Industrial Application of Gas Turbines

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Comparison of Gas Turbine Degradations Employed at Five Natural Gas Compressor Station Sites

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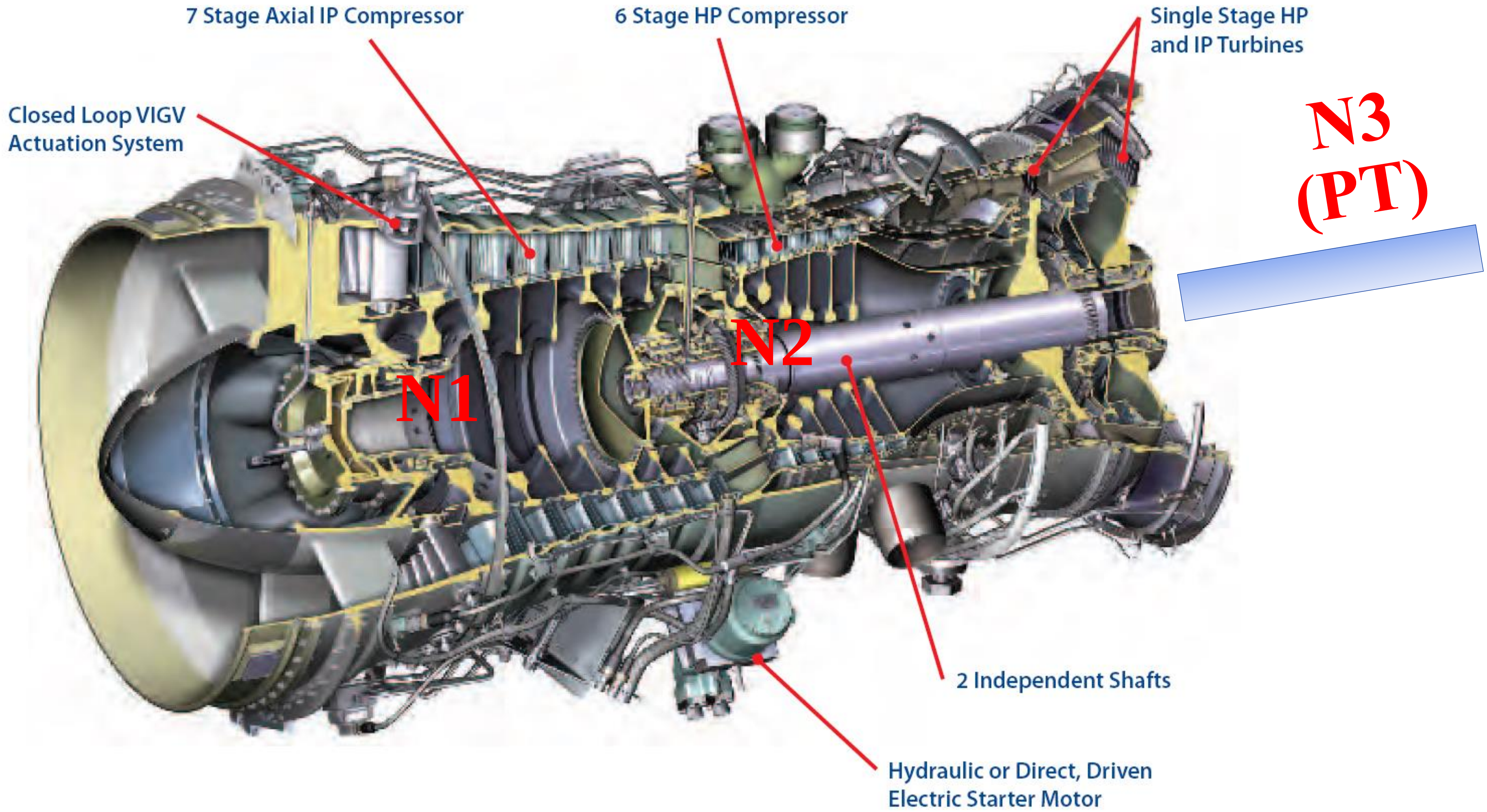
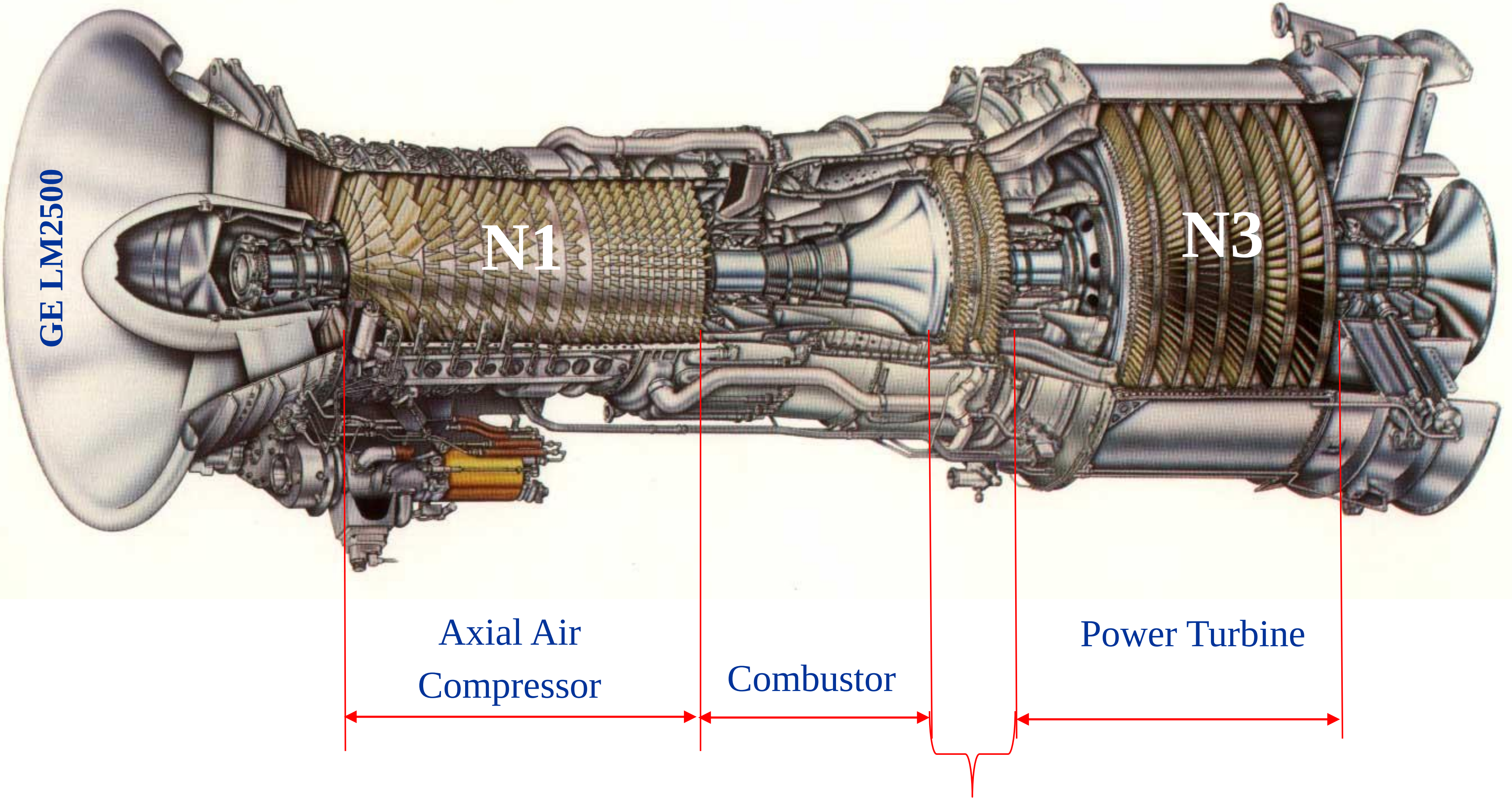
RR-RB211-24G

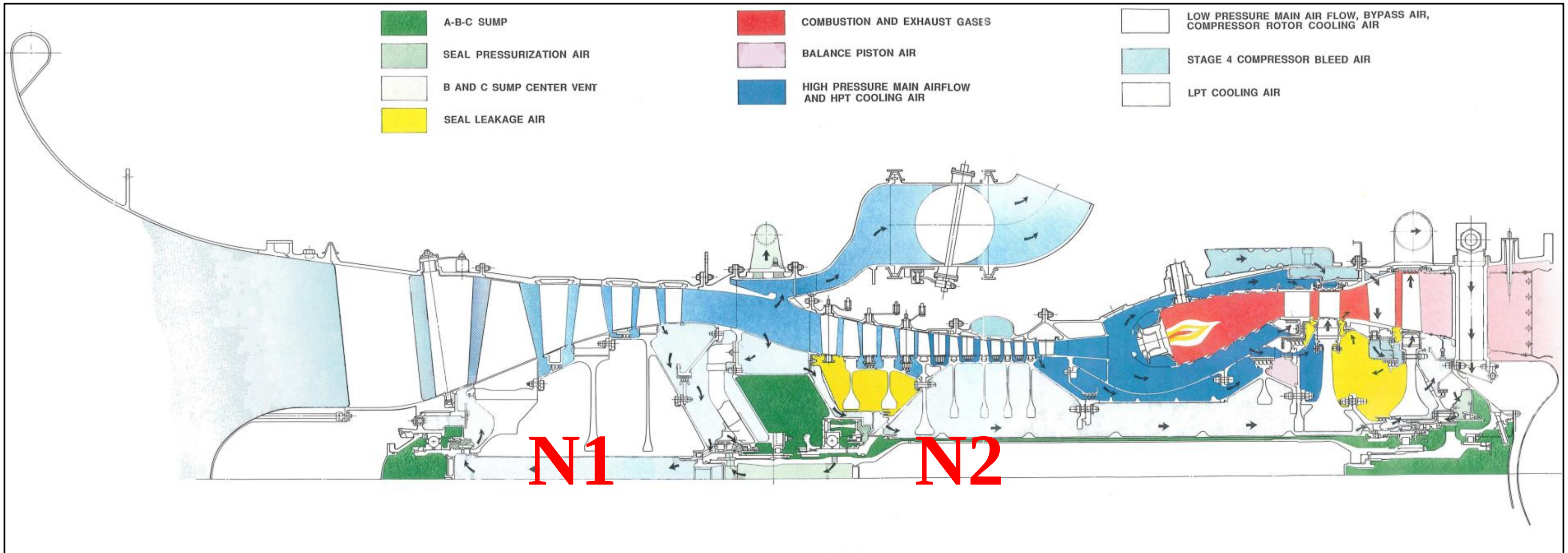

7 Stage Axial IP Compressor
6 Stage HP Compressor
Single Stage HP and IP Turbines
Closed Loop VIGV Actuation System
N3 (PT)
N2
N1
2 Independent Shafts
Hydraulic or Direct, Driven Electric Starter Motor

GE LM2500+



GE LM2500
N1
N3
Axial Air Compressor
Combustor
Power Turbine
Compressor Turbine (CT)

GE LM1600



LM1600 AIRFLOW

Outline

1. Motivation of this work.
2. Objectives.
3. Approach to Quantify GT Degradation.
4. Results.
5. Notes on Recoverable vs. Un-recoverable Degradation.
6. Summary of Findings & Conclusions.

Performance Degradation/Increased Fuel Consumption

- A 30 MW GT employed in s compressor station transporting 2 BSCFD of gas, the fuel consumption is approximately 6.0 MMSCFD.

- At NG Price of $3.00/GJ and 36 MJ/M3 LHV; This Unit will consume 6.7 MM$/Year worth of NG.

- A 2.0 percentage points change in the isentropic efficiency of the engine air compressor amounts to $158k per year for this unit.

GT Degradation

The performance of a gas turbines is subject to degradation due to several factors.

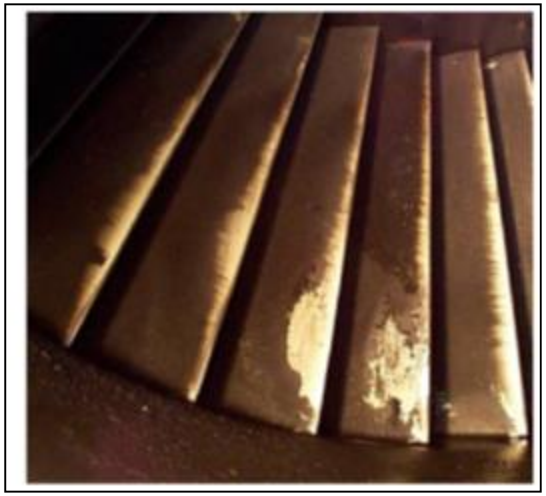
1. ***Deposits*** *causing change in blade surface quality*
2. ***Fouling*** *of the airfoils and annulus by particulate matter*

Recoverable

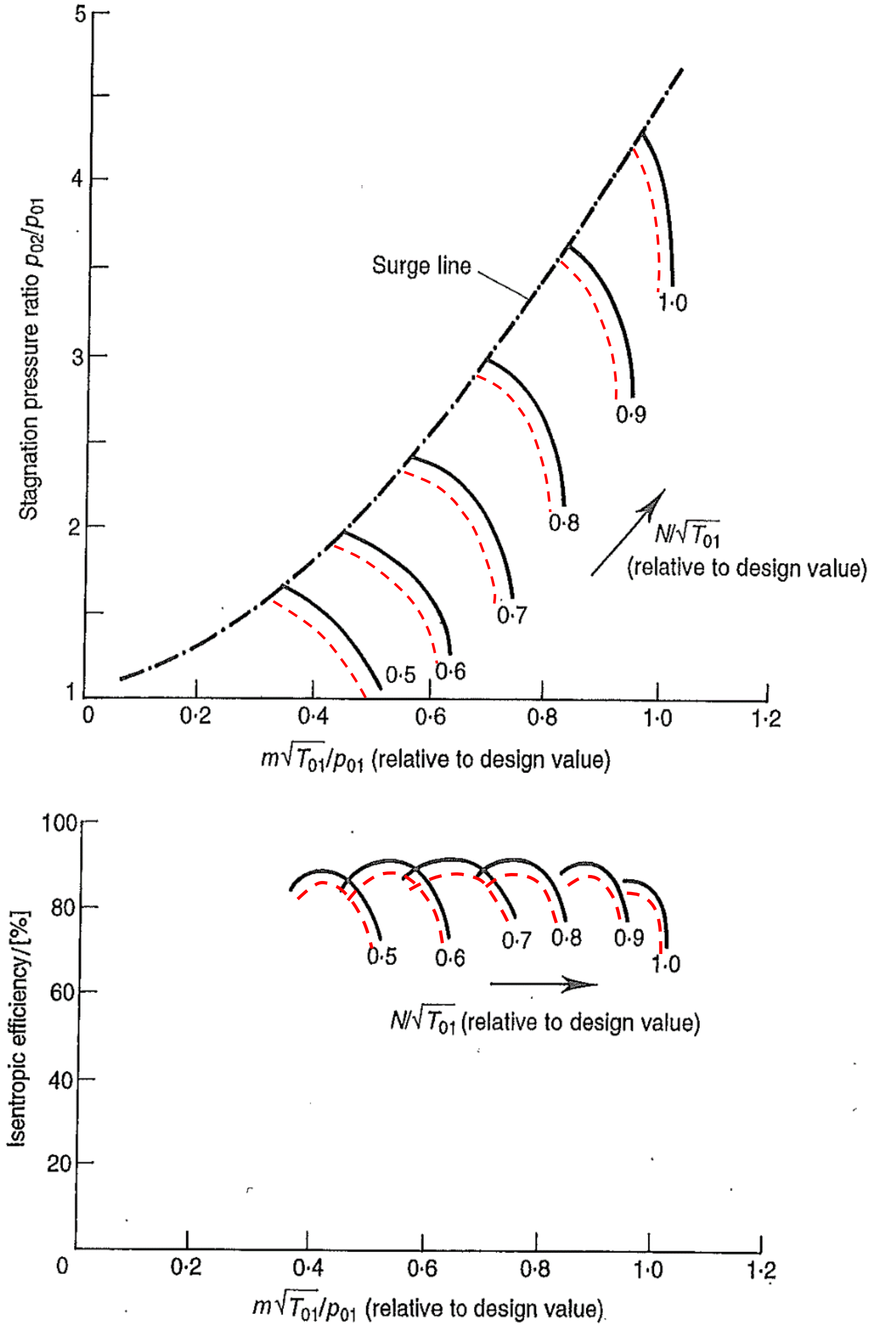
3. ***Corrosion*** *caused by removal of material due to corrosive environment .*
4. ***Damage caused by large foreign objects*** *striking the components of the engine*
5. ***Abrasion*** *caused by particles (~20 microns) impinging on the blades also when rotating surface rubs against the stationary components.*
6. *General wear and tear.*

Un-recoverable

Examples of GT Degradation



The most notable manifestation of engine degradation is in its ***axial compressor***



TransCanada NOVA Chemicals

K. K. Botros et al. (October 19-21, 2015)

Objectives

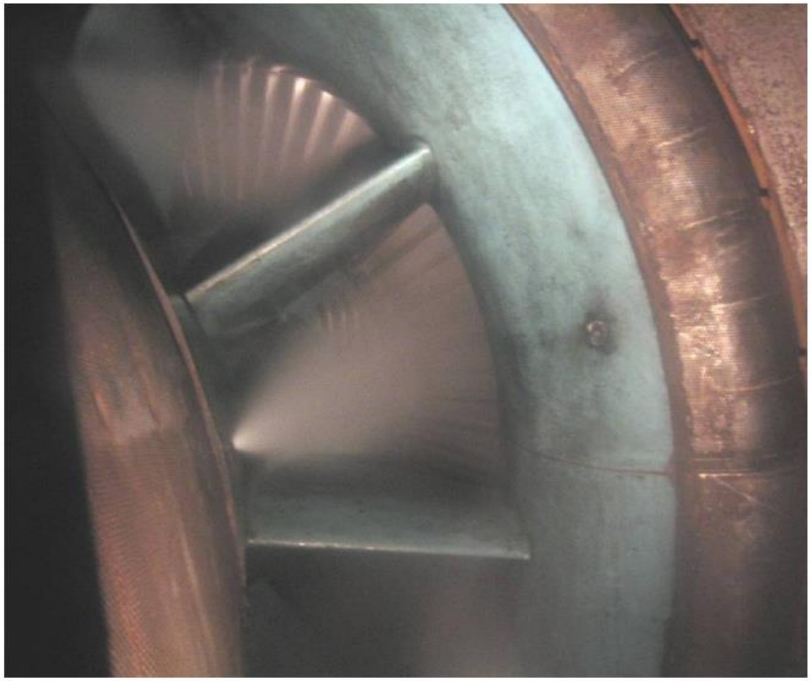
The ability to predict the performance degradation ahead of time when the GT is operating, is important for two reasons:

1. To ensure that the engine is available to deliver maximum load when needed (reliability);
2. To plan corrective/preventive maintenance at the appropriate time/intervals;

   → Engine soak-wash is neither done unnecessary, or done too late (cost).

3. To develop a guideline for fleet maintenance program.

What is Engine Wash?



Offline Wash

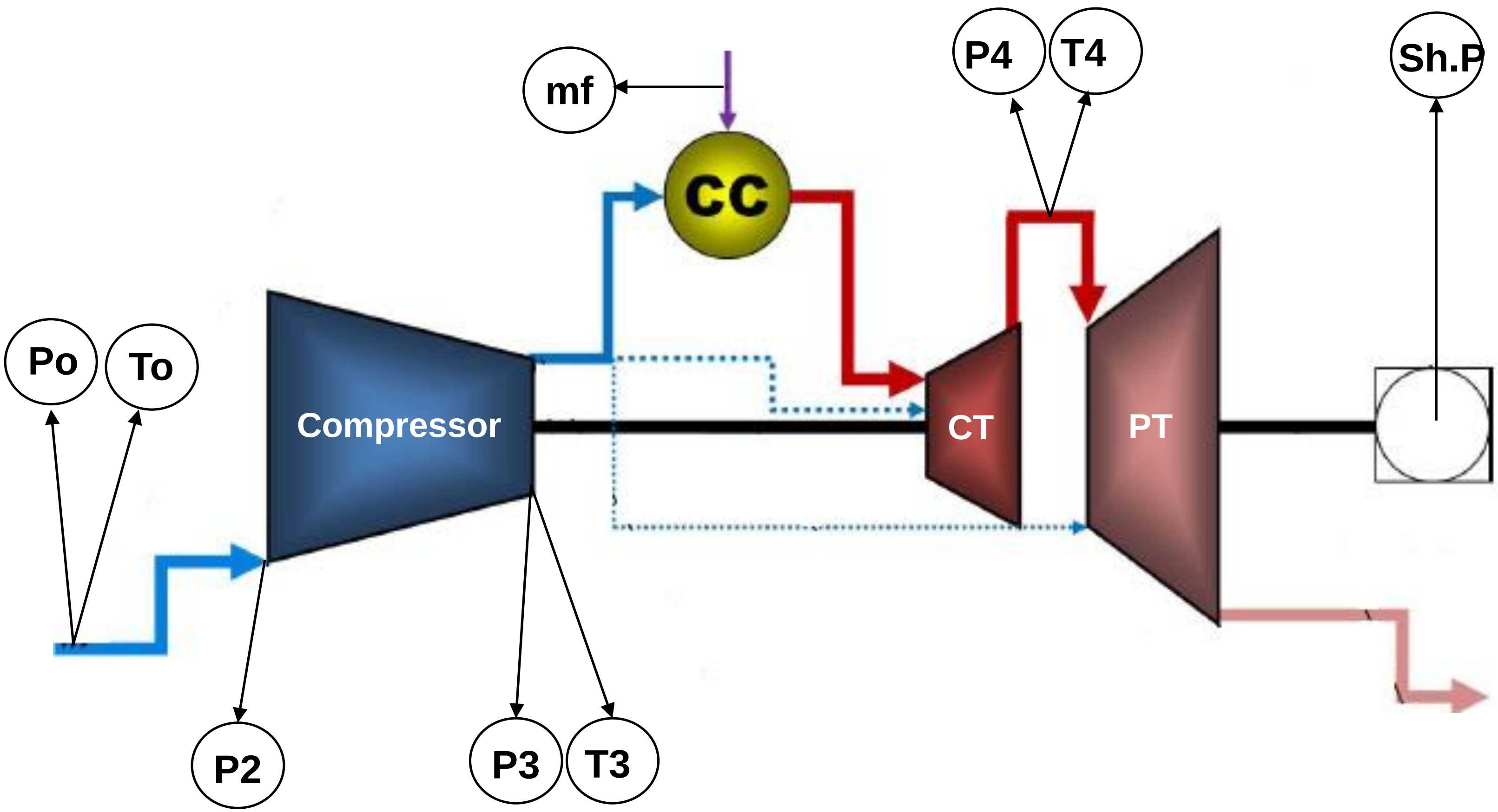
Also known as *soakwash*, performed with engine shut down.

What is Engine Wash?

- An off-line Soak-Wash typically takes 4-8 hours
- If the unit is running, we shut it down, crank it over a few times, in order to cool it down. This will avoid thermally shocking the engine.
- Spray the soak wash liquid in during a slow wash crank
- Rinse the engine with a slow crank
- Drain from various ducts, tubing, ignitors, etc.
- Crank the engine and fire it up for a bit to finish drying
- Turn the engine over to gas control/operations or shut it down

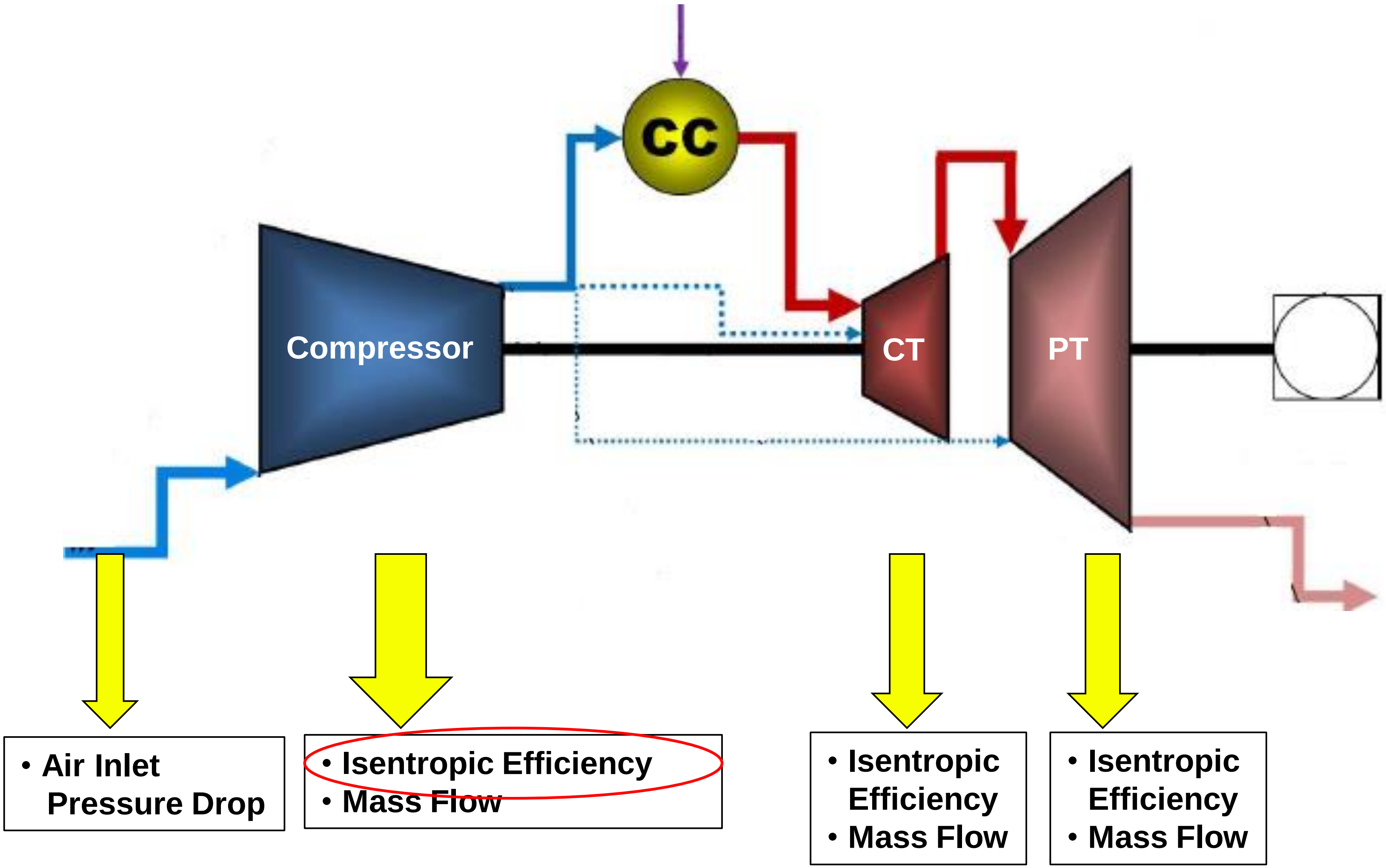
Approach

Measured Parameters (m = y + ε)



9 Measured Parameters

Goal: To Extract Health Parameters (H)



7 Health Parameters

Degradation Model

Step 1

- Measured Engine Variables (m) obtained from DSS

Step 2

- Evaluate the Health Parameters (GPA)
  - ***Using GasTurb11***

measurement uncertainty

Step 3

- Map out and Analyze Health Parameters

Degradation Model

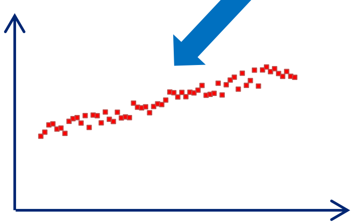
Step 1
- <u>Measured Engine Variables (m)</u> obtained from DSS

Step 2
- Evaluate the <u>Health Parameters</u> (GPA)
  - ***Using GasTurb11***

Step 3
- Filter the Noisy Data to Establish Correct Trend
- ***Bayesian Error-in-Variables Model (EVM)***

Step 4
- Map out and Analyze Health Parameters

measurement uncertainty



Bayesian EVM Parameter Estimation Model
(for the Isentropic Efficiency)

Variables:

$$\bar{Y} = \begin{pmatrix} P_2 \\ P_3 \\ T_2 \\ T_3 \\ N_{1,corrected} \\ \eta_{is} \end{pmatrix}$$

Parameters to be Estimated:

$$\bar{\Theta} = \begin{pmatrix} c_0 \\ c_1 \\ c_2 \end{pmatrix}$$

Objective Functions to Minimize:

$$F_1 = \eta_{is} - [c_0 + c_1\Psi + c_2\Psi^2]$$

$$F_2 = \eta_{is} - \frac{T_2\left[\left({P_3}/{P_2}\right)^{(k-1)/k} - 1\right]}{T_3 - T_2}$$

Where:

$$\Psi = \frac{1}{N^2_{1,corrected}} \frac{ZRT_2}{(k-1)/k}\left[\left(\frac{P_3}{P_2}\right)^{\frac{k-1}{k}} - 1\right]$$

Variance/Co-Variance:

$$\bar{V} = \begin{pmatrix} \sigma^2_{P_2} & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{P_3} & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{T_2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{T_3} & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{N_1} & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma^2_{\eta_{is}} \end{pmatrix}$$

$$\sigma_{P_2} = 1kPa$$
$$\sigma_{P_3} = 20kPa$$
$$\sigma_{T_2} = 0.5°C$$
$$\sigma_{T_3} = 5°C$$
$$\sigma_{N_1} = 10RPM$$
$$\sigma_{\eta_{is}} = 0.05$$

Bayesian EVM Parameter Estimation Model

Minimization Scheme (based on Fischer Method of Scoring):

$$\overline{\theta}^{(u+1)} = \overline{\theta}^{(u)} - \overline{G}^{-1}\overline{q}$$

where

$$\overline{G} = \sum_{p=1}^{n} \overline{Z}_p^T (\overline{B}_p V \overline{B}_p^T)^{-1} \overline{Z}_p$$

and

$$\overline{q} = \sum_{p=1}^{n} \overline{Z}_p^T (\overline{B}_p V \overline{B}_p^T)^{-1} \overline{B}_p (\overline{Y} - \overline{Y}_{true})$$

$$\overline{Z} = \left(\frac{\partial f_i}{\partial \theta_j} \right)$$

(*i*x*j*) Jacobian vector w.r.t the estimated parameters

i=1,…2 and j=1,….3

$$\overline{B} = \left(\frac{\partial f_i}{\partial y_k} \right)$$

(*i*x*k*) Jacobian vector w.r.t the variables

i=1,…2 and k=1,….6

Bayesian EVM Parameter Estimation Model

Once the parameters are evaluated, the new true value $Y_{true}^{(u+1)}$ is updated in a separate iteration:

$$\overline{Y}_{true}^{(u+1)} = \overline{Y}^{(u)} - V\overline{B}^{T}\overline{t}$$

where $\overline{t}$ is calculated by solving the following matrix equation:

$$\overline{S}\overline{t} = \overline{h}$$

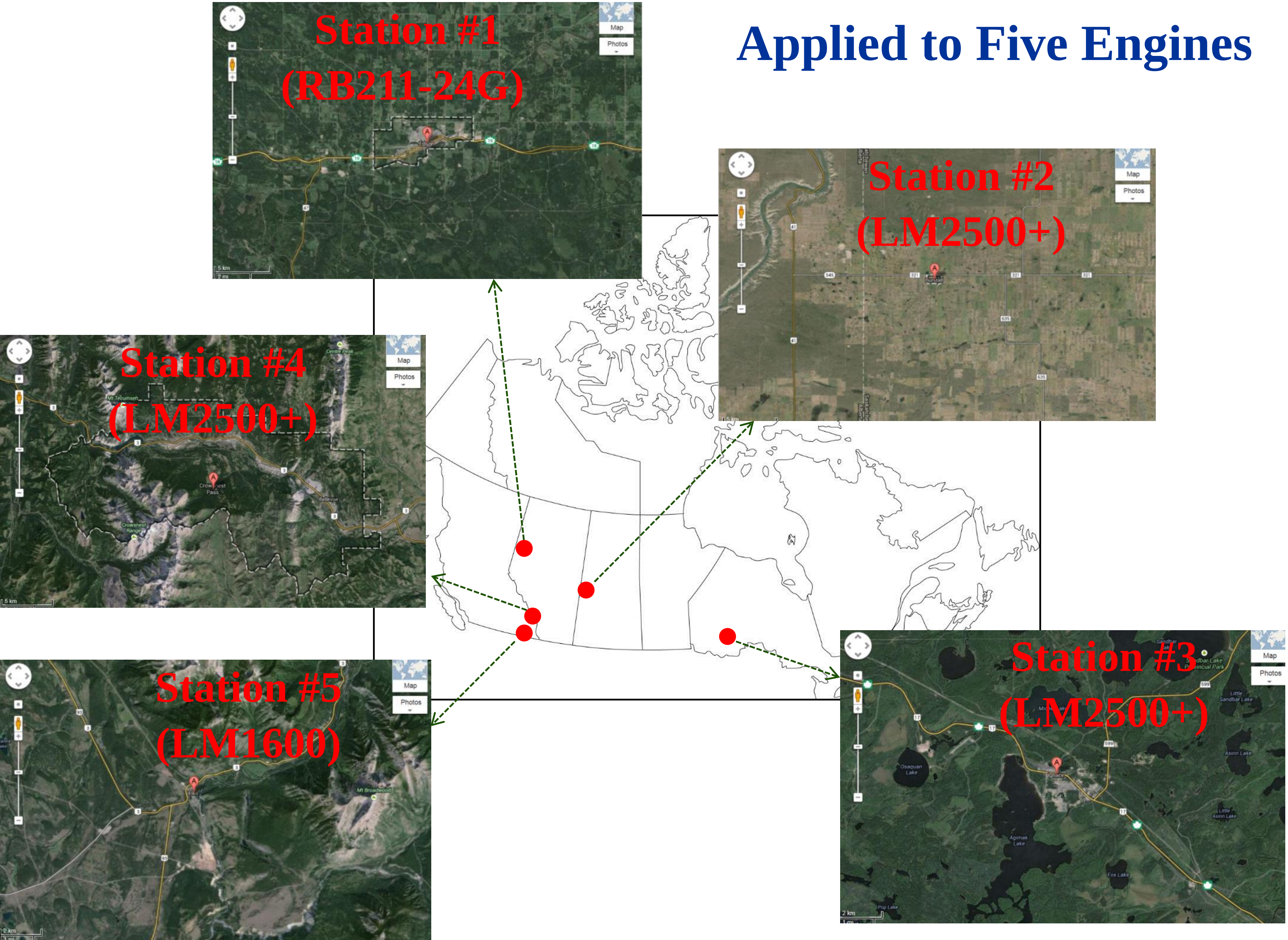
$$\overline{S} = \overline{B}\overline{V}\overline{B}^{T}$$

and

$$\overline{h} = \overline{f}_{obj}(\overline{Y}_{true}^{(u)}, \overline{\theta}^{(u)}) + \overline{B}(\overline{Y}^{(u)} - \overline{Y}_{true}^{(u)})$$

*Parameter Estimation in Error-in-Variables Model, *Reilly, Park, M. and Reilly, H, V.* Appl. Statist. *(1993)*

Applied to Five Engines



Characteristics of the Five Engines

Station	Engine	DLE	Elevation	Sea Level Power Rating @ 15°C (with Losses)	Site Power Rating @ 15°C (with Losses)
			(m)	(MW)	(MW)
1	RB211-24G	Yes	946	27.67	24.698
2	LM2500+	Yes	730	29.5	27
3	LM2500+	Yes	471	29.5	27.25
4	LM2500+	Yes	1359	29.292	24.881
5	LM1600	Yes	843	14.064	12.709

Results (Engine 2)

LM2500+ (DLE) at Station #2

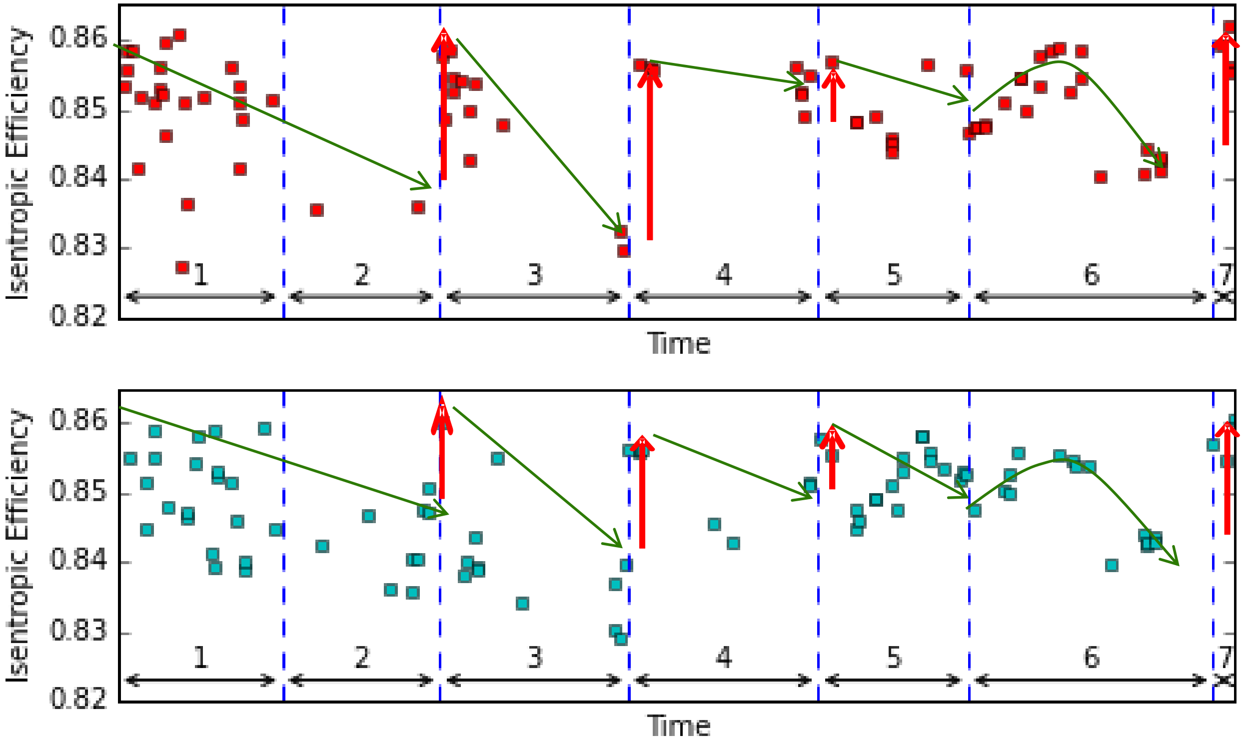
Data Timeline

Note:

The same engine undergoing 6 washes over 6 years.

Date	Event	Event #
April 8, 2009	New Engine Installed	
Period 1 (OH = 3310)		
November 6, 2009	Offline Soak Wash	**E1**
Period 2 (OH = 3176)		
April 27, 2010	Offline Soak Wash	**E2**
Period 3 (OH = 3800)		
March 24, 2011	Offline Soak Wash	**E3**
Period 4 (OH = 3841)		
May 26, 2012	Offline Soak Wash	**E4**
Period 5 (OH = 3014)		
December 2, 2013	Offline Soak Wash	**E5**
Period 6 (OH = 4954)		
April 14, 2015	Offline Soak Wash	**E6**
Period 7 (OH = 426)		
August 18, 2015	End of Data Acquisition	

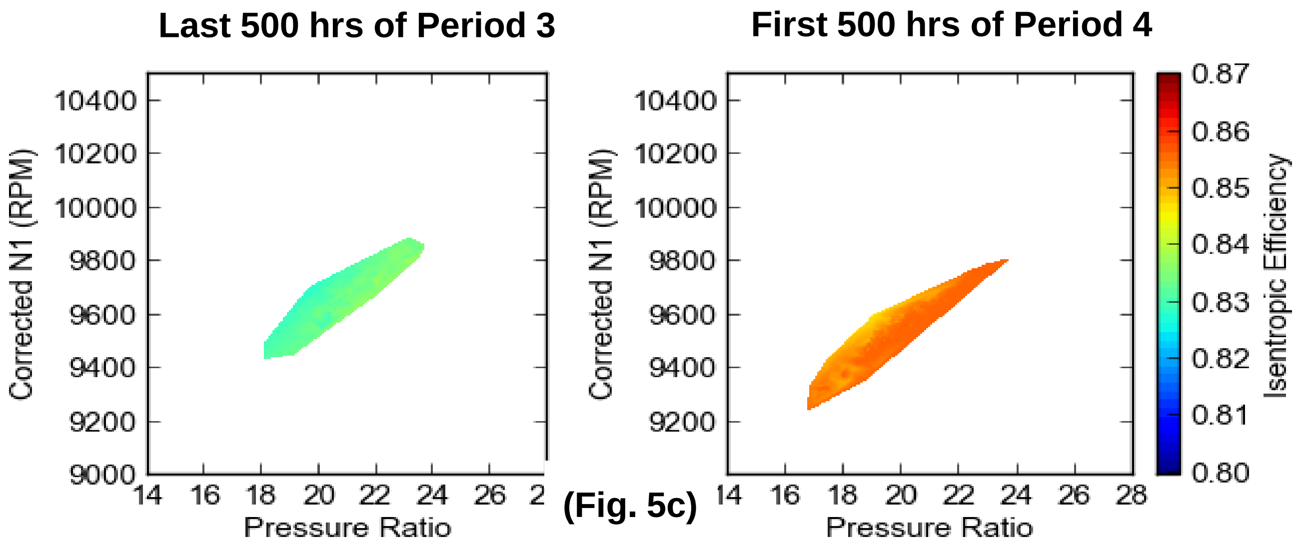
Isentropic efficiency (@ Specific N1corrected)



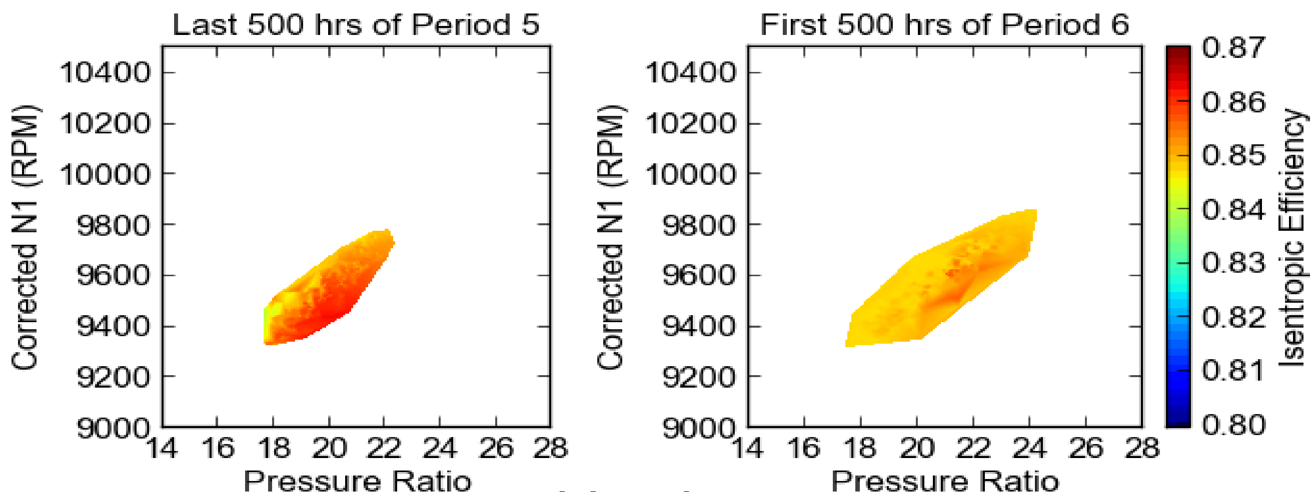
<u>Observation</u>:

1. Substantial gain from engine wash.
2. Little un-recoverable degradation.
3. Scattered data, but mapping on next slide tells the story.

Isentropic efficiency Mapping



(Fig. 5c)



(Fig. 5e)

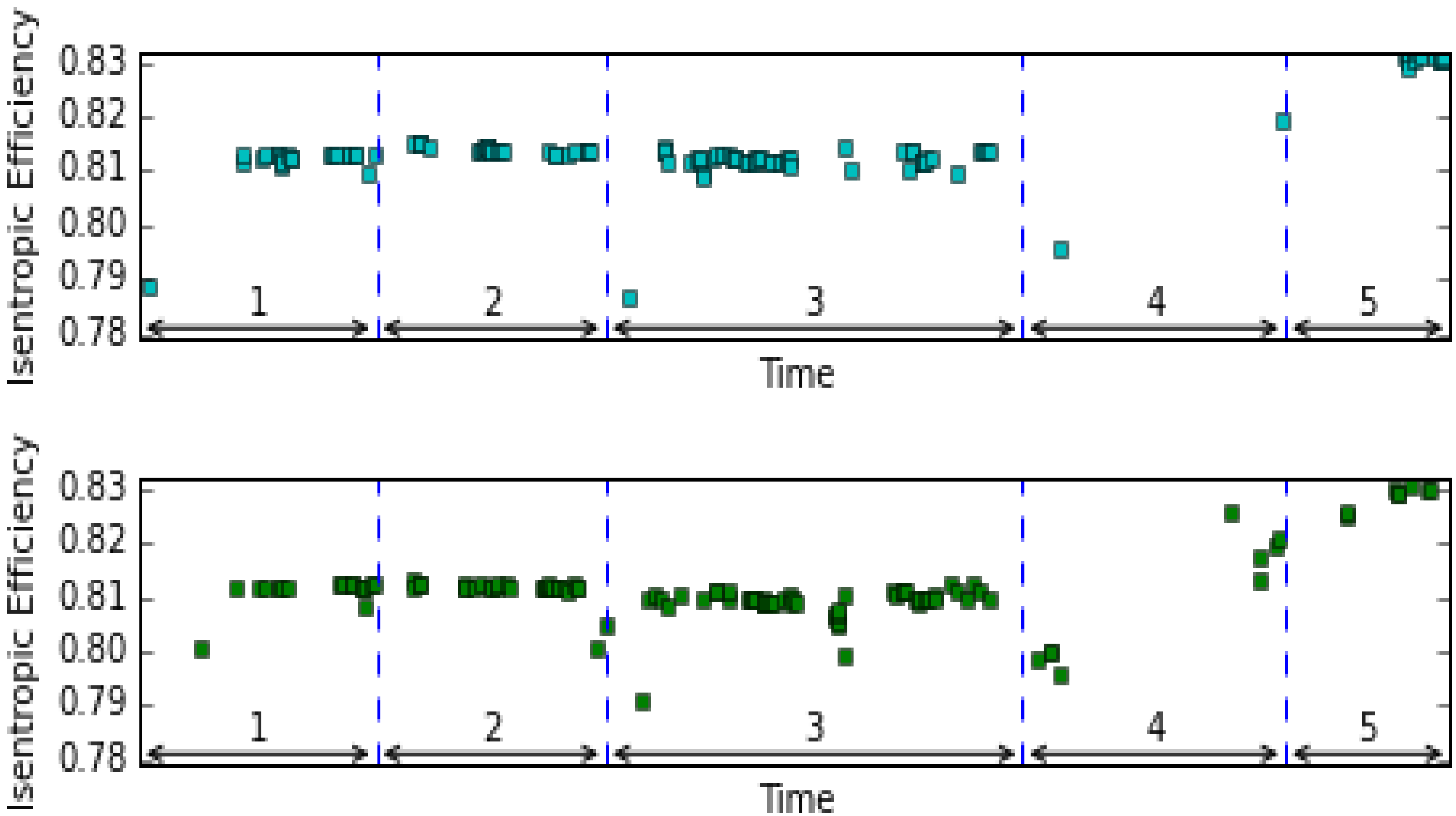
Results (Engine 5)

LM1600 (DLE) at Station #5

Data Timeline

Date	Event	Event #
December 14, 2007	Start of Data Acquisition	
Period 1 (OH = 2303)		
Septemebr 20, 2008	Offline Soak Wash	**E1**
Period 2 (OH = 2231)		
November 16, 2009	Offline Soak Wash	**E2**
Period 3 (OH = 4048)		
September 23, 2013	Offline Soak Wash	**E3**
Period 4 (OH = 2552)		
January 30, 2015	Components Relpacement	**E4**
Period 5 (OH = 1599)		
August 18, 2015	End of Data Acquisition	

Isentropic efficiency (@ Specific N1corrected)

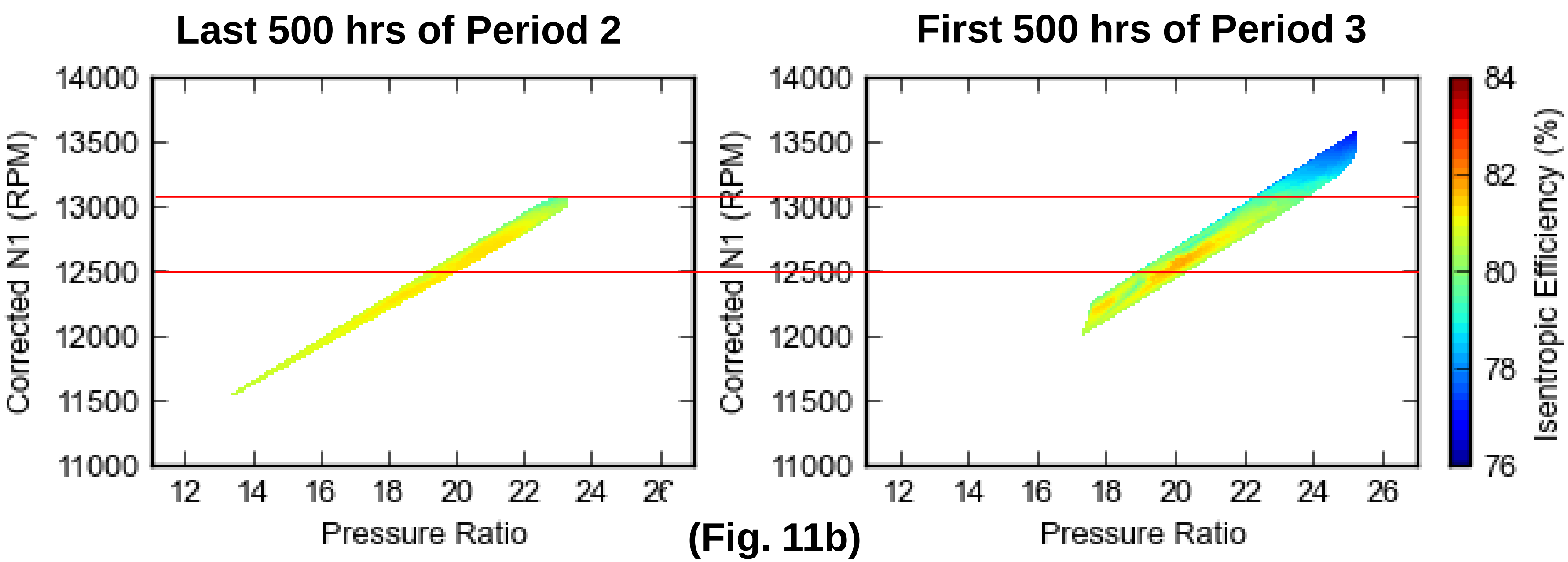


Observation:

1. Hardly any un-recoverable degradation.

2. Hardly any gain from engine washes.

Isentropic efficiency (Due to Physical Changes)



(Fig. 11b)

Findings and Conclusions

1. **Recoverable** degradation

   correlates well with cumulative engine air intake between soak washes for that engine at the specific site condition.

2. **Un-recoverable** degradation

   correlates well with engine loading (defined as hourly averaged shaft power / site rated power).

Findings and Conclusions

Event	OH from Previous Period	Gain in η_{is}	Air Intake during the period prior to the event	Average Site Rated Power	Air Intake / Average Site Rated Power
		(% points)	(10^6 kg)	(MW)	(10^6 kg/MW)
Station #2					
E1	3310	?	856	27.9	30.7
E2	3176	1.2	868	30.4	28.6
E3	3800	2.2	1025	30.0	34.2
E4	3841	0.2	969	29.4	33.0
E5	3014	0.5	706	28.2	25.1
E6	4954	1.1	1126	29.3	38.4
Station #5					
E1	2303	0	308	12.9	23.9
E2	2231	0	320	12.5	25.6
E3	4048	0	564	12.4	45.5
E4*	2552	0.3	374	13.8	27.1

Findings and Conclusions

	Un-recoverable Deg. (Loss in η_{is})	Average Shaft Load During the Period	Site Rated Power	Average Shaft Power / Rated Power
Period	(% points / 1000 OH)	(MW)	(MW)	-
		Station #2		
1	0	21.799	27.882	0.78
2	0	24.831	30.391	0.82
3	-0.08	21.959	30.005	0.73
4*	0.09	21.093	29.386	0.72
5	-0.28	20.065	28.152	0.71
6*	0.17	21.1	29.3	0.72
		Station #5		
1	-	8.716	12.863	0.68
2	-0.18	9.595	12.509	0.77
3	-0.09	9.263	12.388	0.75
4**	0.74	10.1	13.8	0.73

* Previous wash was ineffective

** Engine service on January 30, 2015

Findings and Conclusions

3. Engines employed in compressor stations in a forested area degraded (from recoverable sense) at a much lower rate than engines located in the prairies. Hence, frequency of engine washes is not critical for the former as compared to the latter.

4. In many cases on time soakwashes could improve the isentropic efficiency of the air compressor by 3-4 percentage points.

5. Outcome: guidelines for engineering/operation using the tools described.

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