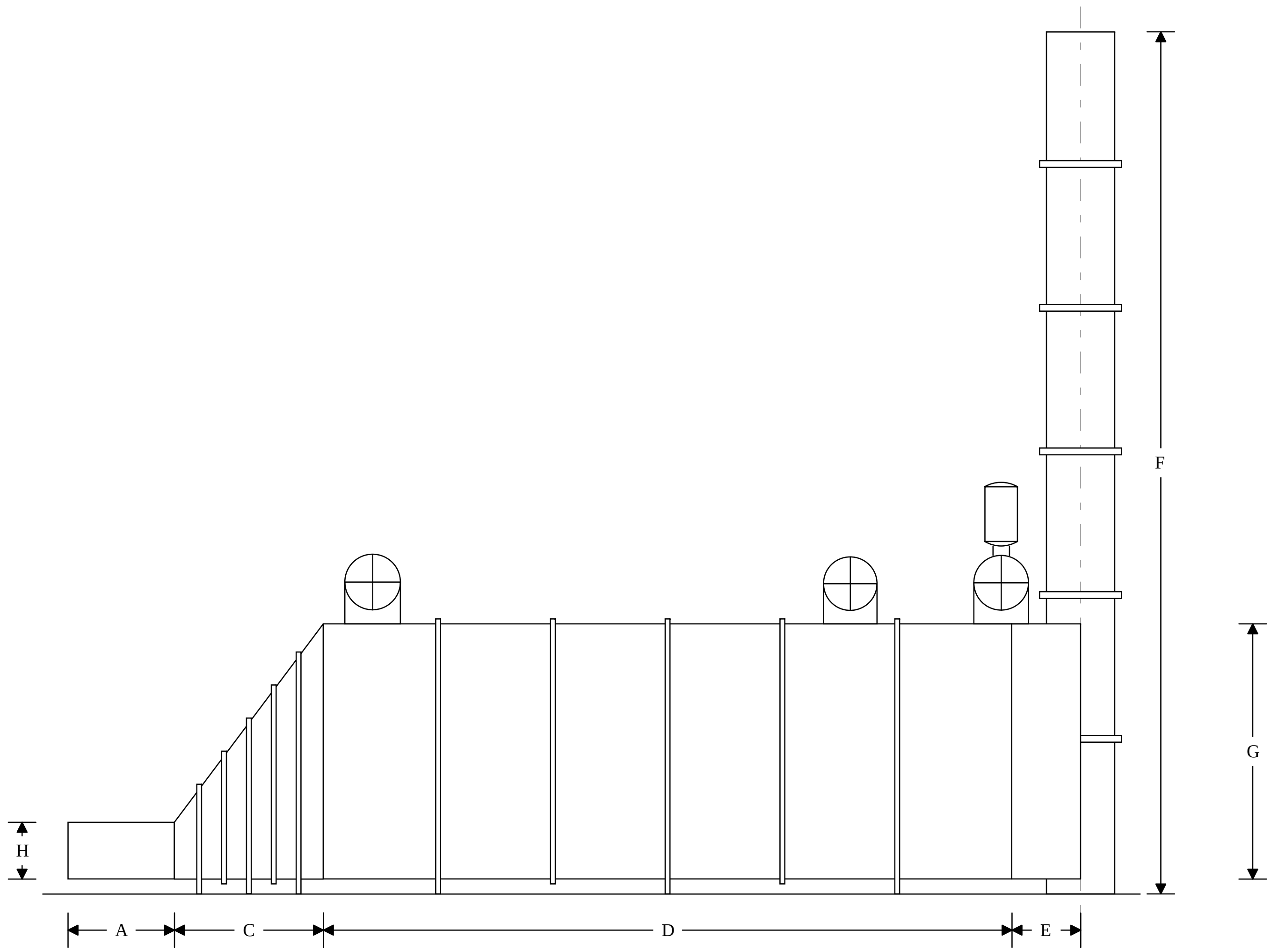
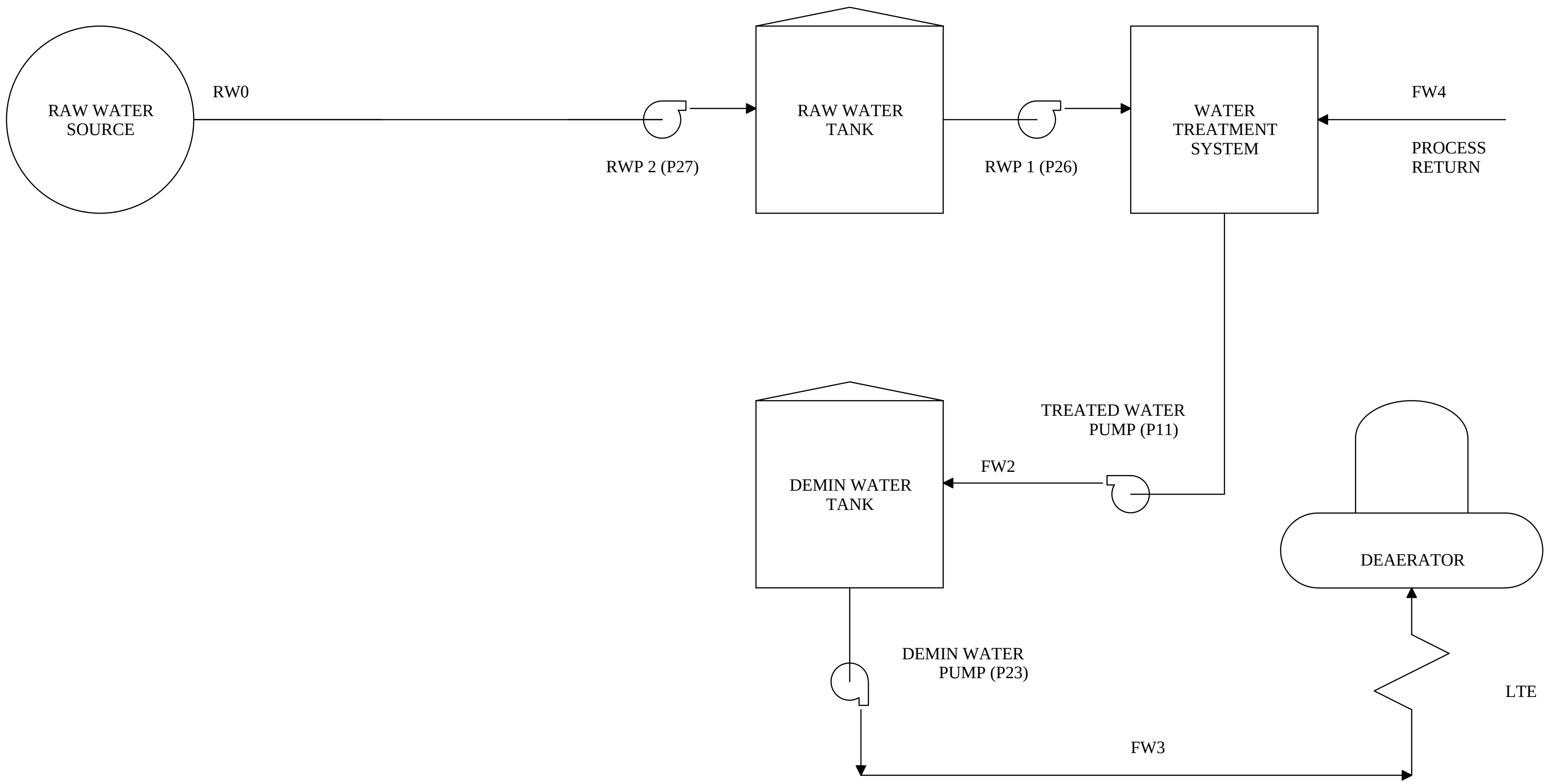


A	B	C	D	E	F	G	H	I	J
6.174 ft	-	8.644 ft	39.96 ft	3.984 ft	50 ft	14.8 ft	3.293 ft	-	-

Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	HEAT RECOVERY STEAM GENERATOR ELEVATION
Date: 07/20/10	
Drawing No:	

FOR QUALITATIVE INDICATION ONLY



ID & # OFF	DIAMETER	LENGTH	SCHEDULE	MATERIAL	DESIGN P	DESIGN T	DESIGN M	DESIGN Q
RW0 x 1	2	1186	40	A-106	175	70	25.84	51.67
FW2 x 1	2.5	252	40	TP316	100	70	43.54	87.1
FW3 x 1	2	172	40	TP316	100	203	27.15	56.37
FW4 x 1	2	1000	40	A-106	50	180	26.88	55.32
	in	ft			psia	F	kpph	gpm

Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	FEEDWATER PIPING DIAGRAM
Date: 07/20/10	
Drawing No:	

PEACE/GT PRO 20.0 David Oehl
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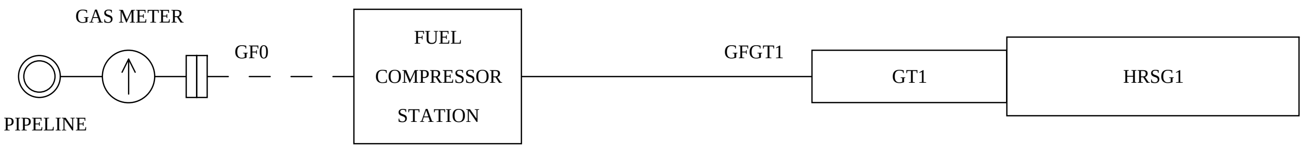
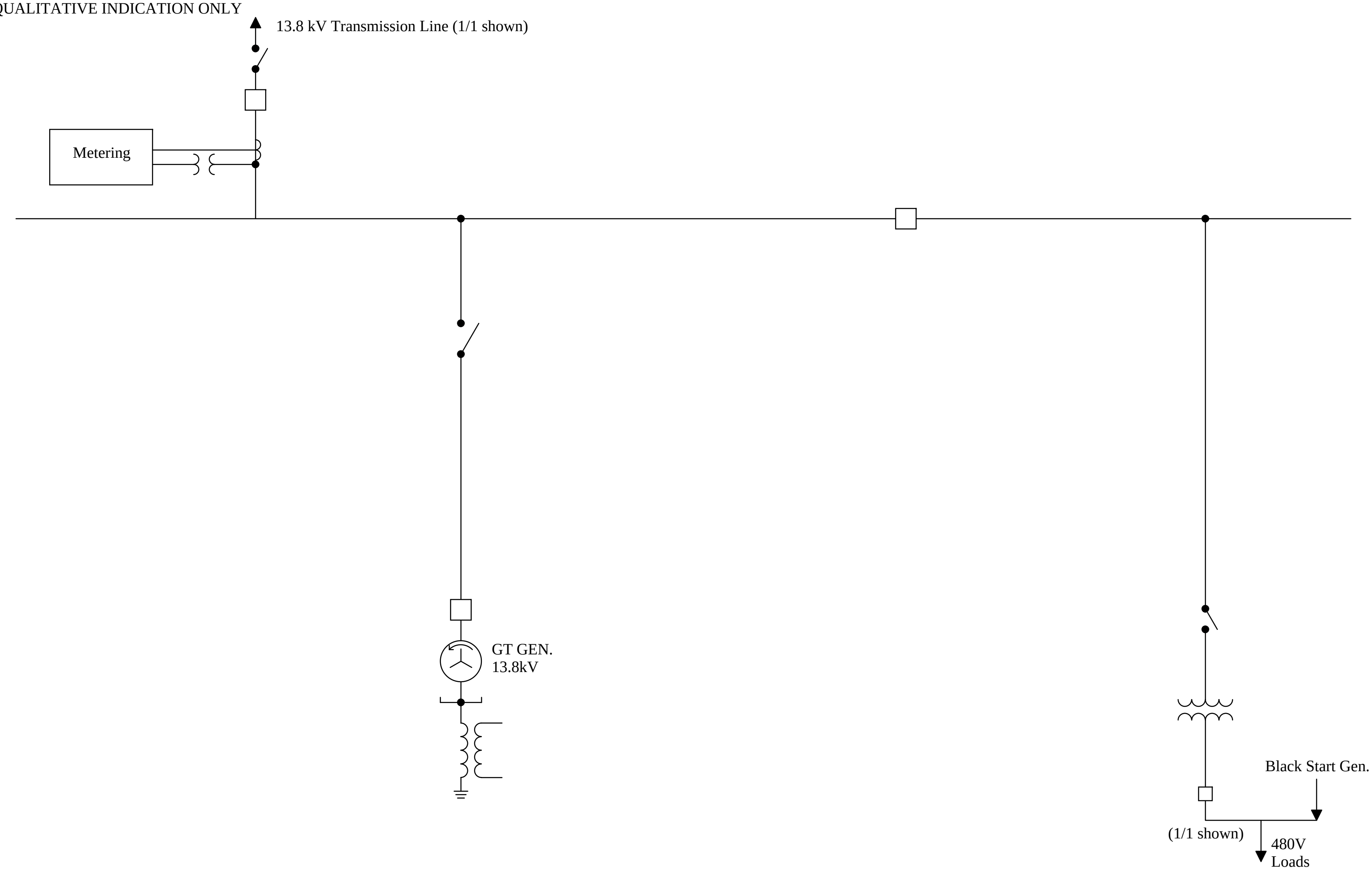
FOR QUALITATIVE INDICATION ONLY



ID & # OFF	DIAMETER	LENGTH	SCHEDULE	MATERIAL	DESIGN P	DESIGN T	DESIGN M	DESIGN Q
GF0 x 1	2.5	429	40	A-106	145	77	2.973	72620
GFGT1 x 1	2	150	40	TP316	253.1	140	2.973	72620
	in	ft			psia	F	kpph	ft^3/hr

Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	GAS FUEL PIPING DIAGRAM
Date: 07/20/10	
Drawing No:	

FOR QUALITATIVE INDICATION ONLY



Thermoflow, Inc.	Company: Maven Power
	User: David Oehl
	ELECTRICAL ONE-LINE DIAGRAM
Date: 07/20/10	
Drawing No:	

PEACE/GT PRO 20.0 David Oehl
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