

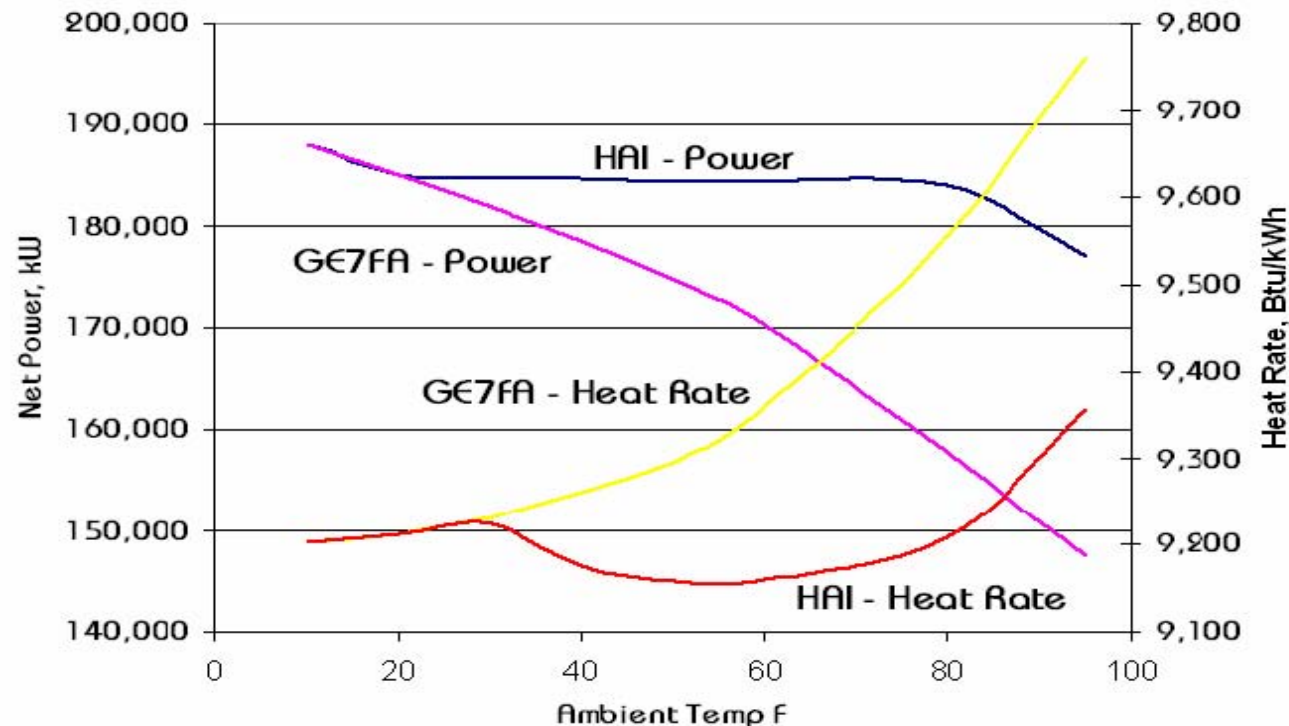
Humid Air Injection (HAI) – Overview

- **The AI power augmentation technology has two applications:**
 - Humid Air Injection (HAI)
 - Dry Air Injection (DAI)
- **The HAI technology:**
 - Increases the power of existing gas turbines by up to 40%
 - Improves heat rate by up to 25-30%
 - Reduces NOx emissions of diffusion combustors by 50% - 80%
- **The DAI technology:**
 - Increases power by up to 15%
 - No water requirements
- **Utilizes standard industrial equipment installed externally to the gas turbine**
- **Capital cost is \$150 - \$200/kW combined cycle or \$200 - \$250/kW simple cycle plants**
- **A commercially proven technology (Calpine Broad River plant)**
 - It was licensed to Calpine Corporation for use only on Calpine's Owned CT/CC Plants.
 - As a Part of the License Agreement Calpine Installed and Validated the AI Technology on GE 7241 (FA) CT at Broad River Project
 - Combustors tests indicated NOx emissions reductions by up to 90%
- **“... the best overall evaluated technology on the market for sizeable capacity increases..” (ref: Ron Hall, GM – Gas Turbine Assets, Tennessee Valley Authority)**

Humid Air Injection

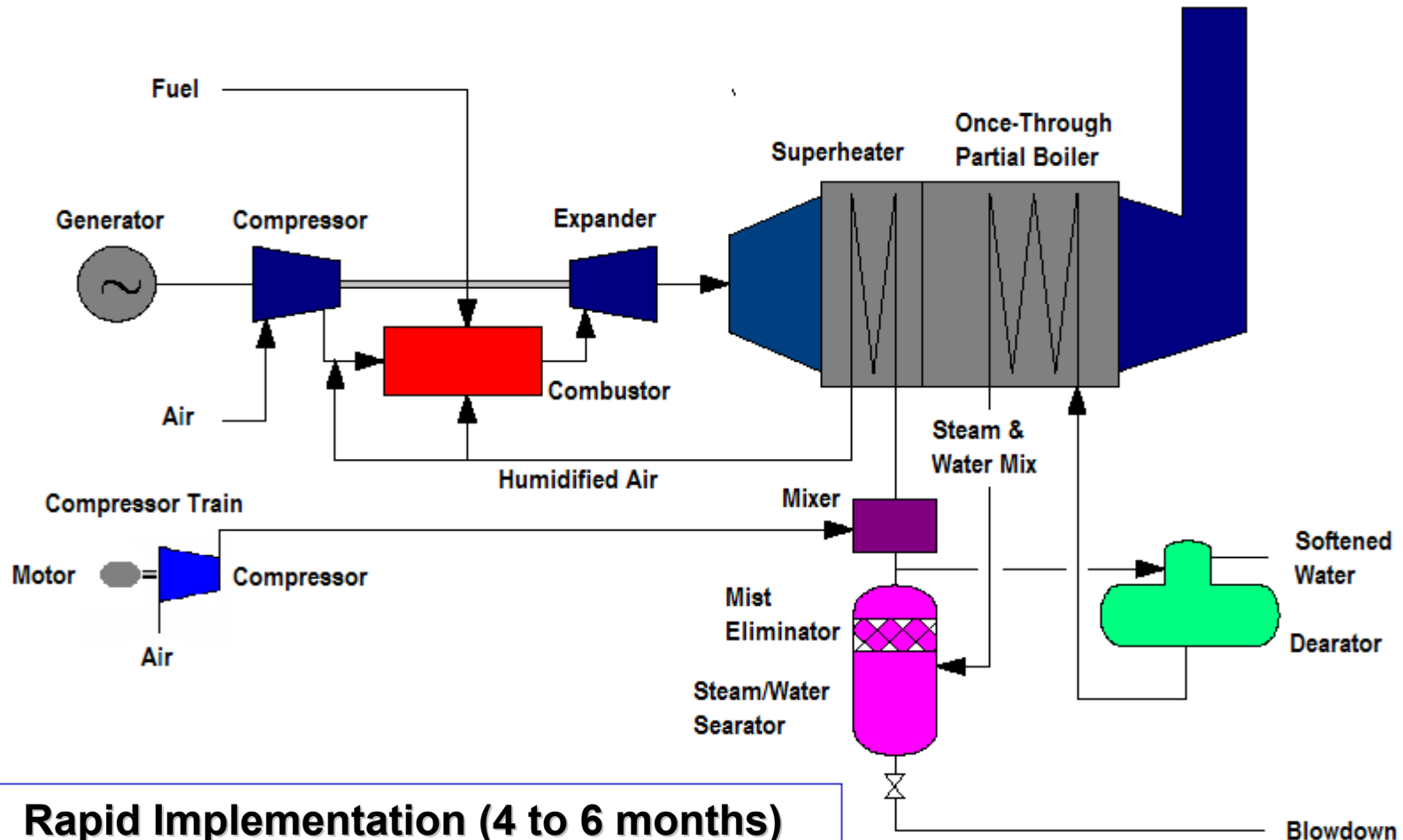
Improves Gas Turbine Performance

(GE 7FA with maximum of 3.5% moisture)



Gas turbine power normally falls off with high inlet temperature because the air mass flow is less. Air injection makes up for the reduction in air flow by adding an additional compressor to the gas turbine. Heat rate improves because the pressure ratio remains high, and the injected steam has high energy content.

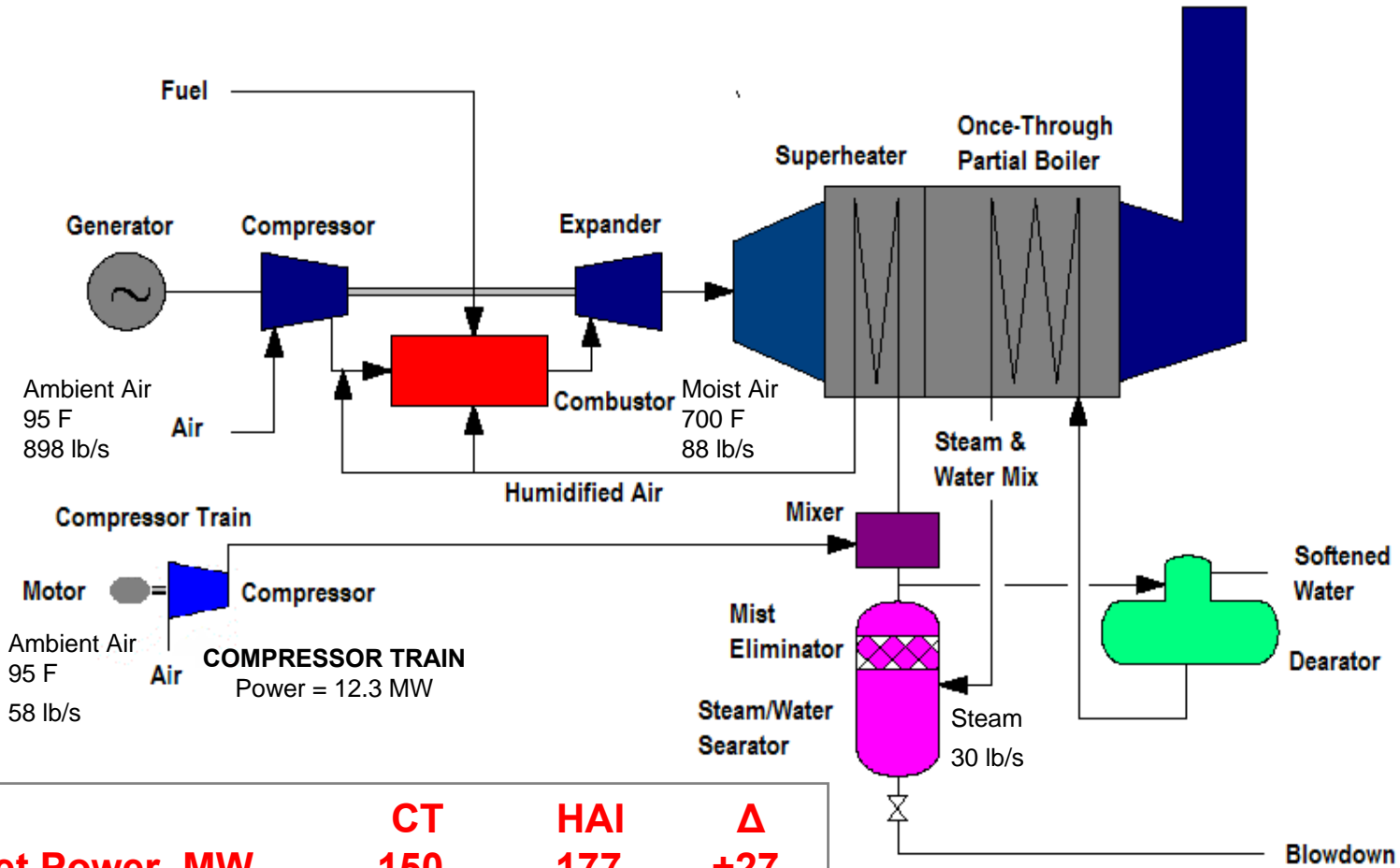
Humid Air Injection – Off the Shelf Components



Rapid Implementation (4 to 6 months)
Little Down Time on Gas Turbine
Low Cost (\$150 to \$250 per kW)
Proven Technology

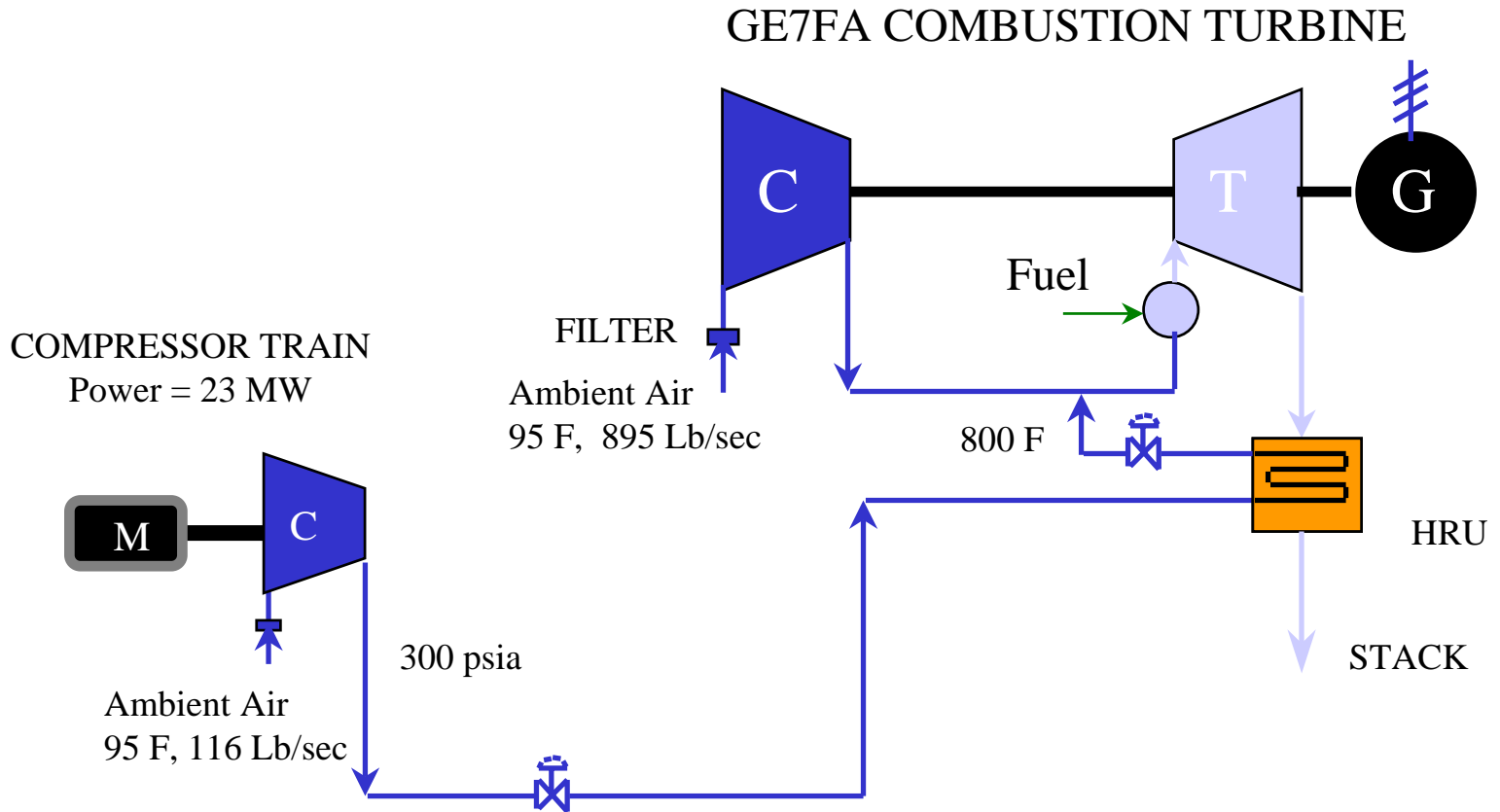
Humid Air Injection - GE7FA

3.5% Ratio: Injected H₂O to Inlet Air



	CT	HAI	Δ
Net Power, MW	150	177	+27
Heat Rate, Btu/kWh	9,760	9380	- 380

Dry Air Injection - GE7FA



	CT	DAI	Δ
NET POWER, MW	150.4	166.4	+16.0
NET HEAT RATE, Btu/kWh	9,760	9,720	-40

Broad River SC – HAI Validation Tests

PG7241FA with DLN (150.4 MW @ 95°F)



Humid Air Injection:

Measured:

- 18.3 MW increase @ 3.5% humidity, 95°F ambient

Predicted:

- 26.6 MW increase @ 5.5% humidity, 95°F ambient

NO_x:

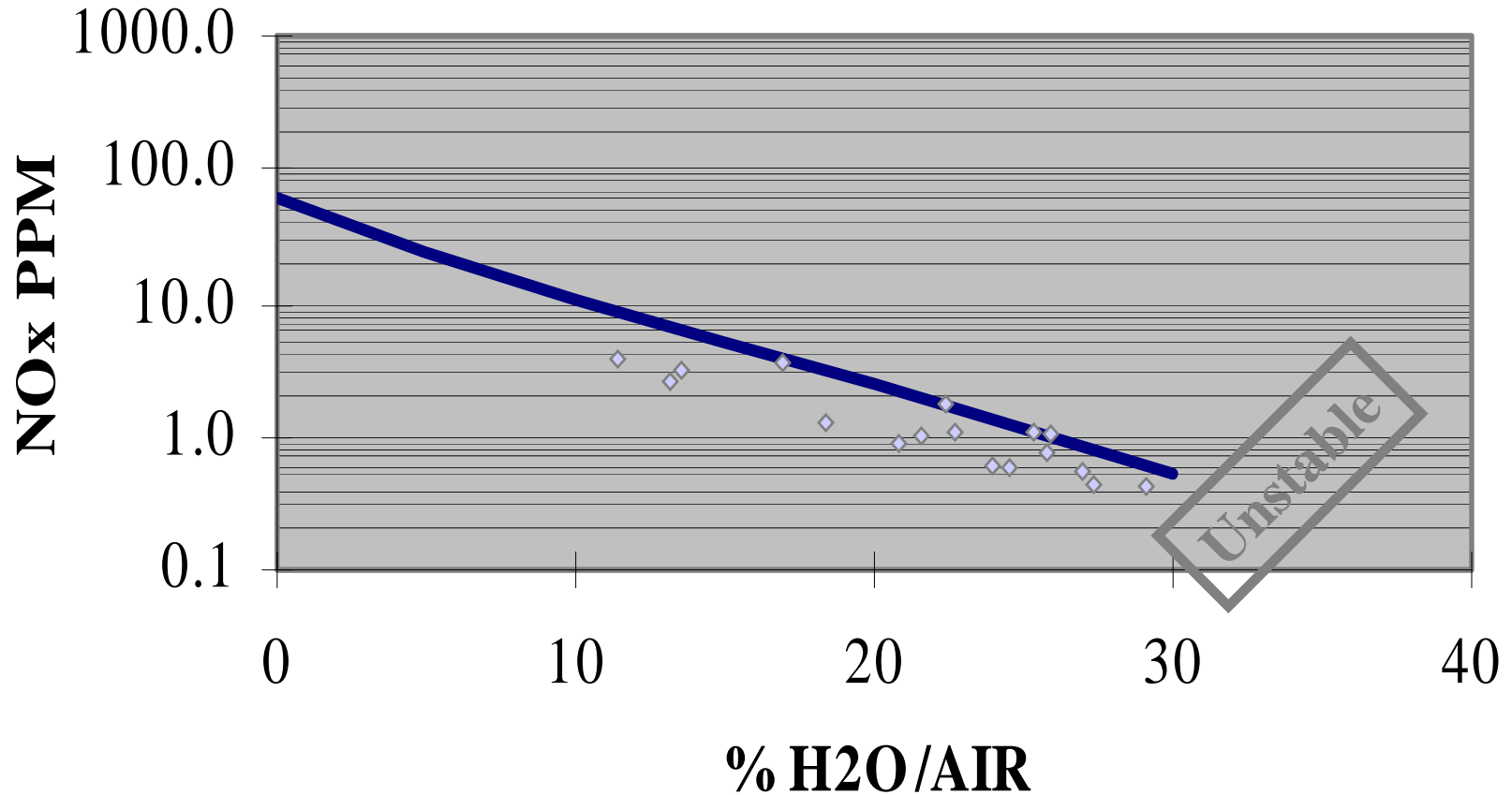
- 9 ppm with DLN combustor
- 12 ppm with steam injection and DLN
- < 9 ppm with HAI and DLN

Summary of test results published in Gas Turbine World, March-April 2002.
You can view this article and others at the web site: www.espcinc.com

Humid Air Technology Significantly Reduces Emissions

- **EPRI Contracted Textron Lycoming Division, CT and Aero Industrial technology, England for Parallel Testing of Diffusion type Combustors**
 - Presented on the Next Page Results of Tests demonstrate NO_x Reductions from over 100 p.p.m.v. to Single Digits. (see Report at www.espcinc.com/publications)
- **The Technology Validation Tests on GE 7241 (FA) with DLN demonstrated no Measurable Increase in NO_x Emissions, while SI Tests (Conducted in Parallel) Showed NO_x Increase from 9 to 12 p.p.m.v.**

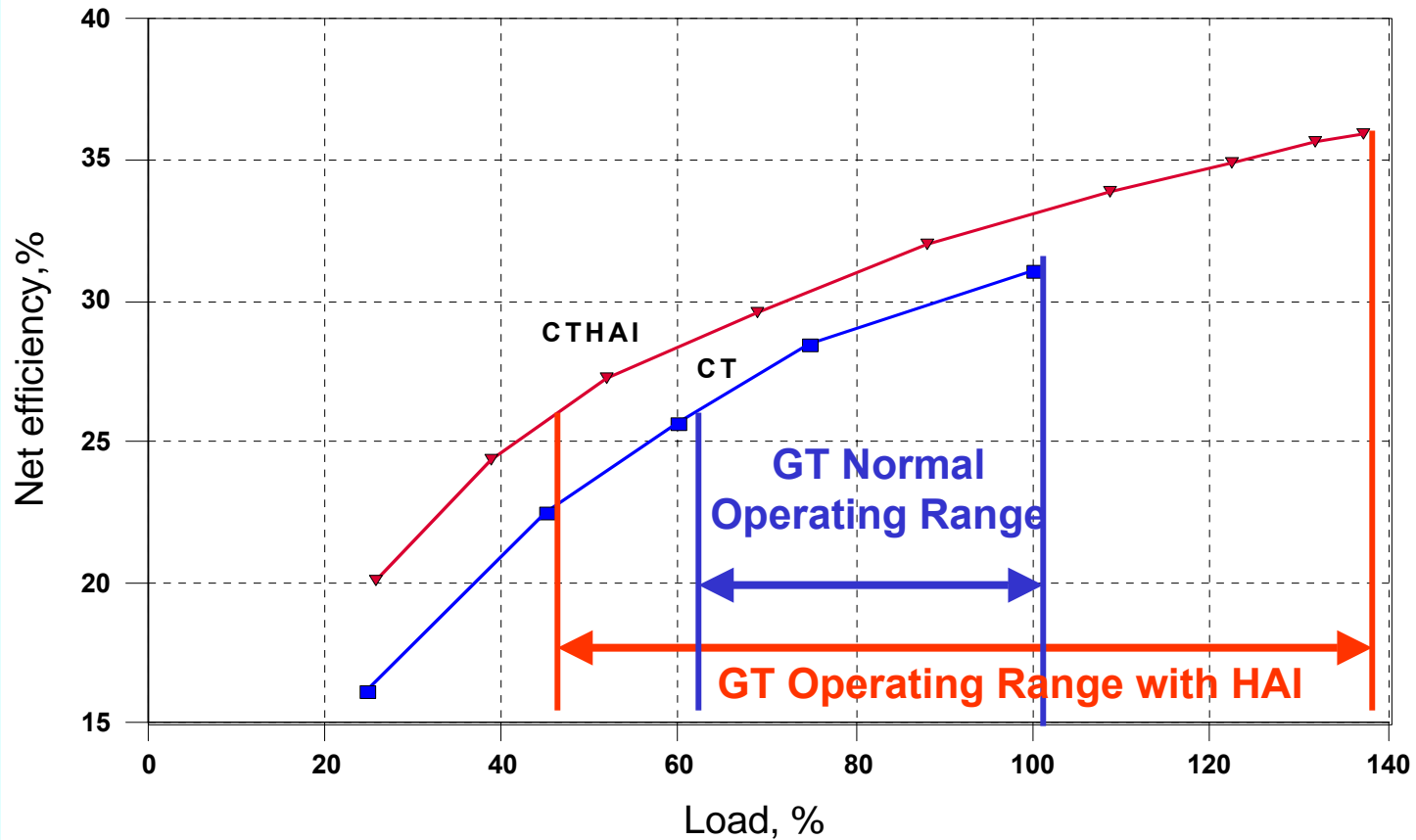
NO_x Emissions Tests with Humid Air Injection



Actual tests of combustors operating with humid air demonstrated significant NO_x reductions from 75 ppmv for dry to single digits for humid air operations. Reference: Combustion Studies of Natural Gas and Syn-Gas with Humid Air, EPRI 1994, TR-103382

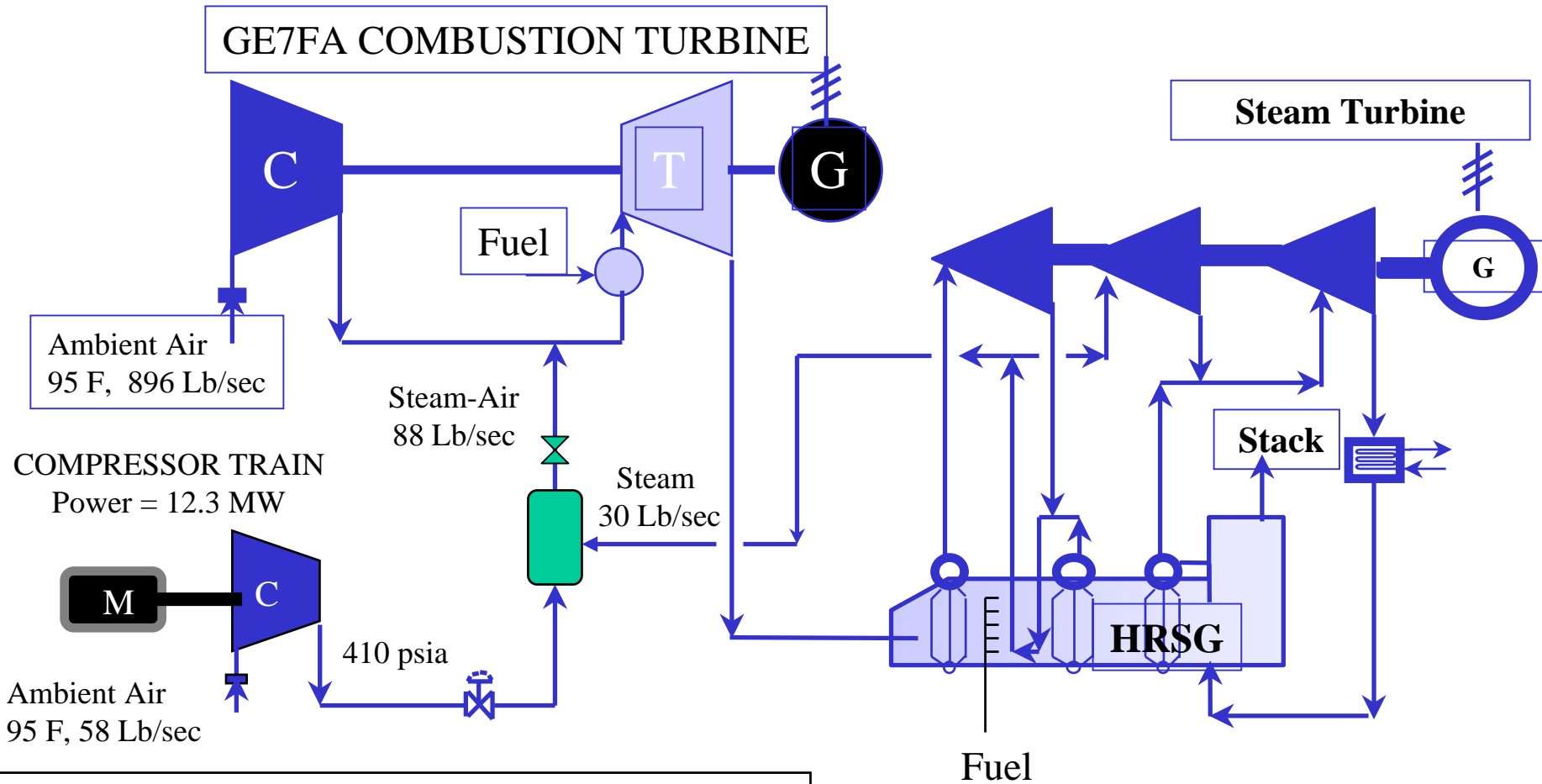
Part Load Performance

GE7EA at 95 F with Humid Air Injection



Humid Air Injection expands gas turbine operating range (max and min power), and improves efficiency (heat rate) over the entire range.

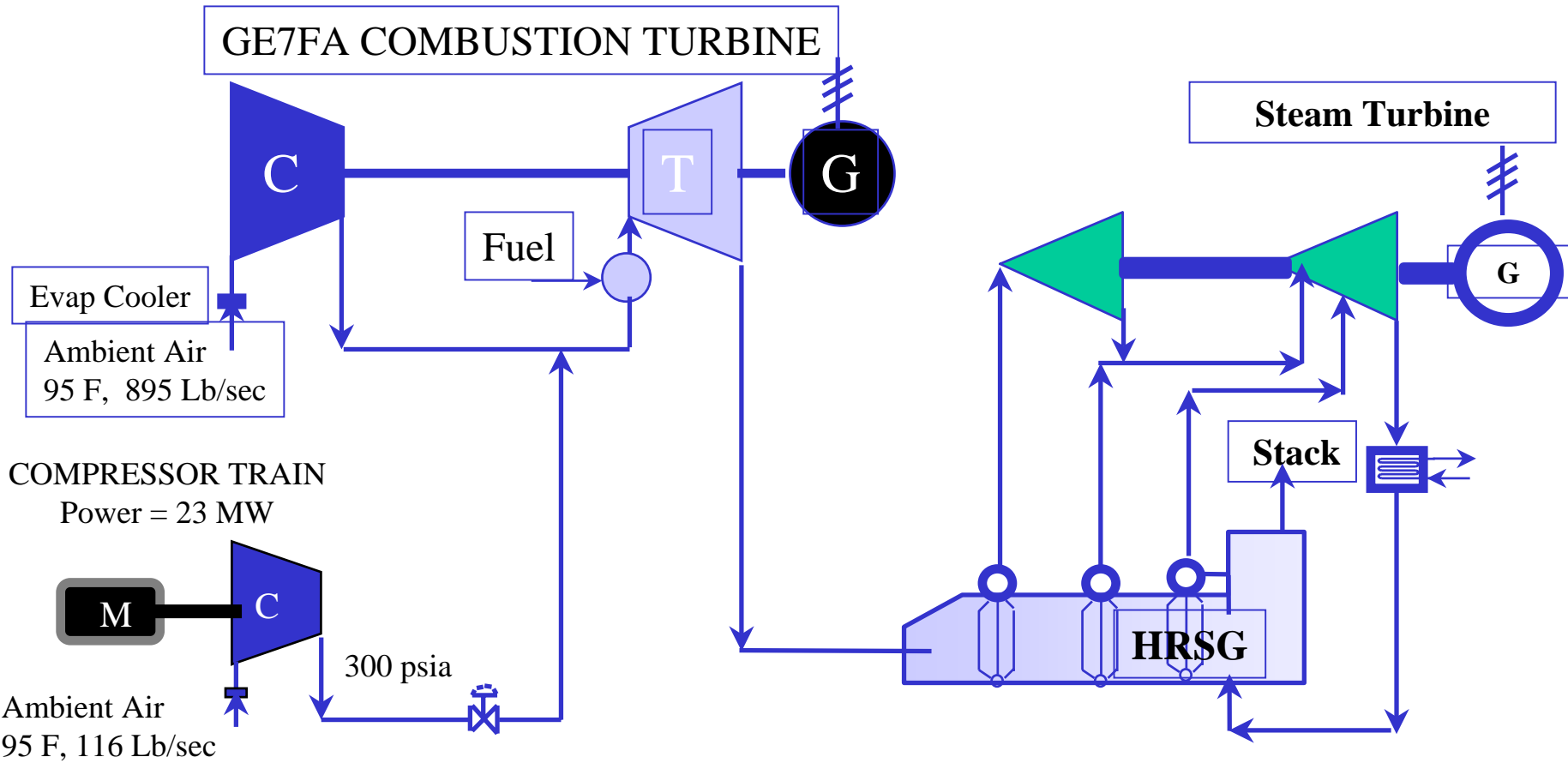
Combined Cycle Humid Air Injection



ESTIMATED PERFORMANCE AT 95 F:

	<u>CC</u>	<u>CC-HAI</u>
NET POWER, MW	243.7	273.0
INCREMENTAL POWER, MW	0	29.3
NET HEAT RATE, Btu/kWh	6,245	6,360

Combined Cycle Dry Air Injection



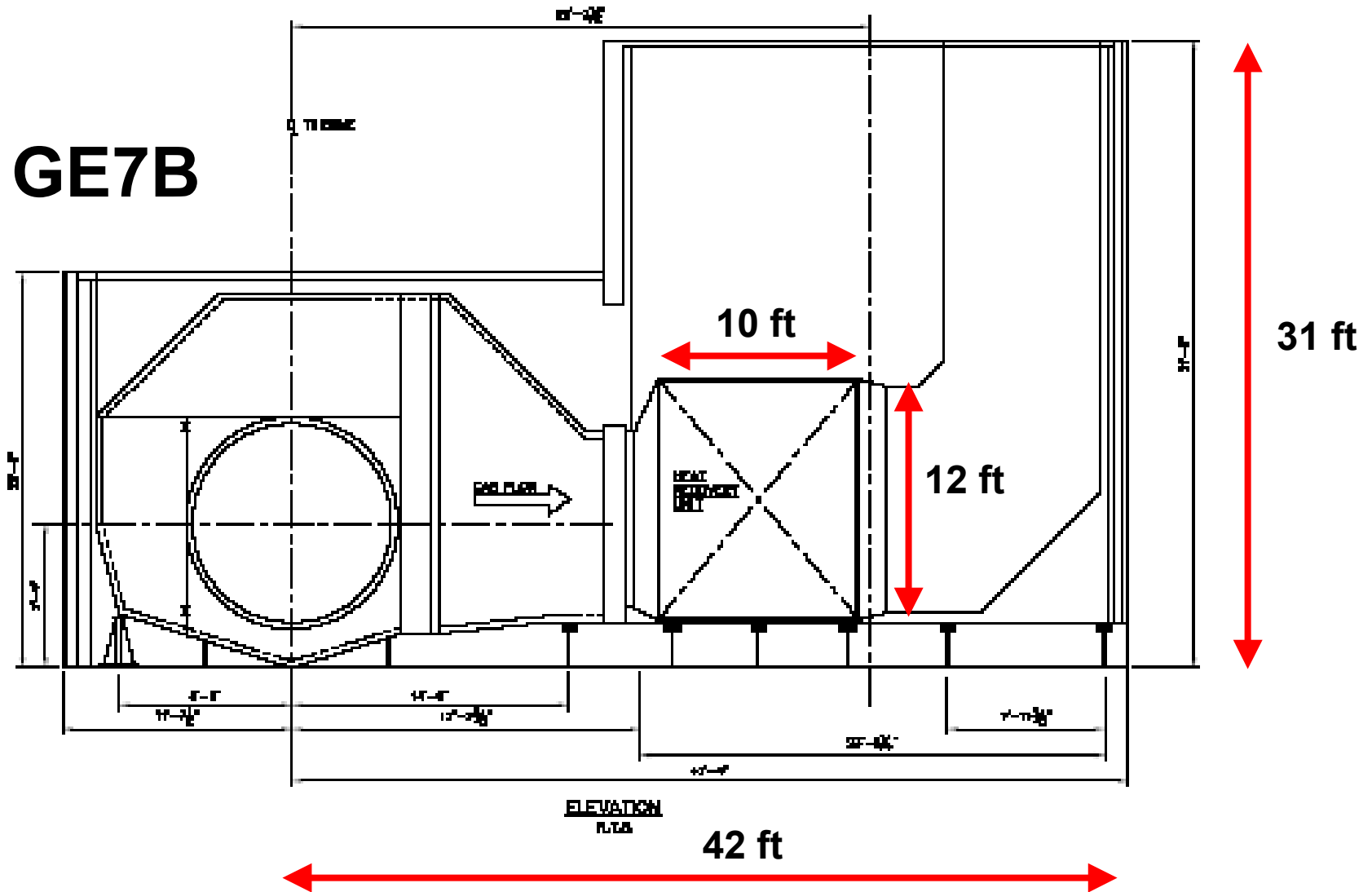
ESTIMATED PERFORMANCE AT 95 F:

	<u>CC</u>	<u>CC-DAI</u>
NET POWER, MW	243.7	263.0
INCREMENTAL POWER, MW	0	19.3
NET HEAT RATE, Btu/kWh	6,245	6,420

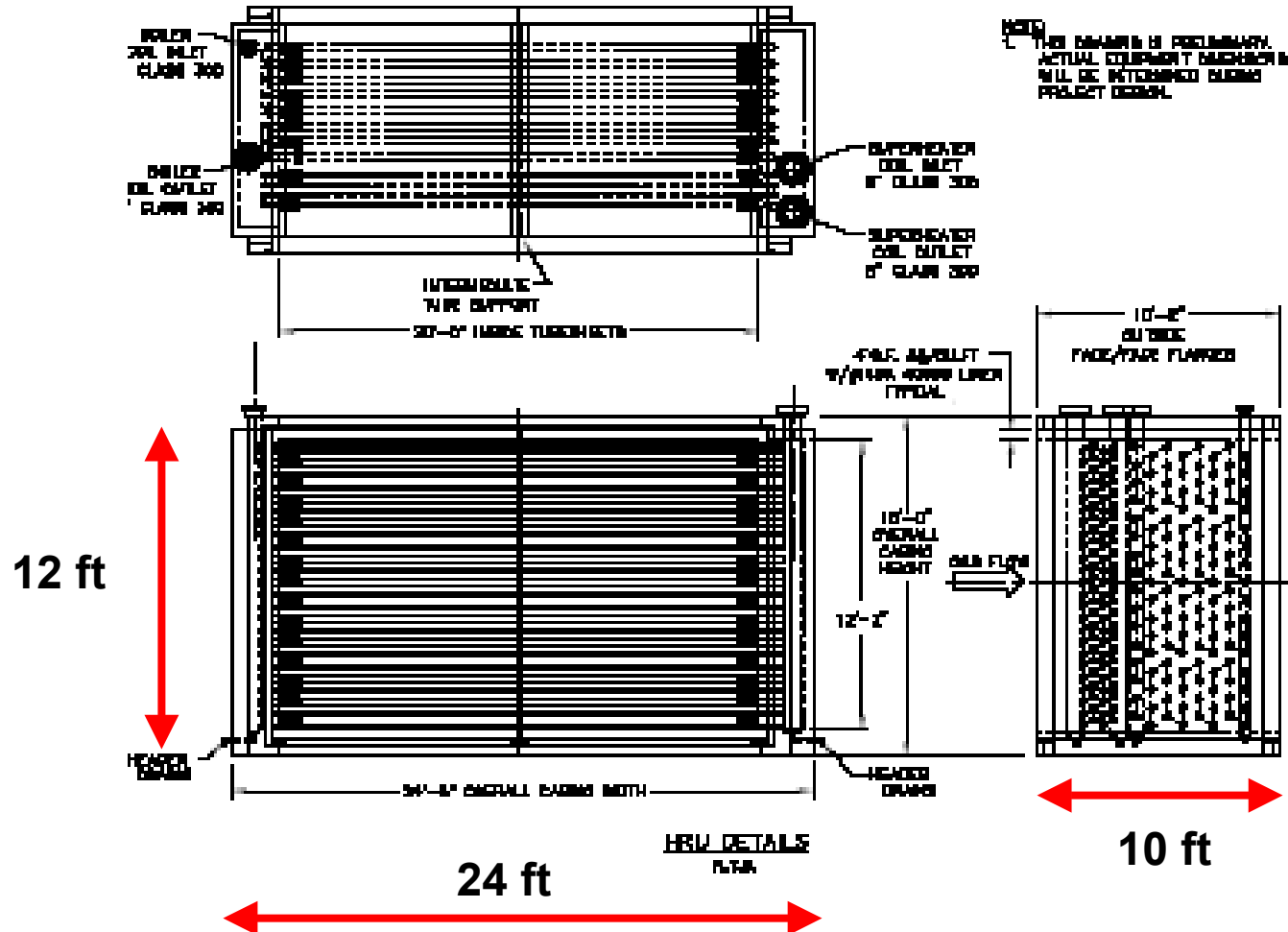
Off-The-Shelf Technology

- Most gas turbines already have injection port at compressor discharge
- Auxiliary compressor is standard product from Cooper Turbocompressor or Ingersoll Rand
- Once-Through-Steam-Generators have been installed at 1200 sites by Struthers-Wells
- Superheater, separator, deaerator and feed pump are standard equipment
- High blowdown (20%) from separator allows use of softened water; no need for demineralized water
- Calpine Corp. tested humid air injection on GE 7FA engine at Broad River; three months from contract signing to running tests. Tests confirm predicted power augmentation and heat rate improvement.

Humid Air Injection – Heat Recovery Unit (OTPSB)



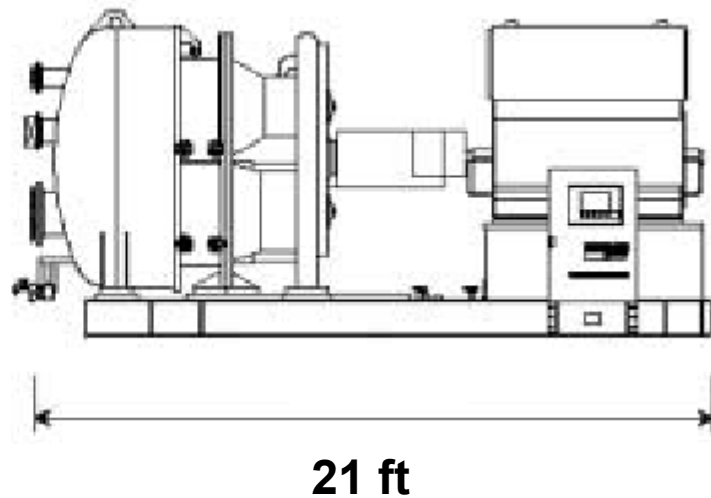
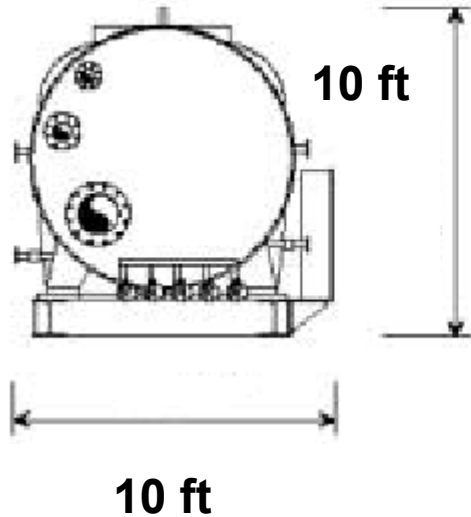
Humid Air Injection – Heat Recovery Unit (OTPSB)



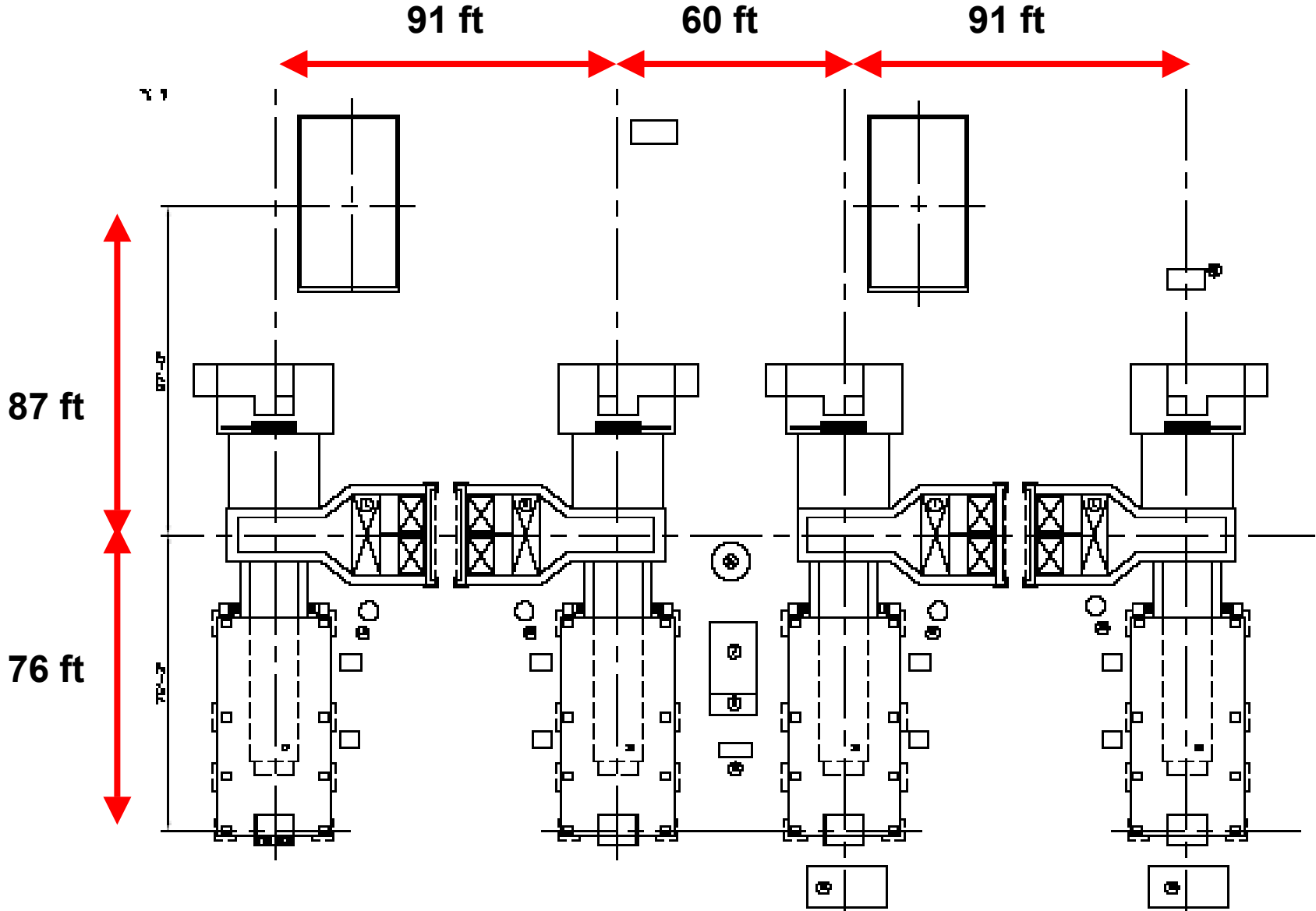
Humid Air Injection – Compressor Train (Coopers, IR)



- Centrifugal Air Compressor
- 5000 hp, 4160 volt
- 17.34 lb/s , 350 psig



Humid Air Injection – System Plan (4 x GE7B)



NOTE

HAI Investment for GE7FA

(Power & Heat Rate from Calpine Broad River Tests)

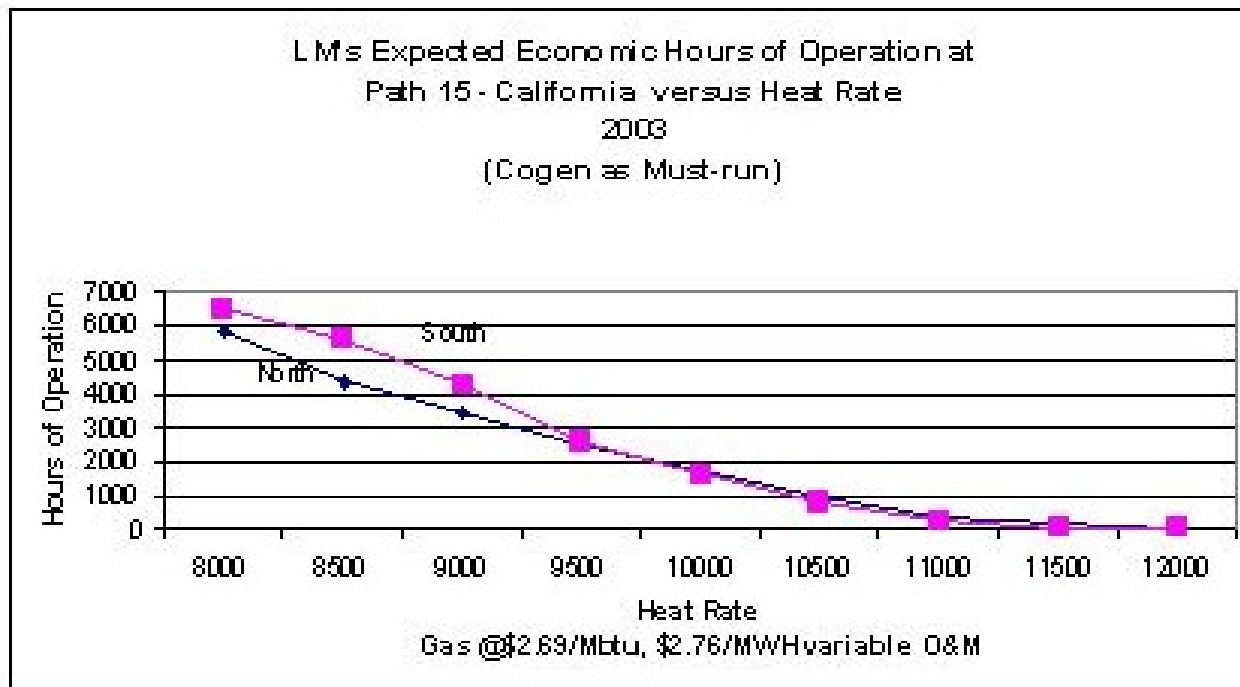
Economic Evaluation of HAI for GE7FA Gas Turbine (Simple-Cycle)

Inputs are in red.

HAI POWER AUGMENTATION ECONOMIC ANALYSIS

	GE7FA	GT with HAI	HAI Upgrade
Power (MW)	150	168	18
Heat Rate (Btu/kWhr LHV)	9800	9460	-340
Hours of Operation per Year (data from chart)	500	1000	500
Capital Cost (\$/kW)	\$400.00	\$378.57	\$200.00
Electric Sales Price (\$/MWhr)	\$90.00	\$90.00	-
Fuel Cost (\$/mmBtu LHV)	\$5.00	\$5.00	-
Yearly Fixed O&M Cost (\$/kW)	\$1.00	\$1.00	-
Variable O&M Cost (\$/MWhr)	\$3.00	\$3.00	-
Operational Fuel Cost [HeatRate*FuelPrice] (\$/MWhr)	\$49.00	\$47.30	-
Spark Spread [ElectricPrice-OperationalFuelCost] (\$/MWhr)	\$41.00	\$42.70	
Yearly Revenues [ElectricPrice*Hours*Power]	\$6,750,000.00	\$15,120,000.00	\$8,370,000.00
Yearly Fuel Cost [OperationalFuelCost*Hours*Power]	\$3,675,000.00	\$7,946,400.00	\$4,271,400.00
Yearly O&M Cost [FixedO&M*kW + VariableO&M*MW*Hours]	\$375,000.00	\$672,000.00	\$297,000.00
Operational Net Income [Revenues-FuelCosts-O&M]	\$2,700,000.00	\$6,501,600.00	\$3,801,600.00
Cost to Install	\$60,000,000.00	\$63,600,000.00	\$3,600,000.00
Payback Period (Years)	22.22	9.78	0.95

Improved Heat Rate Leads to More Hours of Operation



DAI for Combined-Cycle Plants

Economic Evaluation of DAI for Peak-Price Operation of Combined-Cycle Plant

Inputs are in red.

HAI POWER AUGMENTATION ECONOMIC ANALYSIS

	Plant	Plant with DAI	DAI Upgrade
Power (MW)	500	560	60
Heat Rate (Btu/kWhr LHV)	6500	6600	100
Hours of Operation per Year (data from chart)	1100	1100	0
Capital Cost (\$/kW)	\$700.00	\$641.07	\$150.00
Electric Sales Price (\$/MWhr)	\$90.00	\$90.00	-
Fuel Cost (\$/mmBtu LHV)	\$5.00	\$5.00	-
Yearly Fixed O&M Cost (\$/kW)	\$1.00	\$1.00	-
Variable O&M Cost (\$/MWhr)	\$3.00	\$3.00	-
Operational Fuel Cost [HeatRate*FuelPrice] (\$/MWhr)	\$32.50	\$33.00	-
Yearly Revenues [ElectricPrice*Hours*Power]	\$49,500,000.00	\$55,440,000.00	\$5,940,000.00
Yearly Fuel Cost [OperationalFuelCost*Hours*Power]	\$17,875,000.00	\$20,328,000.00	\$2,453,000.00
Yearly O&M Cost [FixedO&M*kW + VariableO&M*MW*Hours]	\$2,150,000.00	\$2,408,000.00	\$258,000.00
Operational Net Income [Revenues-FuelCosts-O&M]	\$29,475,000.00	\$32,704,000.00	\$3,229,000.00
Cost to Install	\$350,000,000.00	\$359,000,000.00	\$9,000,000.00
Payback Period (Years)	11.87	10.98	2.79

HAI Offers Fast Payback for Peakers

Economic Evaluation of HAI for FT4 Gas Turbine

Inputs are in red.

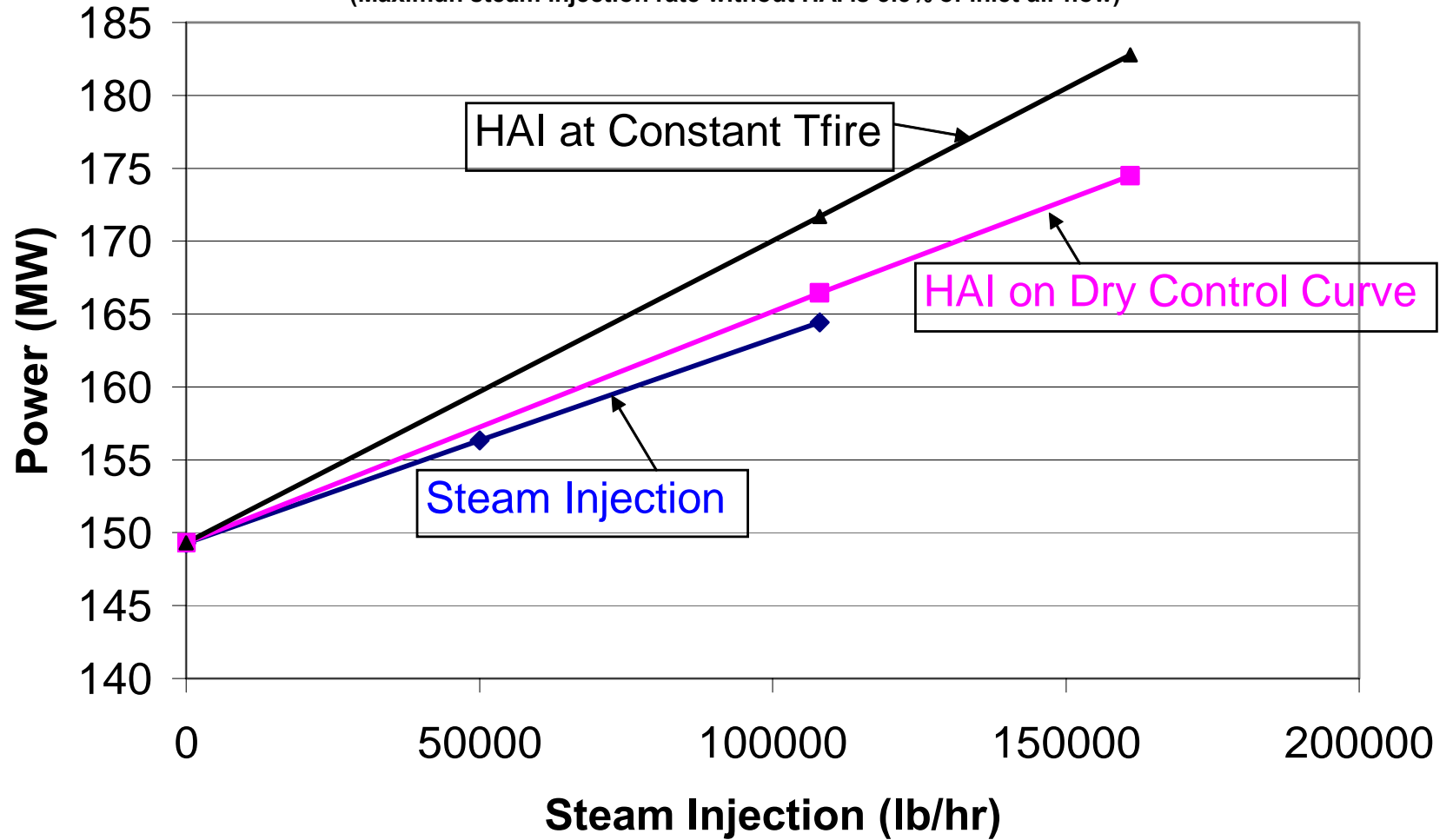
HAI POWER AUGMENTATION ECONOMIC ANALYSIS

	FT4	FT4 with HAI	HAI
Power (MW)	27.7	40	12.3
Heat Rate (Btu/kWhr LHV)	11800	9600	-2,200
Hours of Operation per Year	200	2000	1,800
Capital Cost (\$/kW)	\$400.00	\$338.50	\$200.00
Electric Sales Price (\$/MWhr)	\$90.00	\$90.00	-
Fuel Cost (\$/mmBtu LHV)	\$5.00	\$5.00	-
Yearly Fixed O&M Cost (\$/kW)	\$1.00	\$1.00	-
Variable O&M Cost (\$/MWhr)	\$3.00	\$3.00	-
Operational Fuel Cost [HeatRate*FuelPrice] (\$/MWhr)	\$59.00	\$48.00	-
Yearly Revenues [ElectricPrice*Hours*Power]	\$498,600.00	\$7,200,000.00	\$6,701,400.00
Yearly Fuel Cost [OperationalFuelCost*Hours*Power]	\$326,860.00	\$3,840,000.00	\$3,513,140.00
Yearly O&M Cost [FixedO&M*kW + VariableO&M*MW*Hours]	\$44,320.00	\$280,000.00	\$235,680.00
Operational Net Income [Revenues-FuelCosts-O&M]	\$127,420.00	\$3,080,000.00	\$2,952,580.00
Cost to Install	\$11,080,000.00	\$13,540,000.00	\$2,460,000.00
Payback Period (Years)	86.96	4.40	0.83

GE7FA Power vs Steam Injection Rate

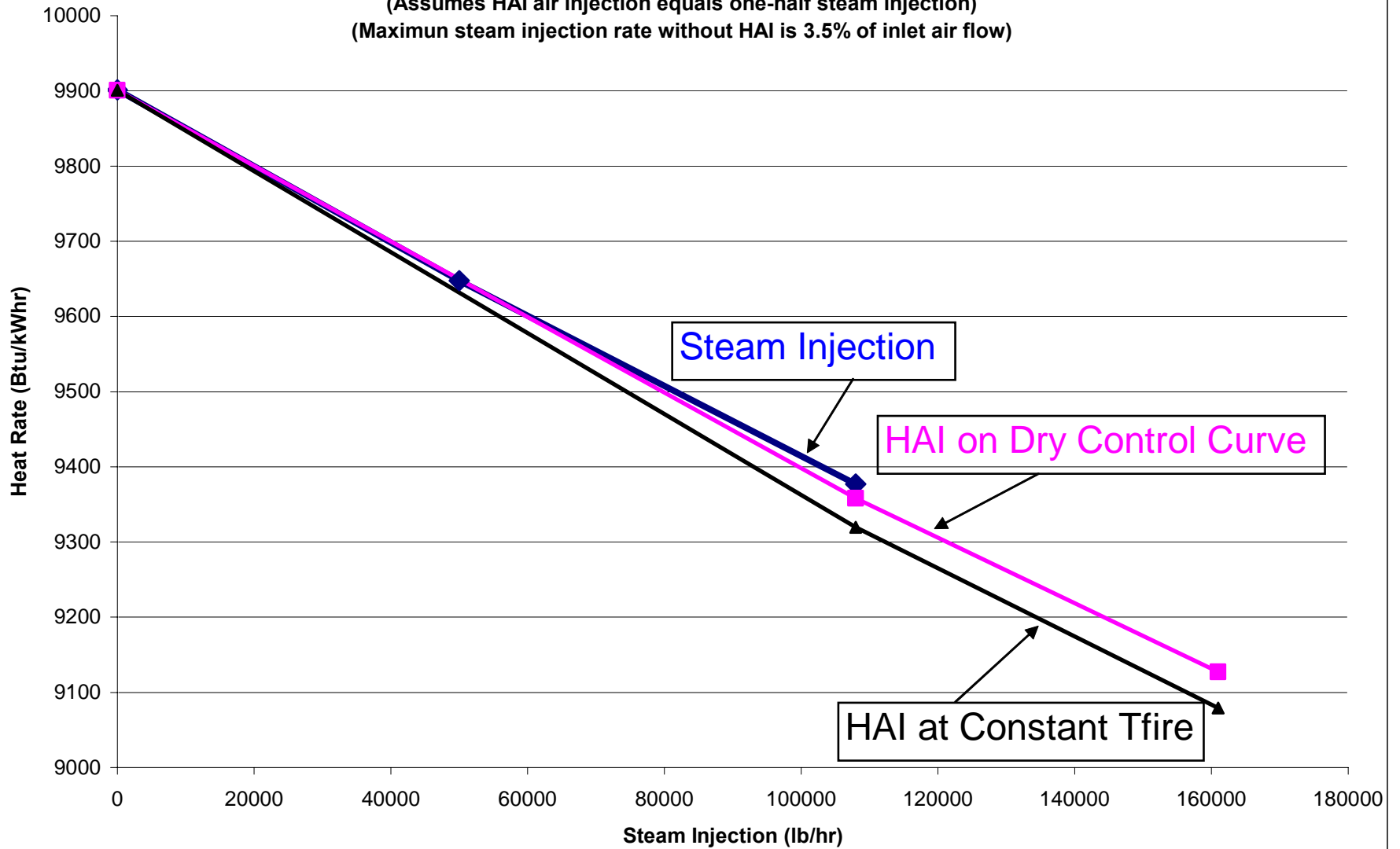
(Assumes HAI air injection equals one-half steam injection)

(Maximum steam injection rate without HAI is 3.5% of inlet air flow)

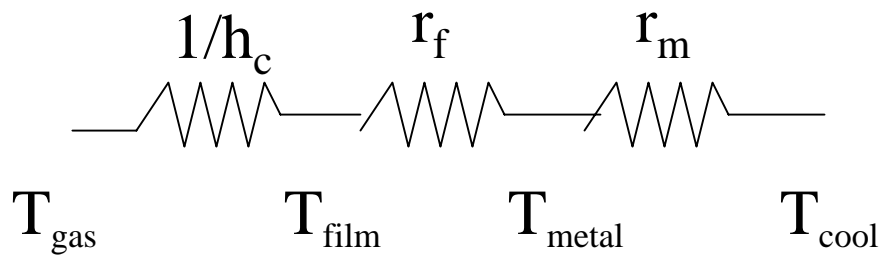
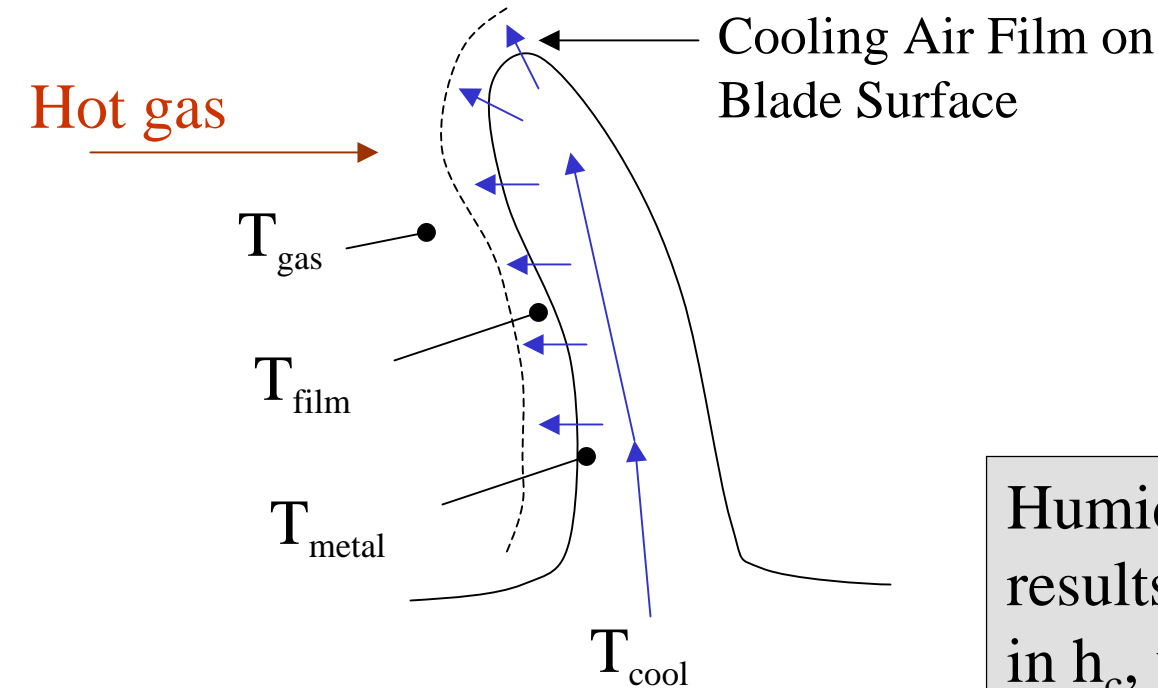


GE7FA Heat Rate vs Steam Injection

(Assumes HAI air injection equals one-half steam injection)
(Maximum steam injection rate without HAI is 3.5% of inlet air flow)

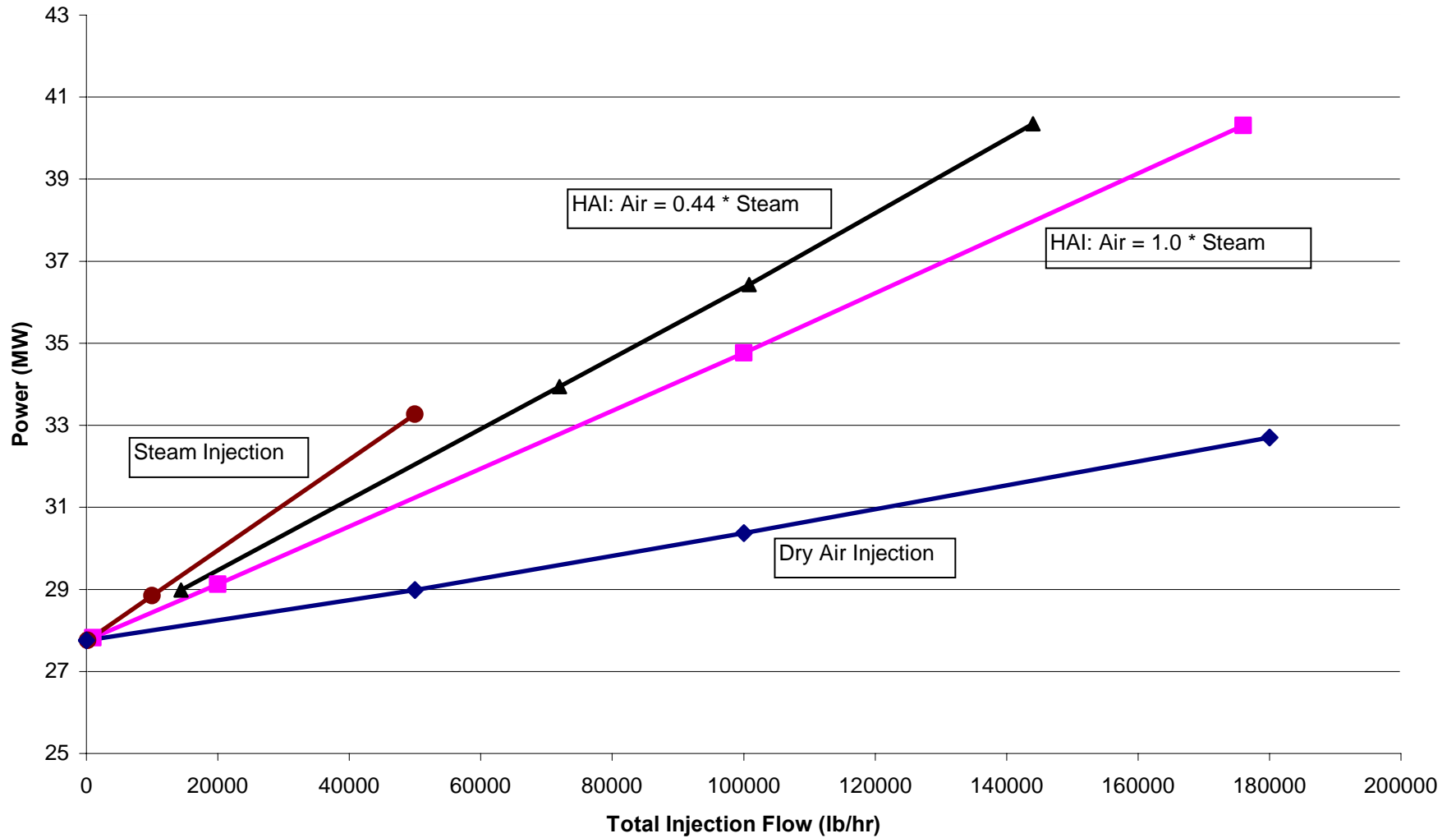


Blade Cooling Temperatures



Humid Air Injection results in an increase in h_c , which depends upon gas velocity; but, T_{metal} does not increase very much because r_f is larger than $1/h_c$.

FT4 Power vs Total Steam/Air Injection
(Maximum Steam Injection is 5% of Inlet Air Flow)



FT4 Heat Rate vs HAI Injection Rate
(Maximum Steam Injection is 5% of Inlet Air Flow)

