A Case Study of Mixed Gas-Steam Cycle GT : LM6000 Class Aeroderivative Gas Turbine

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ABSTRACT

Many ideas were proposed to aim the generation thermal efficiency up to 60%, such as "Steam-Cooled H-Tech. Combined Cycle", "Methanol Conversion Regenerative Gas Turbine", "Kalina Cycle" etc.[*1, *2, *3, *4]

The target thermal efficiency of 60% based upon LHV, could be also attained, when applying mixed gas-steam cycle like ISTIG and/or GAS3D for advanced aeroderivative gas turbines, which comprise of multiple shafts with overall pressure ratio more than 50, and TIT more than 2600 F (1700 K).[*5]

It might be meaningful to evaluate existing aeroderivative gas turbines like LM6000 etc. by applying such an improving concept, as the more advanced gas turbines to be derived from GE90, PW4000, and Trent800 are not available to date for land applications.

The intercooled ICAD GT of 77 MW was adopted as a base engine, and it was derived that the water /steam-injected WI/GAS3D GT version could produce 106 MW with 56% thermal efficiency, and it must be emphasized that the power curve in variation with ambient temperature is very flat than conventional GT plants.

NOMENCLATURE

A**	Turbine Effective Nozzle Area
Cp	Specific Heat at Constant Pressure
f**	Variable defined as m*K for Comp. or Turbine
g**	Specific Heat Ratio defined as 1+S for Comp. or Turbine
G**	Mass Flow at each station
GEN	Abbreviation of Electric Generator
h**	Variable defined as 1-0.5*m for Turbine
Hw**	Latent Heat of Water
HN**	Variable defined as 1+0.5*(28.96/18.01+N) for Turbine
HPC	Abbreviation of High Pressure Comp.
HPT	Abbreviation of High Pressure Turbine
HRSG	Abbreviation of Heat Recovery Steam Generator
I**	Index for Water/Steam Injection defined as (1+Gw/Ga)
J**	Latent Heat Enthalpy Index defined as H/Cpa/Ta
K**	Temp. Difference Ratio Index defined as (To-Ti)/Ti
L**	Mixing Temp. Difference Ratio defined as (Tw-Ta)/Ta
LPC	Abbreviation of Low Pressure Comp.
LPT	Abbreviation of Low Pressure Turbine
m**	Temp. Rise/Drop Index
MPC	Abbreviation of Medium Pressure Comp.
MPT	Abbreviation of Medium Pressure Turbine
N**	Mixed Temp. Index defined as L*(S-1) or L*(S-1)-J
P**	Pressure at each station
PW	Shaft Horsepower at GT Coupling
PWT	Abbreviation of Power Turbine
R	Gas Constant: air; 287.0, steam; 461.7 J/kg/K
S**	Specific Heat Difference Ratio Index as (Cps-Cpa)/Cpa
T**	Temperature at each station
X**	Shaft Speed
Wf	Fuel flow
Suffix	
a	Air (Molecular Weight: 28.96)
g	Combustion Gas or Mixed Gas
s	Steam (Molecular Weight: 18.01)
w	Water
Numbering suffix	
2	Compressor Inlet (LP Compressor Inlet)
24	LPC Outlet
25	MP Compressor Inlet
27	MP Compressor Outlet
28	HP Compressor Inlet
3	Compressor Outlet (HP Compressor Outlet)
34	Combustor Inlet
4	Combustor Outlet
41	Turbine Inlet (HP Turbine Inlet)
42	HP Turbine Outlet
44	MP Turbine Inlet
46	MP Turbine Outlet
47	LP Turbine Inlet
48	LP Turbine Outlet
49	Power Turbine Inlet
8	Turbine Outlet (PWT Outlet)
91 thru 98	Refer to Fig. 1
100(am)	HRSG Outlet (Economizer Outlet)

1. INTRODUCTION

The popular method to increase the efficiency is the adoption of a steam bottoming cycle. In order to overcome intrinsically poor "Rankine" cycle due to the moderate temperature of 1000 F (810 K) or less class, it might be appropriate to heat up the steam to 2500 F (1700 K) or higher, by mixing in a main gas stream. Mixed gas-steam cycles, however, have considerable impacts to the basic GT cycle mainly due to the specific heat increase by steam mixing, and due to the bigger mass flow in the turbine by steam injection.

The performance analysis method to evaluate the operational parameters' changes by steam mixing, is already discussed[*5], which was established based upon the following concepts, subject to the small perturbation range.

1) Comp. Characteristic — Enthalpy Rise $\propto$ Speed^2
2) Turbine Characteristics — $G^*(R^*T)^{0.5}/P \propto A$
3) Gas Constant — Change $\propto$ 1+28.96/18.01*(I-1)
4) Specific Heat — Change $\propto$ 1+ (Cps-Cpa)/Cpa*(I-1)
5) Specific Heat Ratio — Unchanged

2. MODIFYING PLAN OF AERODERIVATIVE GT

The original gas turbine for the study is adopted from existing available aeroderivative models, because those are of multiple shaft type with bleed ports, which would be suitable for intercooling and/or steam injections. It is expected to have better thermal efficiencies as the evaporated steam to be worked in much higher temperature region by being injected into the main gas flow. The concept of steam injected GT is not new, and the water ingestion has been also adopted as the measure to recover the power degradation in high ambient temperature, mainly at the GT inlet. And since early 1980's, really steam injected gas turbines have been successfully operated with middle 40's thermal efficiency level, which were further beyond the original cycle efficiency.

In this study, the leading particulars of LM6000 class is settled with the addition of newly designed power turbine for both 50 and 60 Hz applications. The rated HPT inlet temperature is 1570 K (2367 F), which is lower than the take-off rating of aircraft, and the leading particulars are as follows. And T-S diagram of an original dry GT is shown in Fig. 1.

Conditions	101.3 kPa (14.7 PSIA) Ambient Pressure
	288.2 K (59.0 F) Ambient Temperature
	4.0 kPa (16.0"H2O) Inlet Duct Losses
	2.6 kPa (10.4"H2O) Exit Duct Losses
Configuration	Standard Dry
Power Output	41.3 MW @ GT Coupling
Efficiency	42.1 % @ GT Coupling
Suction Air Flow	121 kg/s (266 lb/s)
Pressure Ratio	30.0
HPT Inlet Temp.	1,570 K (2367 F)
GT Exit Temp.	731 K (856 F)

It would be granted for the gas turbine as a triple shaft engine type, because of investigating the impacts of steam injections in the middle of compression and expansion processes, i.e., mid-HPC and mid-HPT. The flow diagram is shown in Fig. 2, where the core HPC is divided into MPC and HPC, and the core HPT is hypothetically separated into HPT and MPT.

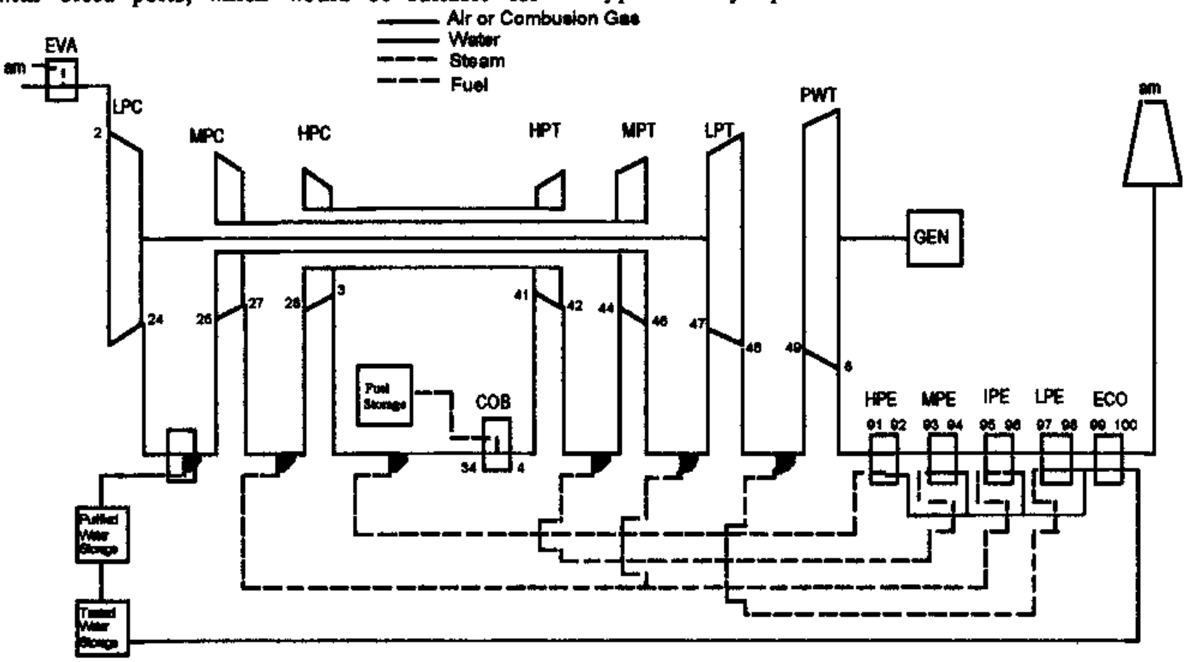

Fig. 2 Gas-Steam Mixed Cycle Flow

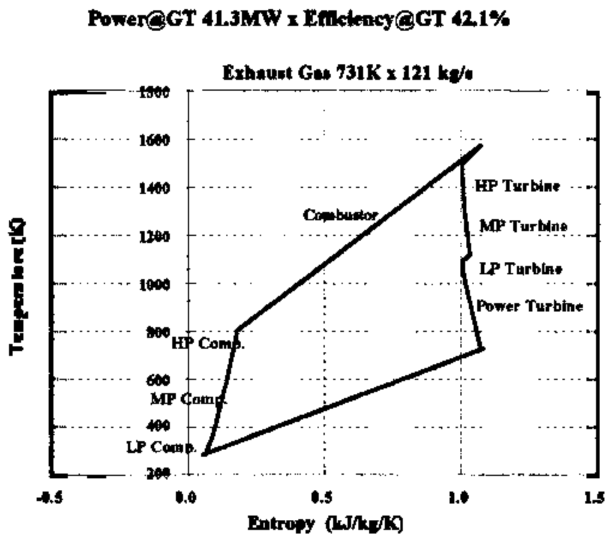

Fig. 1 T-S Diagram of an Original Dry GT

Firstly, it is to investigate parameters of the intercooled cycle to check whether the resultant pressure ratio and shaft power are within the specified limits or not, by the performance transfer matrix.

Secondly, it is to make case studies for thermal efficiency improvement plans with steam injection at the existing different ports, in the search of best binary cycle.

3. A CASE STUDY OF MIXED GAS-STEAM CYCLE

3.1 MODELING OF INTERCOOLED GAS TURBINE

The air from LP Compressor is intercooled down to 305 K (90 F) prior to MP Compressor inlet, indirectly through a heat exchanger by the supply of 298 K (77 F) city water.

The cooling effectiveness is to be defined as (HPT Inlet Temp. - Nozzle Bulk Temp.)/(Nozzle Bulk Temp. - Cooling Air Temp.), and in this case, that effectiveness is assumed to be kept constant.

Newly allowable raised HPT temperature is calculated as in following manner.

$T4 = (1150 - 750)*(1570 - 1150)/(1150 - 808) + 1150 = 1641$ K

Taken into account the cooling air temperature rise, newly rated HPT Inlet Temp. should be settled at 1620 K (2457 F), i.e., 50 K (90 F) raised from the original figure of 1570 K (2367 F).

	dP2/P	dT2/T	dT25/T	dA4/A	dT4/T	dA47/A	dA49/A	dP8/P
dP24/P	1	-0.80	0	0.18	0.80	-4.14	3.96	0
dP3 /P	1	-0.80	-1.87	-1.34	2.67	-2.17	3.96	0
dP48/P	1	-0.80	-1.87	-0.22	2.67	-2.16	2.84	0
dT24/T	0	0.75	0	0.06	0.25	-1.30	1.25	0
dT25/T	0	0	1	0	0	0	0	0
dT34/T	0	0	0.41	-0.47	0.59	0.62	0	0
dT49/T	0	0	0	0.22	1	0.02	-0.24	0
dT8 /T	-0.21	0.17	0.39	0.27	0.44	0.47	-0.83	0.21
dG2 /G	1	-0.80	-1.87	-0.34	2.17	-2.17	3.96	0
dG49/G	1	-0.80	-1.87	-0.34	2.17	-2.17	3.96	0
dPW/PW	1.33	-1.06	-1.63	-0.19	4.06	-2.87	4.66	0.33
dWf/Wf	1	-0.80	-1.31	0.00	3.47	-2.62	3.96	0

Table.1 Performance Transfer Matrix for an Original Dry GT

The performance transfer matrix for this case is listed in Table. 1 and the performance of intercooled advanced GT (ICAD version) is able to calculate as follows.

$dT25/T25 = (305 - 380) / 380 = -0.197$

$dT4 /T4 = (1620-1570)/1570 = +0.032$

$dA4 /A4 = +0.040$

$dA49/A49 = -0.030$

The adjustment of every turbine nozzle areas could be settled for optimizing thermal efficiency and avoiding to hit P3 limit figure.

Any parameters including power output (PW) can be settled by this transfer matrix formulae. The resultant leading particulars are as below, and corresponding T-S diagram is shown in Fig.3.

Configuration	4% larger HPT and 3% Smaller PWT Nozzles
Power Output	77.1 MW @ GT Coupling
Efficiency	47.4 % @ GT Coupling
Suction Air Flow	176 kg/s (389 lb/s)
Intercooled Temp.	305 K (90 F)
Pressure Ratio	41.9
HPT Inlet Temp.	1,620 K (2,457 F)
Water Injection	0 (None)
Steam Injection	0 (None)
GT Exit Temp.	701 K (802 F)

Compared with the original dry GT, the changes are as below.

Power	87 % Bigger
Efficiency	13 % Better
Pressure Ratio	40 % Bigger (Close to 42.0 Maximum)

This ICAD GT of 77 MW class is assigned as a base engine instead of an original GT for the further planning, as modifications from ICAD GT are expected to be relatively less and easy.

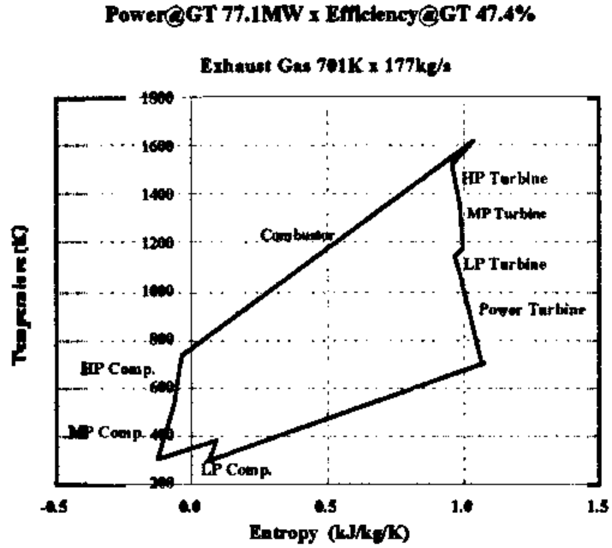

Fig. 3 T-S Diagram of an Intercooled Base GT

3.2 MODELING OF MIXED GAS-STEAM CYCLE GT

INDIRECTLY COOLED ISTIG (ICAD/ISTIG)

The rated HPT inlet temperature is kept as 1620 K as above, and the leading particulars of this cycle are as follows.

Configuration	11% larger HPT and 9% Smaller PWT Nozzles
Operation Mode	Indirectly Cooled(ICAD)/ISTIG
Power Output	106.2 MW @ GT Coupling
Efficiency	55.0 % @ GT Coupling
Suction Air Flow	178 kg/s (392 lb/s)
Intercooled Temp.	305 K (90 F)
Pressure Ratio	41.7
HPT Inlet Temp.	1,620 K (2,457 F)
Steam Injection	20.1 kg/s (44.4 lb/s) in Total
Steam Injection I @ HP Compressor Exit	
Conditions	6,000 kPa (870 PSIA) x 660 K (728 F)
Flow	14.8 kg/s (32.6 lb/s)
Steam Injection II @ LPT Inlet	
Conditions	4,000 kPa (580 PSIA) x 539 K (510 F)
Flow	2.3 kg/s (5.1 lb/s)
Steam Injection III @ PWT Inlet	
Conditions	2,000 kPa (290 PSIA) x 514 K (465 F)
Flow	3.0 kg/s (6.6 lb/s)
GT Exit Temp.	680 K (765 F)
HRSG Exit Temp.	424 K (303 F)

Compared with the original intercooled ICAD GT, parametric changes are resulted as below.

Power	38 % Bigger
Efficiency	16 % Better
Pressure Ratio	Kept as Maximum (42.0)

The resultant performance particulars are listed in Table 2, and the its transfer matrix listed in the lower half of the table, where any parameters are controlled by ambient and operating parameters, are calculated in Exel or Lotus 1-2-3 tabular calculation software by using indices listed in the upper half.[*5]

And the corresponding T-S diagram is shown as in Fig.4.

ISTIG Cycle		Performance Analysis															
Base Engine :		ICAD GT							Iw24 (-)	0.0000		Cpw24	4.29		Hw24	2139	
Mode :		1620	K ICAD/STIG						Is27 (-)	0.0000		Cps27	3.54		Hw27	1712	
Modification:		dA49/A=	-0.09	dA47/A=	-0.01	dA4/A4=	0.11		Is3 (-)	0.0831		Cps3	2.57		Hw3	1571	
	Power (MW)		106.2		Efficiency (%)		55.0		Is42 (-)	0.0000		Cps42	2.57		Hw42	1571	
	Fuel Flow (t/Hr)		15.7						Is46 (-)	0.0121		Cps46	3.54		Hw46	1712	
									Is48 (-)	0.0153		Cps48	2.80		Hw48	1913	
St.	Design'tn	T**	p**	G**	Cpg**	Mixed Cp.	Cps**	S**	m**	K**	f**	h**	g**	L**	N**	HN**	
(-)	(-)	(K)	(kPa)	(kg/s)	(kJ/kg/K)	(kJ/kg/K)	(kJ/kg/K)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	
2	LPC Inlet	288.2	97.3	178.0	1.00	1.00	1.86	0.86	0.33	4.44	1.45		0.10	0.03	-8.39		
24	LPC Exit	372.0	213.0		1.01	1.01	1.89	0.87									
25	MPC Inlet	305.4	204.5	178.0	1.00	1.01	1.87	0.89	0.30	2.22	0.66		0.02	-0.20	-6.07		
27	MPC Exit	555.1	1508.5		1.04	1.04	1.99	0.91									
28	HPC Inlet	555.1	1508.5	167.3	1.04	1.04	1.99	0.91	0.30	3.88	1.17		0.05	-0.03	-0.06		
3	HPC Exit	748.0	4058.4		1.09	1.09	2.11	0.95									
34	COB Inlet	726.7	4058.4	130.5	1.08	1.16	2.10	0.80		1.68	0.68		1.80	-0.12	-0.23		
4	COB Exit	1620.2	3855.5		1.34	1.45	2.75	0.90									
41	HPT Inlet	1539.3	3855.5	165.2	1.31	1.42	2.63	0.86	0.21	9.34	1.96	0.90	1.86	-0.63	-1.20	1.20	
42	HPT Exit	1390.4	2372.2		1.30	1.39	2.55	0.83									
44	MPT Inlet	1390.4	2372.2	165.2	1.30	1.39	2.55	0.83	0.21	6.61	1.39	0.89	1.83	-0.53	-0.96	1.32	
46	MPT Exit	1207.7	1216.3		1.27	1.36	2.43	0.79									
47	LPT Inlet	1164.3	1216.3	188.4	1.26	1.37	2.40	0.76	0.20	19.93	4.03	0.90	1.76	-0.55	-0.99	1.31	
48	LPT Exit	1108.7	954.6		1.25	1.34	2.37	0.76									
49	PWT Inlet	1092.6	954.6	198.7	1.24	1.36	2.35	0.73	0.21	1.65	0.35	1.35	1.73	-0.54	-0.94	1.33	
8	PWT Exit	680.2	103.9		1.14	1.23	2.07	0.68									
am	HRSG Exit	423.6	101.3	198.7	1.07	1.16	1.91	0.65									
		dP2/P2	dT2/T2		dT25/T25	dI27/I27	dI3/I3	dA4/A4	dT4/T4	dI42/I42	dA44/A44	dI46/I46	dA47/A47	dI48/I48	dA49/A49		dP8/P8
	dP24/P24	1	-0.69		0	1.21	1.21	0.16	0.69	0.76	0.00	0.74	-3.26	-4.05	3.10		0
	dP27/P27	1	-0.69		-1.50	3.97	3.97	0.51	2.20	2.29	-2.70	-2.33	-0.92	-4.05	3.10		0
	dP3 /P3	1	-0.69		-1.98	3.36	4.85	-1.45	2.67	-0.39	-0.14	-1.54	-1.52	-4.05	3.10		0
	dP42/P42	1	-0.69		-1.98	3.36	4.85	-0.33	2.67	1.09	-1.25	-2.02	0.58	-4.05	3.10		0
	dP46/P46	1	-0.69		-1.98	3.36	4.85	-0.33	2.67	1.09	-0.13	-0.08	-2.63	-4.05	3.10		0
	dP48/P48	1	-0.69		-1.98	3.36	4.85	-0.33	2.67	1.09	-0.13	-0.08	-1.52	-2.57	1.98		0
	dT24/T24	0	0.77		0	0.40	0.40	0.05	0.23	0.18	0.00	0.24	-1.06	-1.32	1.01		0
	dT25/T25	0	0		1	0	0	0	0	0	0	0	0	0	0		0
	dT27/T27	0	0		0.55	0.82	0.82	0.11	0.45	0.53	-0.81	-0.92	0.70	0	0		0
	dT34/T34	0	0		0.41	0.58	1.97	-0.49	0.59	-0.35	-0.03	-0.68	0.52	0	0		0
	dT44/T44	0	0		0	0	0	0.234	1	-0.652	-0.234	0	0	0	0		0
	dT47/T47	0	0		0	0	0	0.234	1	-0.652	0.002	-0.686	-0.236	0			0
	dT49/T49	0	0		0	0	0	0.234	1	-0.652	0.002	-0.686	-0.011	-0.645	-0.225		0
	dT8 /T8	-0.21	0.15		0.42	-0.72	-1.04	0.30	0.43	-1.27	0.05	-0.67	0.31	-0.10	-0.65		0.21
	dG2 /G2	1	-0.69		-1.98	1.96	3.55	-0.45	2.17	-0.39	-0.14	-1.54	-1.52	-4.13	3.10		0
	dG3 /G3	1	-0.69		-1.98	2.96	3.55	-0.45	2.17	-0.39	-0.14	-1.54	-1.52	-4.13	3.10		0
	dG49/G49	1	-0.69		-1.98	2.96	4.55	-0.45	2.17	0.61	-0.14	-0.54	-1.52	-3.13	3.10		0
	dX2 /X2	0	0		0	0.88	0.88	0.12	0.5	0.40	0.00	0.54	-2.36	-2.98	2.24		0
	dX25/X25	0	0		0	0.91	0.91	0.12	0.5	0.59	-0.90	-1.02	0.78	0	0		0
	dX3 /X3	0	0		0	-0.03	0.93	-1.09	0.5	-1.45	1.09	0	0	0	0		0
	dPW /HP	1.35	-0.94		-1.82	5.05	7.06	-0.33	4.11	1.81	-0.18	-0.49	-2.06	-3.94	3.57		0.35
	dWf /Wf	1	-0.69		-1.41	3.47	4.01	-0.11	3.44	1.68	-0.11	-0.32	-1.87	-3.39	3.10		0

Table 2 Performance Particulars and Transfer Matrix of a ICAD/STIG Mode Gas Turbine (Base Engine: ICAD GT)

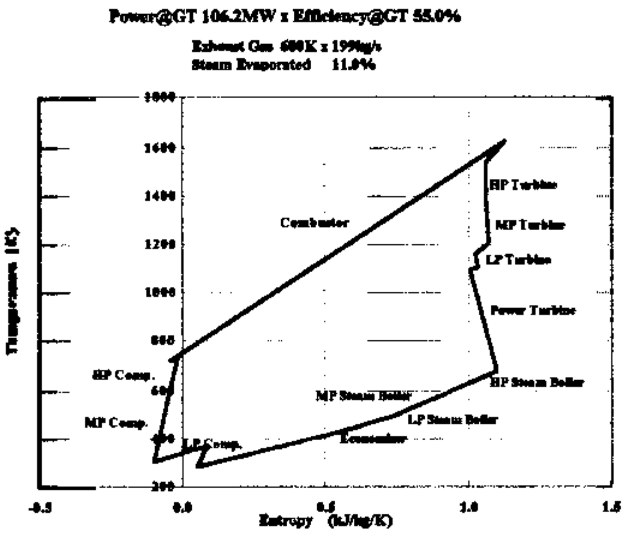

Fig. 4 T-S Diagram of an ICAD/STIG GT

WATER-INJECTED ISTIG (WI/ISTIG)

The water, the amount of which is settled to the dew point, is injected at the exit of LPC. It should be noted that the cooled temperature (T25) would be changeable in variation with the LPC discharge pressure, raised by the water injection.
The flow diagram of this intercooled gas turbine cycle is shown in Fig. 2, where the purely treated water is injected at LPC exit. The rated HPT inlet temperature is kept as 1620 K as above.

	dI24/I	dI3/I	dA4/A	dI46/I	dA47/A	dI48/I	dA49/A	dP8/P
dP24/P	1.50	1.50	0.16	0.83	-2.63	-1.99	2.44	0
dP3 /P	11.93	4.36	-1.33	-0.82	0.41	-0.79	0.97	0
dP48/P	11.93	4.36	-0.22	0.06	0.40	0.12	-0.14	0
dT25/T	-5.36	0.48	0.05	0.26	-0.83	-0.63	0.78	0
dT34/T	-2.19	1.22	-0.39	-0.25	0.11	-0.26	0.32	0
dT49/T	0	0	0.21	-0.85	-0.02	-0.80	-0.22	0
dT8 /T	-2.53	-0.91	0.49	-0.87	-0.10	-1.26	-0.19	0.21
dG2 /G	10.72	2.72	-0.33	-0.82	0.41	-0.79	0.97	0
dG49/G	11.72	3.72	-0.33	0.18	0.41	0.21	0.97	0
dPW/PW	17.44	6.41	-0.66	0.27	0.56	1.17	0.69	0.41
dWf/Wf	14.06	3.83	-0.06	0.25	0.34	0.28	0.74	0

Table.3 Performance Transfer Matrix for WI/ISTIG GT

The performance transfer matrix is expressed in Table 3 and the performance of water injection intercooled advanced GT with various steam injection (WI/ISTIG version) is able to calculate.

dI24/I24 = 1+ 3.6/158 = +1.023
dI3 /I3 = 1+ 11.3/158/1.023 = +1.070
dT4 /T4 = (1620-1620)/1620 = 0.0
dA4 /A4 = -0.010
dI46/I46 = 1+2.2/158/(1+0.023+0.070) =+1.013
dI48/I48 = 1+2.9/158/(1+0.023+0.070+0.13)=+1.016
dA49/A49= -0.090

The resultant particulars are as below, and the T-S diagram is shown in Fig. 4.

Configuration	1% Smaller HPT and 9% Smaller PWT Nozzles
Operation Mode	Water Injected(WI)/ISTIG
Power Output	94.0 MW @ GT Coupling
Efficiency	55.6 % @ GT Coupling
Suction Air Flow	158 kg/s (348 lb/s)
Pressure Ratio	41.4
HPT Inlet Temp.	1,620 K (2,457 F)
Water Injection	3.6 kg/s (8.0 lb/s) @ LPC Exit
Intercooled Temp.	302 K (83 F)
Steam Injection	16.3 kg/s (36.0 lb/s) in Total
GT Exit Temp.	658 K (725 F)
HRSG Exit Temp.	430 K (315 F)

Compared with the base ICAD GT, parametric changes are:
Power 22 % Bigger
Efficiency 17 % Better

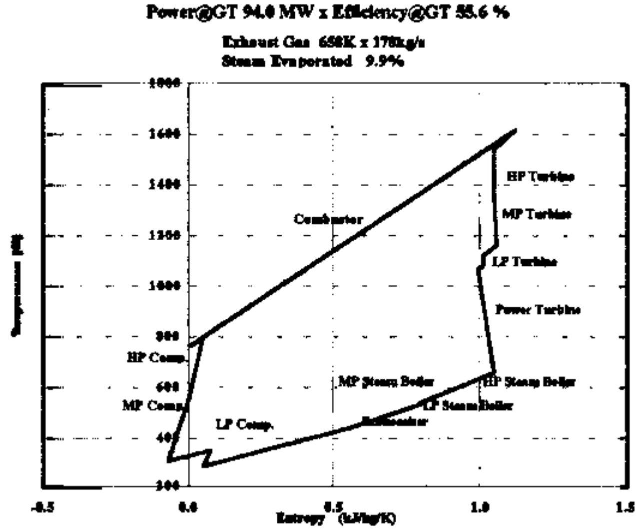

Fig. 5 T-S Diagram of a WI/STIG GT

WATER-INJECTED GAS3D (WI/GAS3D)

The water is injected as in the WI/ISTIG cycle, where the medium pressure steam is to be injected at the exit of MP compressor, instead of LP turbine inlet. The performance of water injection intercooled GT with steam injection (WI/GAS3D version) is calculated as shown in Table 4.

	dI24/I	dI27/I	dI3/I	dA4/A	dI46/I	dA47/A	dI48/I	dA49/A
dP24/P	1.05	1.05	1.05	0.15	0.66	-3.54	-4.55	3.40
dP3 /P	12.40	2.42	3.92	-1.50	-1.99	0.48	-1.52	1.14
dP48/P	12.40	2.42	3.92	-0.38	-0.51	0.48	-0.03	0.02
dT25/T	-5.72	0.35	0.35	0.05	0.22	-1.18	-1.51	1.13
dT34/T	-2.26	0.65	0.95	-0.43	-0.60	0.06	-0.59	0.44
dT49/T	0	0	0	0.24	-0.64	0.00	-0.63	-0.23
dT8 /T	-2.66	-0.75	-0.83	0.56	-0.54	-0.11	-1.54	-0.24
dG2 /G	11.20	0.93	2.42	-0.50	-1.99	0.48	-1.52	1.14
dG49/G	12.20	1.93	3.42	-0.50	-0.99	0.48	-0.52	1.14
dPW/PW	17.39	4.01	5.53	-0.78	-1.08	0.65	1.05	0.91
dWf/Wf	14.65	2.31	3.48	-0.18	-0.83	0.44	-0.39	0.82

Table.4 Performance Transfer Matrix for WI/GAS3D GT

dI24/I24 = 1+ 4.3/169 = +1.026
dI27/I27 = 1+2.3/169/1.026 = +1.013
dI3 /I3 = 1+ 15.4/169/(1+0.026+0.013) = +1.088
dA4 /A4 = -0.010
dI48/I48 = 1+2.9/169/(1+0.026+0.013+0.088)=+1.015
dA49/A49= -0.090

The resultant specifications are as below, and corresponding T-S diagram is shown in Fig. 6.

Configuration	9% Larger HPT and 9% Smaller PWT Nozzles
Operation Mode	Water Injected(WI)/GAS3D
Power Output	107.6 MW @ GT Coupling
Efficiency	55.6 % @ GT Coupling
Suction Air Flow	169 kg/s (373 lb/s)
Pressure Ratio	41.9
HPT Inlet Temp.	1,620 K (2,457 F)

Water Injection	4.3 kg/s (9.6 lb/s) @ LPC Exit
Intercooled Temp.	305 K (90 F)
Steam Injection	20.6 kg/s (45.4 lb/s) in Total
GT Exit Temp.	687 K (777 F)
HRSG Exit Temp.	422 K (299 F)

Compared with the base ICAD GT, parametric changes are:

Power	40 % Bigger
Efficiency	17 % Better

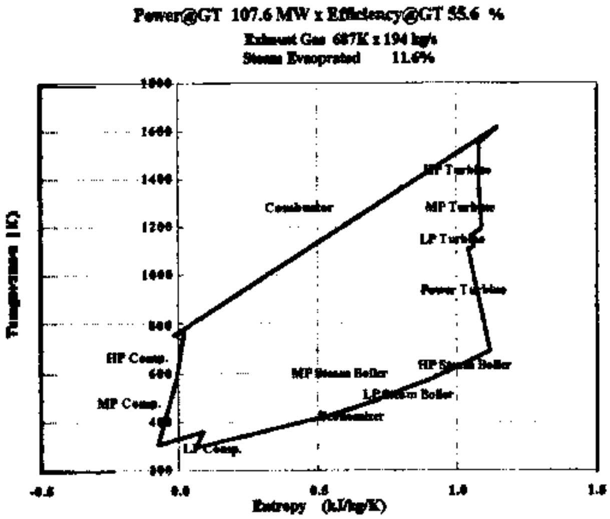

Fig. 6 T-S Diagram of a WI/GAS3D GT

The heat balance in this Heat Recovery Steam Generator is shown in Table 5 and temperature variation as in Fig. 7.

Mode	1620	K GAS3D/WI					fw24(-)	0.0257
dA49/A	-0.09	dA47/A	-0.02	dA4/A4	0.09		ls27(-)	0.0132
Inlet	Gg	169					ls3 (-)	0.0876
Exhaust	Gg	194	Tg	687	Cpg	1.26	ls48(-)	0.0154
	Gg	Tg	Cpg	Gs	Ts	Cps	Hw	Ps
HP St Ex	194	687	1.26	15.4	672	2.49		6000
HP Ev Ex	194	659	1.25	15.4	549	4.59	1571	6300
HP Ev In	194	559	1.24	15.4	549	5.08		6300
IP Sp Ex	194	559	1.24	2.3	544	3.35		4000
IP Ev Ex	194	558	1.24	2.3	523	3.78	1713	4200
IP Ev In	194	533	1.23	17.7	523	4.86		4200
LP Sp Ex	194	533	1.23	2.9	518	2.67		2000
LP Ev Ex	194	532	1.23	2.9	486	3.03	1888	2100
LP Ev In	194	496	1.22	20.6	486	4.53		2100
Econzr Ex	194	496	1.22	20.6	481	4.53		2100
Econzr In	194	422	1.19	20.6	298	4.53		2100

Table 5 Heat Balance in HRSG of WI/GAS3D GT

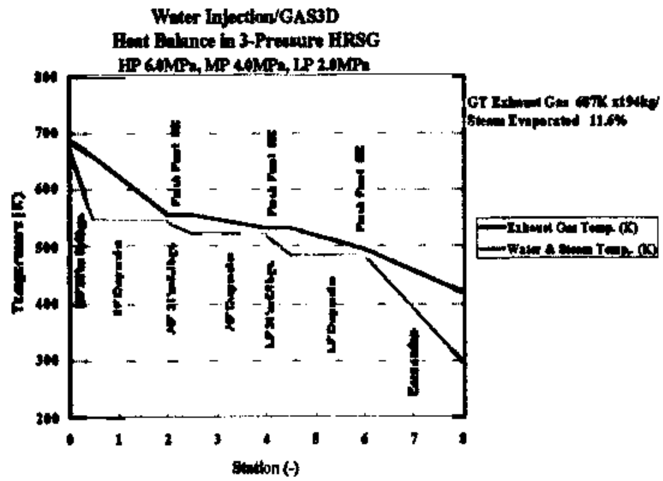

Fig. 7 HRSG Heat Balance of WI/GAS3D GT

It can be seen in Fig. 8 that any injected water/steam cycles are subject to very high temperature-based Rankine Cycle, of which the maximum cycle temperature is very same as main gas temperature.

This would be a main reason for offering better resultant efficiency than those in conventional combined cycles.

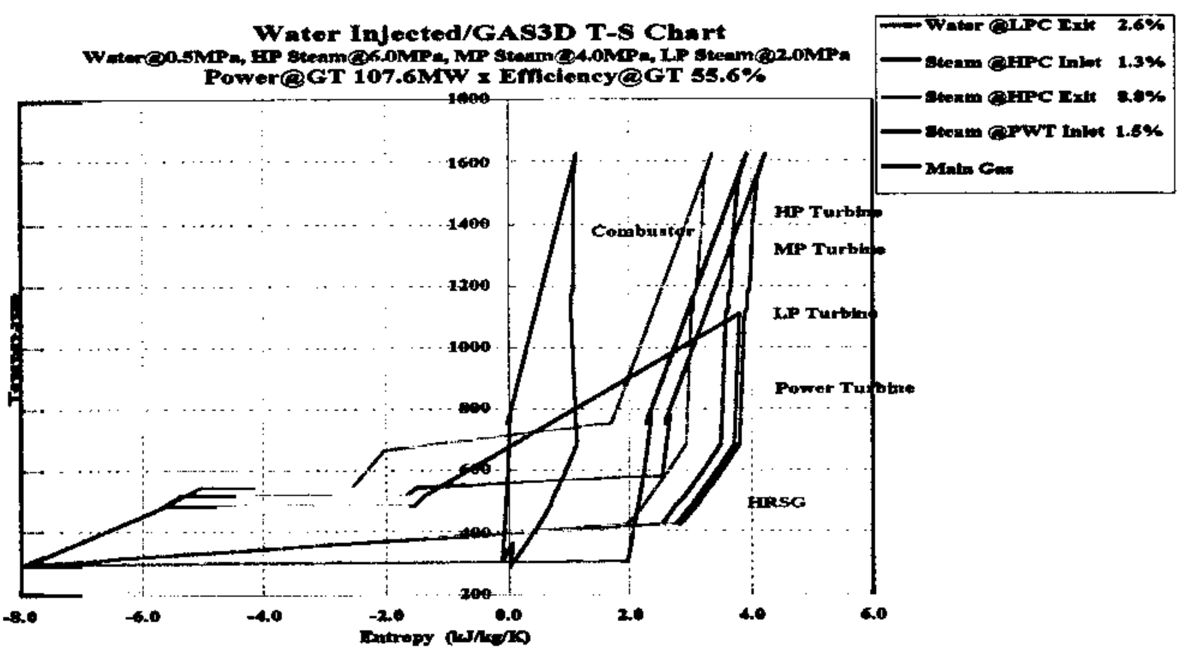

Fig. 8 Gas & Steam T-S Diagram of a WI/GAS3D GT

4. EVALUATION OF CASE STUDIES

MIXED GAS-STEAM CYCLE GT

The ISTIG or GAS3D cycle is not of conventional combined cycle type, from view points of mechanical definitions, which is of dual-fluid cycle type, combined thermodynamically inside.

The "Brayton" Cycle of 1600 K maximum temperature brings about thermal efficiency of 42 %, and, on the contrary, the "Rankine" Cycle of 700 K maximum temperature, which would be appropriate for the bottoming cycle, may have 30 % efficiency at best. Accordingly, it might be anticipated that it is better for the evaporated steam to be used in much higher "Rankine" Cycle due to 1600K steam. For example, under the condition of 80 % total extract of the heat and power from the base gas turbine cycle, following total efficiencies are expected, respectively.

Combined Cycle with "Rankine" Cycle			
GT Brayton Cycle Efficiency		0.42	
Heat Recovery (Heat)		0.38	
Steam "Rankine" Cycle Efficiency			0.30
Heat Recovery Efficiency (Power)			0.11
Resultant Efficiency	0.53		
GAS-3D Cycle			
GT Brayton Cycle Efficiency		0.42	
Heat Recovery (Heat)		0.38	
Steam "Rankine" Cycle Efficiency			0.40
Heat Recovery Efficiency (Power)			0.15
Resultant Efficiency	0.57		

In principle, in order to have a successful ISITIG/GAS3D cycle, it
is essential to check carefully what degrees of parametric changes are expected from pure air fluid into dual fluid working.

INTERCOOLING METHOD

The parametric changes by indirectly intercooling without steam injections were described at Section 3.2. And the changes by water injection intercooling are listed as below.

Configuration	6% smaller HPT and 3% Smaller PWT Nozzles
Power Output	75.4 MW @ GT Coupling
Efficiency	48.6 % @ GT Coupling
Suction Air Flow	162 kg/s (358 lb/s)
Water Injection	4.8 kg/s (10.6 lb/s)
Intercooled Temp.	311 K (99 F)
Pressure Ratio	41.9
HPT Inlet Temp.	1,620 K (2,457 F)
GT Exit Temp.	689 K (802 F)

Compared with the base ICAD GT, the efficiency is better by 3%, relatively, although intercooled temperature is higher than in indirectly intercooling case. This is mainly caused from the larger turbine output producing by mixing steam flow of bigger specific heat value than pure air.

It is seen that this tendency appears even in ISTIG/GAS3D analyses, where the efficiency in water injected mode is better than ICAD mode, relatively by 2%.

Power@GT 75.4MW x Efficiency@GT 48.6%

Exhaust Gas 689K x 168kg/s

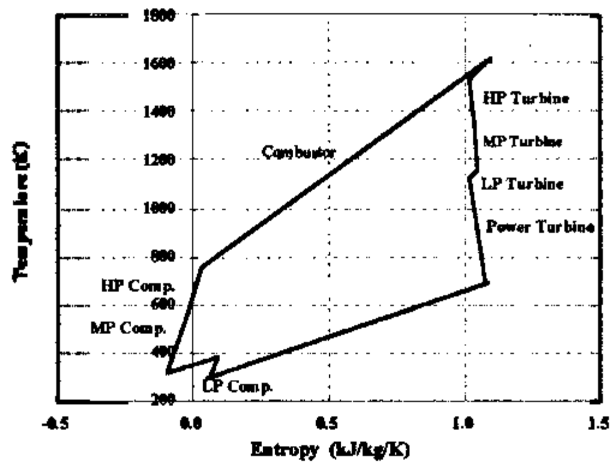

Fig. 9 T-S Diagram of Intercooled GT by Water Injection

TURBINE NOZZLE AREA CHANGES

When injecting steam into the turbine gas flow, it is normal that the turbine inlet pressure has to be increased to maintain the corrected gas flow as constant, corresponding to the speed-up of rotating speed. These two parameters are very important factors for making decision of the gas turbine life, to limit thrust bearing capacity and mechanical strength of rotating parts. Not to increase these two parameters, the enlargement of the turbine nozzle area with the adjustment of turbine nozzle setting angle is to be considered.

It was acknowledged in case studies that the countermeasure of enlarging the nozzle areas is very useful to avoid the speed increase when injecting steam/water into the gas turbine without any sacrifices of the performance parameters or sometimes with better performance. It would not be so difficult to adjust the nozzle area within the range of plus or minus 10 %, by rotating the setting angle of nozzle cascade rows with buckets as it is.

RAISE OF HPT INLET TEMPERATURE

It is possible to raise HPT inlet temperature for the sake of cooler HPC delivery air, which is used as cooling media to the hot parts of GT, because the water injection at LPC and steam injection during/after HPC brings about lowering HP compressor discharge temperature. The enlargement of turbine nozzle areas has also the cool-down effects by lowering the revolutional speed as mentioned above. In comparison with the original dry cycle, and the modified & water injected cycle gas turbine, the combustor inlet temperature has dropped from 808 K down to 750 K by nearly 60 K difference. The cooling effectiveness is to be defined as (HPT Inlet Temp. - Nozzle Bulk Temp.)/(Nozzle Bulk Temp. - Cooling Air Temp.), and in this case, that effectiveness is assumed to be kept constant.

As described in Sec. 3.2, HPT Inlet Temp. was settled at 1620 K, i.e., 50 K raised from the original figure of 1570 K in this study.

Much higher TIT like H-technology of 1770 K (2730 F) would be preferable for realizing 60% or better thermal efficiency figures.

In this study, however, it was intended to improve existing gas turbines by applying mixed gas-steam cycle, and it is understood that it is difficult to get such high TIT without major modifications. Such preliminary analyses were done by assuming more powerful and advanced aeroderivative GTs from turbofan engines.[*8]

5. CONCLUSIONS

The performance transfer matrix method[*5] could be applied to check the performance variation when applying water/steam injections to existing GTs.

ISTIG/GAS3D gas turbine cycles could be counted as an excellent cycle improvement ideas. The assumed limits, i.e., 1620 K (2467 F) for TIT and 42 for CDP pressure ratio, yields in the results of 107 MW capacity with 56% LHV efficiency at GT coupling. It was difficult to get 60% efficiency, however, those figures are further better than those of existing LM6000 class combined cycle plants. And this kind of mixed gas-steam cycle is of much more flexible operability with or without water/steam injection, offering faster start capability, comparing with conventional combined cycle plants.

1) Performance Analyses Method

It is said that STIG version from the original dry engine results in 55% power augmentation and 20% efficiency improvement, and such results were acquired by applying this method.

Configuration 9% smaller HPT and 12% larger PWT Nozzles

Power Output	65.1 MW	(57% Bigger)
Efficiency	51.5 %	(22% Better)
Pressure Ratio	32.4	(10% Larger)
HPT Inlet Temp.	1,570 K (2,367 F)	(Kept as Same)

It is easy to estimate the power characteristics in variation with ambient temperature (T2), by using dT2/T2 in the transfer matrix.

	dP2/P	dT2/T	dI24/I	dI3/I	dP3/P	dA4/A	dA49/A	dP8/P
dT34/T	0	1	-5.2	-0.3	0.3	0.0	0.0	0
dT4 /T	0	1	-4.7	-2.0	0.5	0.5	-0.5	0
dPW/PW	-0.2	0.5	-1.7	-0.7	1.8	1.5	-1.1	0.5
	dP2/P	dT2/T	dI24/I	dI3/I	dT4/T	dA4/A	dA49/A	dP8/P
dP3/P	1	-2.1	9.9	4.1	2.1	-1.1	1.0	0
dT34/T	0	0.4	-2.2	1.0	0.6	-0.3	0.4	0
dPW/PW	1.5	-3.3	16.1	6.7	3.8	-0.5	0.8	0.5
	dP2/P	dT2/T	dI24/I	dI3/I	dT3/T	dA4/A	dA49/A	dP8/P
dP3 /P	1	-3.3	17.1	0.0	3.3	-0.1	-0.1	0
dT4 /T	0	-0.6	3.4	-2.0	1.6	0.5	-0.5	0
dPW/PW	1.5	-5.4	28.9	-0.7	5.9	1.4	-1.3	0.5

Table 6 Power Variation with T2, under P3, T4, & T3 Control for an Original Dry Engine

The following is an example for comparing characteristics of dry and GAS3D cycles under P3, T4, and T3 control, showing the very steep power curve under T3 control.

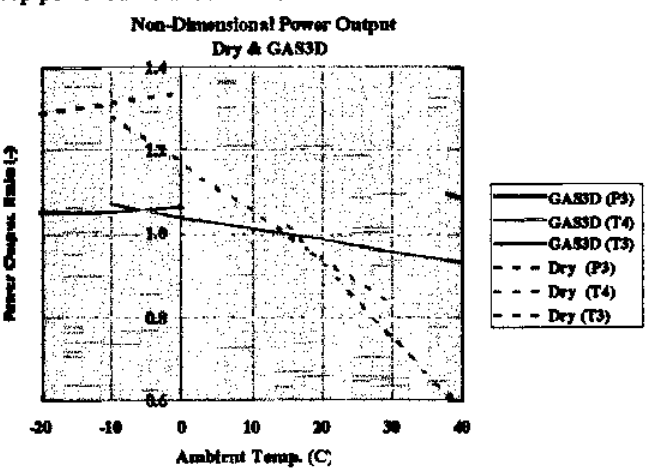

Fig. 10 Power Characteristics of Dry and GAS3D Cycle GTs

It can be seen that GAS3D GT has very flat curve and T3 control parameter is meaningless for GAS3D, which is most important control parameter for Dry GT at high ambient temperature region.

2) Feasibility Study on ISTIG/GAS3D Cycle

It is assured that ISTIG/GAS3D Cycle is equivalent or superior to other cycle improvement ideas such as "Kalina-Cycle", "H-Technology" etc. There are some features comparing with the combined cycle with the bottoming cycle of 700 K (800 F) class.

-Unnecessary to have a bottoming cycle components, saving a lot of investment related to the equipment of a bottoming cycle.

-Better Rankine cycle efficiency due to much higher steam maximum cycle temperature of 1600 K (2400 F) class by mixing in the advanced efficient gas turbine.

3) Applicability of Aero-Derivative GT into ISTIG/GAS3D Cycle

It is learned that upper fifty (50) percent class efficiency can be attainable in GAS3D Cycle, for the sake of excellent efficiency of original supposed advanced engine. When increasing maximum temperature by 50 K, and adjusting turbine nozzle areas within the range of 10 %, the produced power grows 107 MW from 41 MW and the thermal efficiency goes up 56 % from 42 %.

And it must be mentioned that such efficiency level will go up more, if the pressure ratio of LP compressor went up. It would be expected to exceed 60 % level by applying up-rated version of LM6000 or equivalent GTs, which have to have much bigger pressure ratio than existing 2.4 level.

REFERENCES

1) J. Corman, 1995, "H Gas Turbine Combined Cycles Power Generation System for the Future" 95-Yokohama-IGTC-143
2) J. Corman, R. Bjorge, A. Kalina, 1995, "Kalina Cycle Looks Good for Combined Cycle Generation"
3) R. Carapellucci, V. Risalvato, C. Bruno, G. Cau, 1996, "Performance and Emissions of CRGT Power Generation Systems with Reformed Methanol", IEEE Paper 96131
4) A. Rao, V. Francuz, P. Bautista, 1993, "An Evaluation of Advanced Gas Turbine Cycles", Power-Gen '93
5) K. Hanawa, 1997, "Thermodynamic Performance Analyses of Mixed Gas-Steam Cycle (1) & (2)", ASME 98-GT117, 118