Overview of Gas Turbine Performance Testing: Preparation, Measurements, Corrections, & Uncertainty Analysis

CleanAir Engineering

March, 2018

Why Do Performance Testing?

- Acceptance Testing
  - Compliance with Guarantees
    - New Units
    - Uprates
- Benchmark Testing
  - Performance Monitoring
  - Power Purchase Agreements
- Performance Parameters
  - Corrected Power Output
  - Corrected Heat Rate
  - Corrected Exhaust Temperature
  - Corrected Exhaust Flow

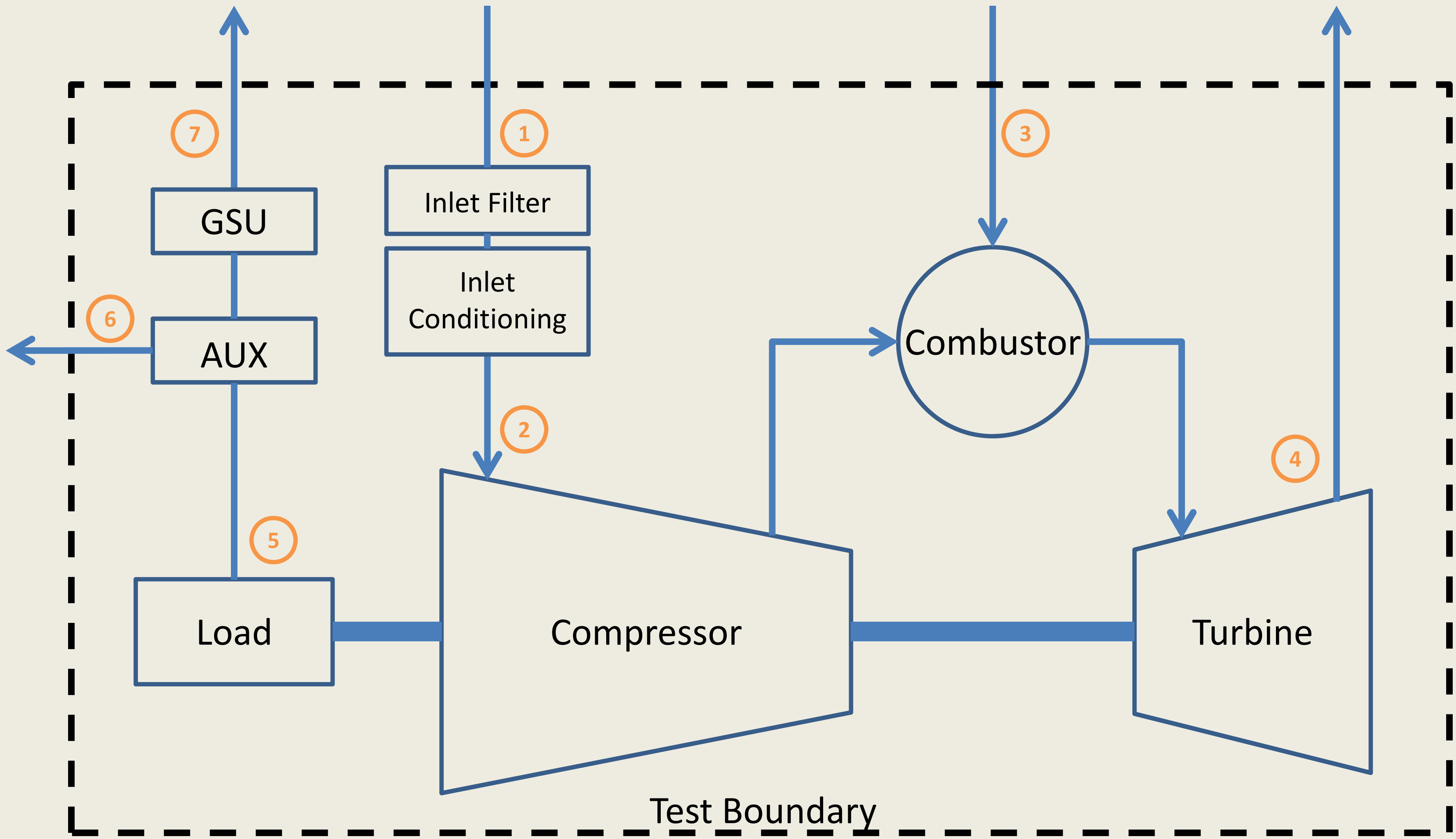
CleanAir PERFORMANCE GROUP

Preparing for a Performance Test

- Site specific Test Plan
  - Outlines specific test objectives
  - Helps with communication and coordination
- Site Preparation
  - Are you using plant instrumentation to collect test data?
    - Ensure proper instrument function and calibration
  - Offline Water Wash

CleanAir PERFORMANCE GROUP

Test Measurement Schematic



CleanAir PERFORMANCE GROUP

Test Measurement Description

#	Measurement	Purpose of Measurement	Uncertainty*
1	Ambient Air Pressure	Stability & primary correction parameter	0.075%
1	Ambient Air Temperature	Stability & primary correction parameter	1ºF
1	Ambient Air Humidity	Primary correction parameter	2.0%
2	Inlet Pressure Loss	Primary correction parameter	10%
2	Compressor Inlet Temp.	Unit control & alternate correction parameter to ambient temperature	1ºF
3	Gas Fuel Pressure	Stability & possibly calculation of fuel flow	N/A
3	Gas Fuel Temperature	Primary correction parameter & possibly calculation of fuel flow	3ºF
3	Gas Fuel Flow	Stability & calculation of corrected heat rate	0.75% Fuel Heat Input
3	Gas Fuel Heating Value	Primary correction parameter and calculation of corrected heat rate	

* Maximum allowable measurement uncertainties per Table 4-1.2.1-1 of ASME PTC 22-2014

CleanAir PERFORMANCE GROUP

Test Measurement Description

#	Measurement	Purpose of Measurement	Uncertainty*
4	Exhaust Pressure Drop	Primary correction parameter	10%
4	Exhaust Temperature	Unit control & heat balance	10ºF
4	Emissions (CO, NO_x, O_2)	Demonstration of emissions compliance during testing	N/A
5	Gross Power Output	Stability & calculation of corrected power	0.25%
5	Generator Power Factor	Primary correction parameter	N/A
5	Grid Frequency	Primary correction parameter	0.1%
6	Auxiliary Loads	Calculation of corrected power (if power guarantee is on high side of GSU)	5%
7	Net Power Output	Calculation of corrected power (if power guarantee is on high side of GSU)	0.25%

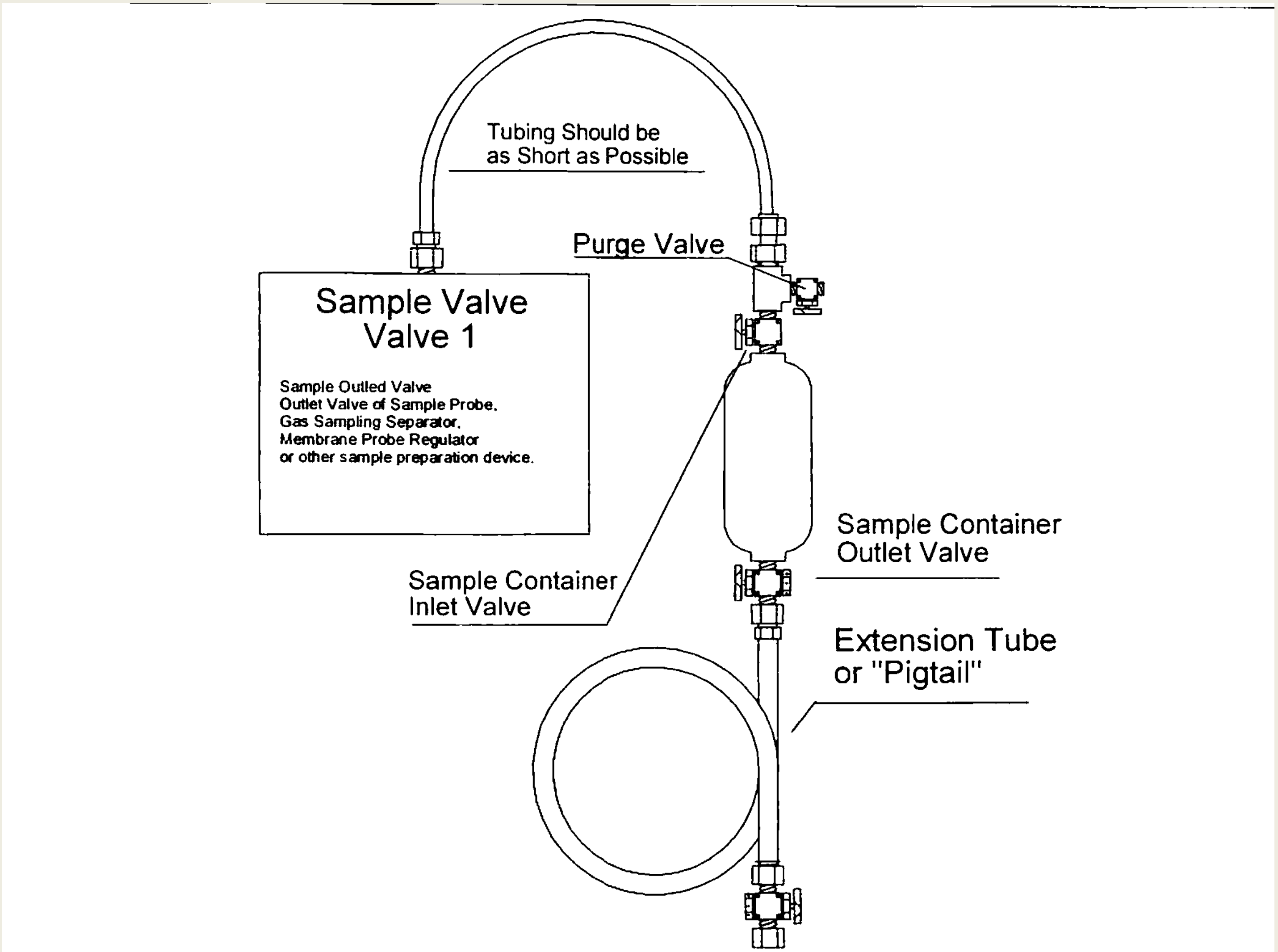
* Maximum allowable measurement uncertainties per Table 4-1.2.1-1 of ASME PTC 22-2014

Test Measurements

- Automated data collection
  - Temperatures, pressures, fuel flow, power, etc.
- Manually Recorded Data
- Fuel Sampling

CleanAir®
PERFORMANCE GROUP

Fuel Sampling Apparatus



CleanAir PERFORMANCE GROUP

Test Execution Considerations

- Weather Conditions
  - Get close to design conditions if possible
- Test Duration
  - 30 minute test period
  - Three test runs are recommended
    - Test code requires one test run
- Coordination and Support
  - Required personnel on hand
    - Additional ops support or maintenance support if needed

CleanAir PERFORMANCE GROUP

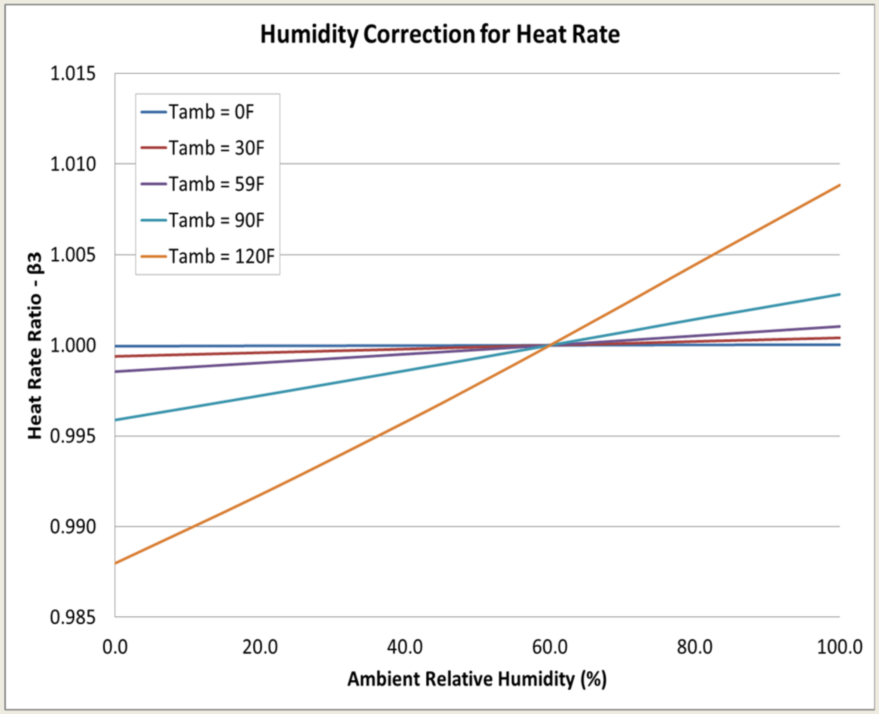
Data Processing

- Measurement Corrections
  - Correction curves
  - Design conditions
- Measurement Uncertainty
- Sensitivity Analysis
  - Measurement impact on overall test uncertainty

Test Measurement Corrections

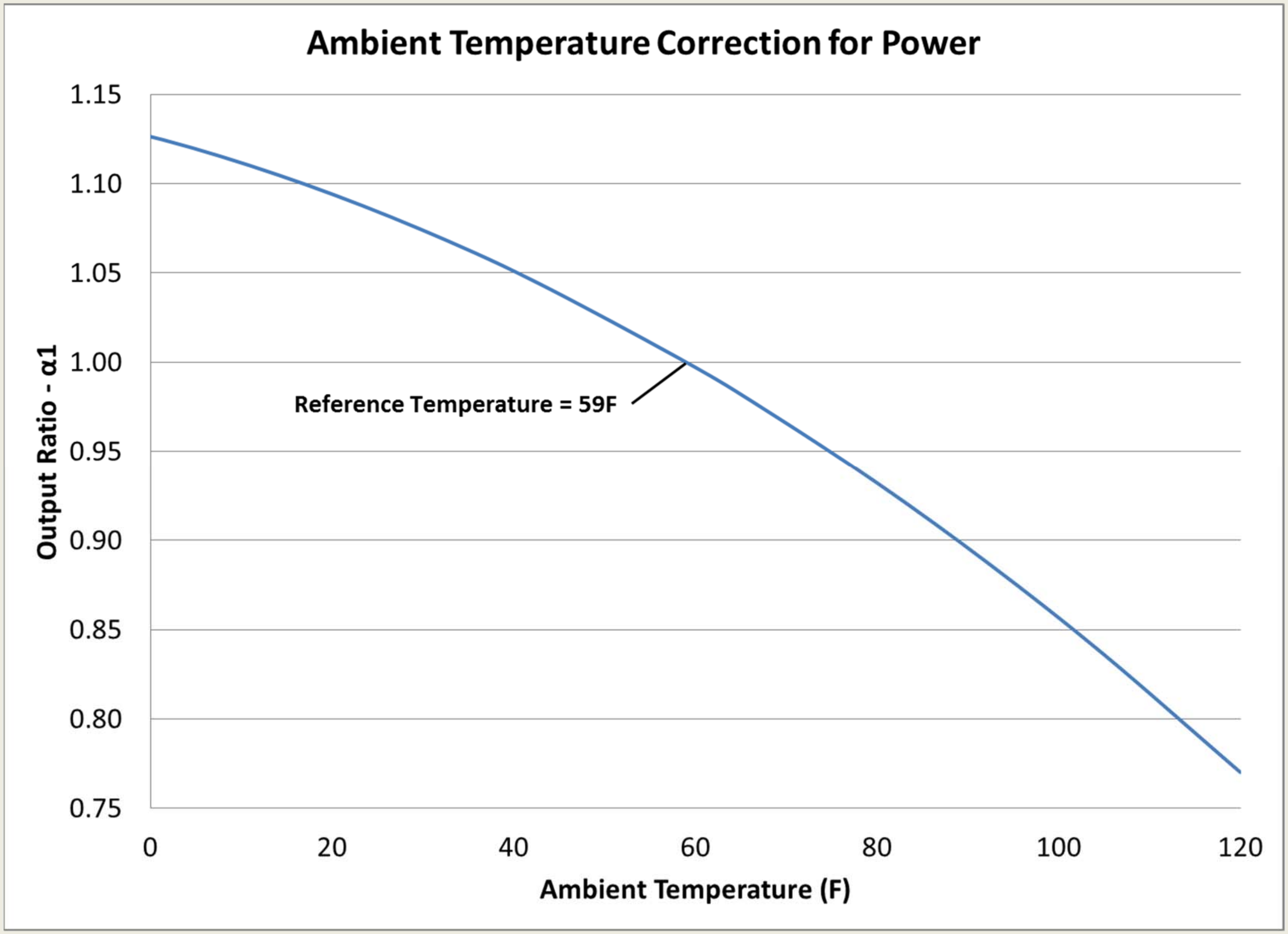
- Correction curves or models are generally used to correct as-tested performance to a set of reference conditions

- Common corrections include
  - Ambient (Inlet) Temperature
  - Barometric Pressure
  - Ambient (Inlet) Humidity
  - Fuel Composition
  - Exhaust Pressure Loss
  - Shaft Speed
  - Fuel Temperature
  - Inlet Pressure Loss
  - Generator Power Factor



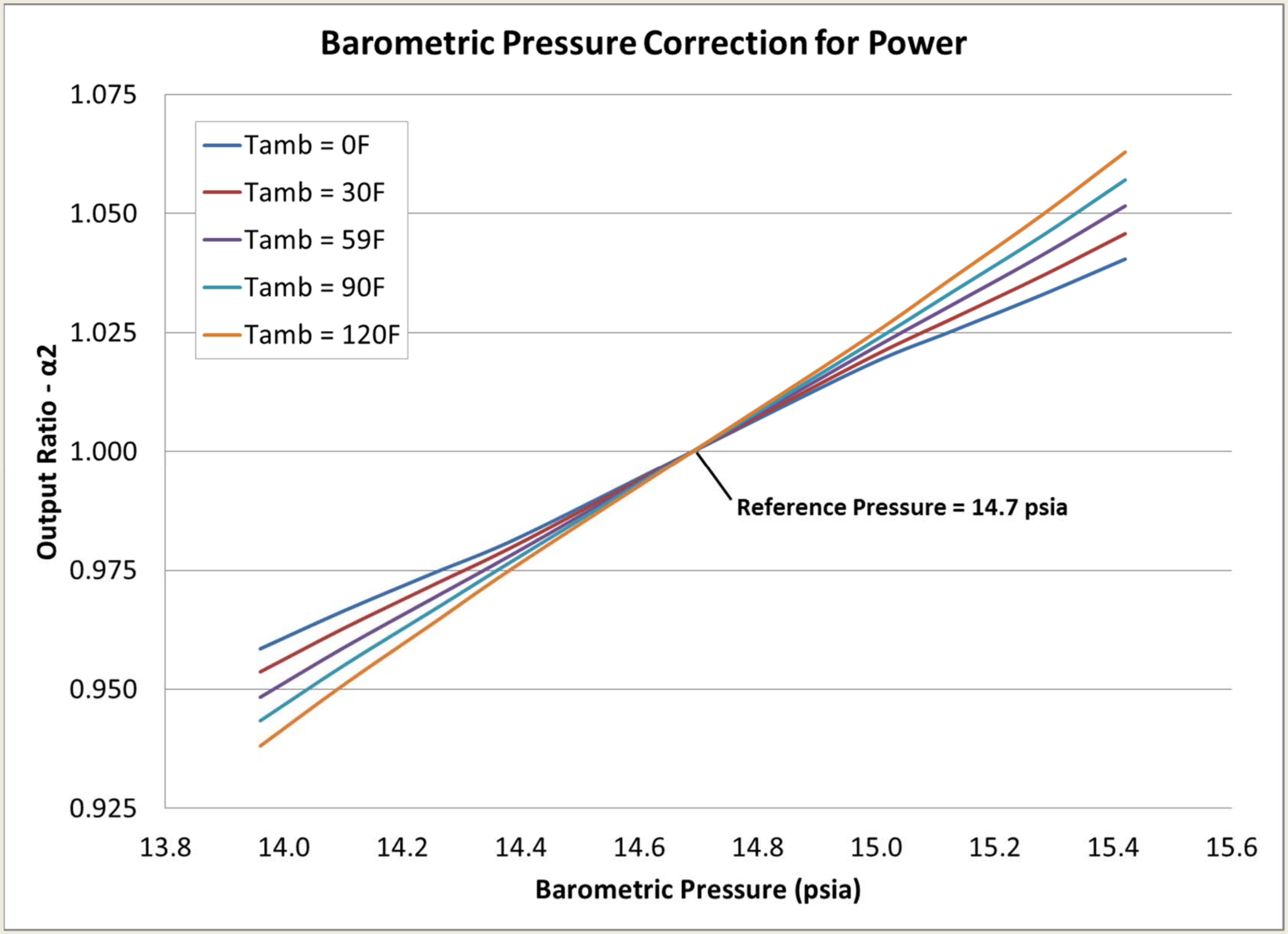
CleanAir
PERFORMANCE GROUP

Example Correction Curve



CleanAir PERFORMANCE GROUP

Example Correction Curve



CleanAir PERFORMANCE GROUP

Applying Corrections - Power

- Generally, corrected power is calculated per ASME PTC 22-2014, Section 5-4 as:

$$P_{corr} = \frac{P_{meas} + \sum_{i=1}^{m} \Delta i}{\prod_{n=1}^{K} \alpha_n}$$

Where

P_{meas} = measured generator power

Δi = additive correction factors

α_n = multiplicative power correction factors

  – Form of correction may differ depending on test procedure and correction curves

CleanAir PERFORMANCE GROUP

Applying Corrections – Heat Rate

- Generally, corrected heat rate is calculated per ASME PTC 22-2014, Section 5-4 as:

$$HR_{corr} = \left(\frac{1}{\prod_{n=1}^{K} \beta_n}\right) \frac{HI_{meas}}{P_{meas} + \sum_{i=1}^{m} \Delta i}$$

Where

HI_{meas} = measured heat input

Δi = additive correction factors

β_n = multiplicative heat rate correction factors

  – Form of correction may differ depending on test procedure and correction curves

CleanAir PERFORMANCE GROUP

Uncertainty Analysis

- Pre-test uncertainty analysis helps identify critical measurements and ensures instrumentation and test design meets overall test uncertainty targets.
- Post-test uncertainty analysis determines actual uncertainty in corrected results based on collected data and test operating conditions.
- ASME PTC 19.1 and ASME PTC 22 are guiding documents for gas turbine uncertainty analysis

CleanAir
PERFORMANCE GROUP

Components of Measurement Uncertainty

- The combined expanded uncertainty (95% confidence) of a measurement is expressed in equation 6-4.3 of PTC 19.1-2013 as:

$$U_{\bar{x}} = 2\sqrt{(b_{\bar{x}})^2 + (s_{\bar{x}})^2}$$

Where

$b_{\bar{x}}$ = systematic standard uncertainty

$s_{\bar{x}}$ = random standard uncertainty

CleanAir
PERFORMANCE GROUP

Components of Measurement Uncertainty

- Systematic uncertainty is constant in a given data set and is the result of all elemental systematic errors
  - Instrument/calibration accuracy, spatial variation, etc.
  - Determined using published information or engineering judgement
- Random uncertainty is a result of the variability or scatter in a given data set caused by elemental random errors
  - Determined statistically from parameter data set
  - May also be determined from result of multiple test runs

CleanAir
PERFORMANCE GROUP

Sensitivity Analysis

- The sensitivity of each measured parameter on the final result must be determined to allow for the calculation of test uncertainty
- Sensitivity coefficient determined by either:
  - Partial derivative
    - Exact but potentially complex

$$\theta_i = \frac{\partial R}{\partial X_i}$$

  - Numerical perturbation
    - Approximate but efficient

$$\theta_i = \frac{\Delta R}{\Delta X_i}$$

CleanAir PERFORMANCE GROUP

Example Sensitivity Analysis

Corrected Power and Heat Rate Sensitivity Summary										
Measured Parameter	Units	Base Test Value	Parameter Change	Corrected Power (kW)		Power Sensitivity	Corrected Heat Rate (Btu/kWhr)		Heat Rate Sensitivity
			ΔP	+	-	ΔkW/2ΔP	+	-	ΔHR/2ΔP
Generator Output	kW	24,500	250	24,750	24,250	1.00	10,220	10,420	-0.40
Excitation Loss	kW	250	25.0	24,475	24,525	-1.00	10,310	10,330	-0.40
Ambient Dry Bulb Temperature	Deg F	80.0	1.00	24,740	24,260	240	10,298	10,342	-22.0
Ambient Wet Bulb Temperature	Deg F	65.0	1.00	24,460	24,540	-40.0	10,321	10,319	0.95
Ambient Pressure	psia	14.60	0.01	24,483	24,518	-1,750	10,320	10,320	25.0
LP Turbine Speed	rpm	3,000	3.00	24,491	24,509	-3.00	10,322	10,318	0.55
Generator Power Factor	-	0.999	0.01	24,488	24,513	-2,500	10,321	10,319	140
Inlet Pressure Drop	inwc	4.00	0.10	24,510	24,490	100	10,319	10,322	-15.0
Exhaust Pressure Drop	inwc	12.00	0.10	24,510	24,490	100	10,319	10,322	-15.0
Fuel Higher Heating Value	Btu/lb	22,250	100	24,530	24,470	0.30	10,360	10,280	0.40
Fuel Flow	lb/hr	11,250	100	24,500	24,500	0.00	10,335	10,305	0.15

Perturb each measured parameter by more than the parameter uncertainty

Record corrected parameter result for positive and negative perturbation

Determine sensitivity numerically

CleanAir PERFORMANCE GROUP

Example Uncertainty Analysis

Power uncertainty is product of sensitivity coefficient and parameter uncertainty

Corrected Power Output Uncertainty

Code Instrumentation Uncertainty							
Parameter	Units	Test Value	Power Sensitivity	Parameter Systematic Uncertainty	Power Systematic Uncertainty	Parameter Random Uncertainty	Power Random Uncertainty
Generator Output	kW	24,500	1.00	121	121	5.3	5.3
Excitation Loss	kW	250	-1.00	12.5	12.5	0.19	0.19
Ambient Dry Bulb Temperature	Deg F	80.0	240	1.00	240	0.06	14.4
Ambient Wet Bulb Temperature	Deg F	65.0	-40.0	1.00	40.0	0.03	1.20
Ambient Pressure	psia	14.60	-1,750	0.005	8.8	0.00	1.6
LP Turbine Speed	rpm	3,000	-3.00	3.00	9.0	0.03	0.08
Generator Power Factor	-	0.999	-2,500	0.001	2.50	0.00	0.00
Inlet Pressure Drop	inwc	4.00	100	0.03	2.5	0.00	0.28
Exhaust Pressure Drop	inwc	12.00	100	0.03	2.50	0.01	0.94
Fuel Higher Heating Value	Btu/lb	22,250	0.30	67.7	20.3	67.7	20.3
Fuel Flow	lb/hr	11,250	0.00	84	0.00	2.0	0.00
					273		**26**
				Combined Uncertainty of Result		**274**	**kW**
						1.12	**%**

Sensitivity coefficients from previous analysis

Combined uncertainty is root-sum-square of systematic and random uncertainties

CleanAir®
PERFORMANCE GROUP

Improve Uncertainty with Precision Instrumentation

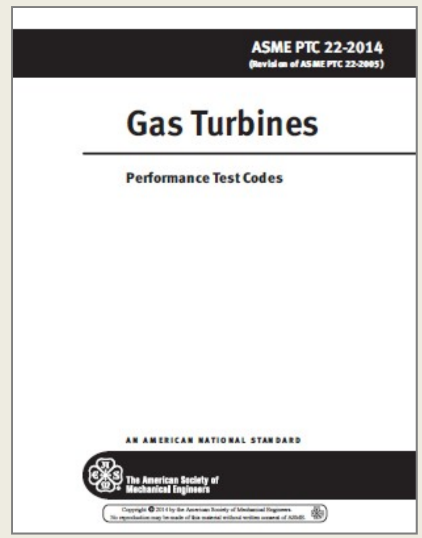
Corrected Power Output Uncertainty							
Precision Instrumentation Uncertainty			Power Sensitivity	Parameter Systematic Uncertainty	Power Systematic Uncertainty	Parameter Random Uncertainty	Power Random Uncertainty
Parameter	Units	Test Value					
Generator Output	kW	24,500	1.00	107	107	5.3	5.3
Excitation Loss	kW	250	-1.00	12.5	12.5	0.19	0.19
Ambient Dry Bulb Temperature	Deg F	80.0	240	0.30	72.0	0.06	14.4
Ambient Wet Bulb Temperature	Deg F	65.0	-40.0	0.30	12.0	0.03	1.20
Ambient Pressure	psia	14.60	-1,750	0.004	6.6	0.00	1.6
LP Turbine Speed	rpm	3,000	-3.00	3.00	9.0	0.03	0.08
Generator Power Factor	-	0.999	-2,500	0.001	2.50	0.00	0.00
Inlet Pressure Drop	inwc	4.00	100	0.02	1.9	0.00	0.28
Exhaust Pressure Drop	inwc	12.00	100	0.02	1.88	0.01	0.94
Fuel Higher Heating Value	Btu/lb	22,250	0.30	67.7	20.3	67.7	20.3
Fuel Flow	lb/hr	11,250	0.00	39	0.00	2.0	0.00
					132		**26**
				Combined Uncertainty of Result		**135**	**kW**
						0.55	**%**

Most reduction in power uncertainty due to precision power meter and ambient temperature instrumentation

CleanAir PERFORMANCE GROUP

Final Thoughts

- This presentation provides an overview of the planning considerations, preparations, measurements, corrections, and uncertainty analysis involved with a gas turbine performance test.
- Refer to latest test codes for additional guidance
  - ASME PTC 22-2014 Gas Turbines
  - ASME PTC 19.1-2013 Uncertainty



CleanAir
PERFORMANCE GROUP

Questions?

Adam Caswell
CleanAir Engineering, Inc.
acaswell@cleanair.com

CleanAir
PERFORMANCE GROUP