Cranfield University: Gas Turbines Since its Inception

1946 **Cranfield College of Aeronautics**
For Education and Research
One of the 4 original units was Aircraft Propulsion
Now Propulsion & Thermal Power Eng Centre
One of the 4 original courses was Aircraft Propulsion
Now Thermal Power & Propulsion MSc

1969 **Cranfield Inst of Technology (University)**

1993 **Cranfield University (change of name)**

P&TP Eng Centre: Comprises 250+ Staff & Postgraduates
8000 m^2 GT Laboratories
Owns 18 Gas Turbine Engines

Education Encompasses Thermal Power & Propulsion MSc
UK and Global Professional

Education 80 Doctoral Researchers

Training Session

Gas Turbine Gas Path Diagnostics

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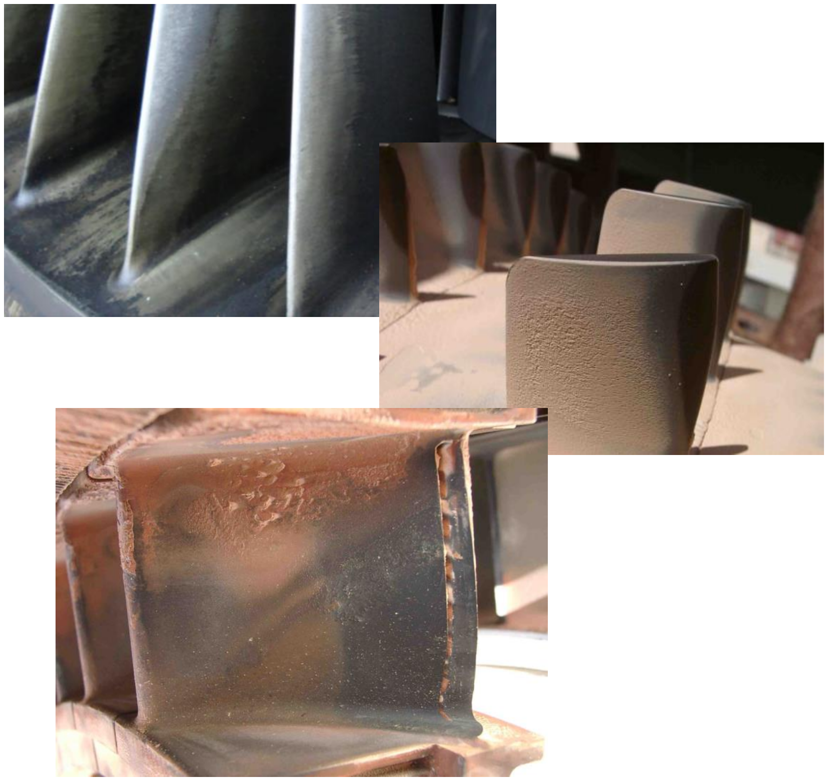
Reader in Gas Turbine Performance and Diagnostics
Faculty of Engineering and Applied Sciences, Cranfield University
Cranfield, Bedford MK43 0AL, United Kingdom

Gas Turbine Degradation & Representation

Phenomena of GT degradations

Recoverable Degradations



RAF Puma Helicopter in Sahara Desert Morocco

Fouling (deposition)

Phenomena of GT degradations

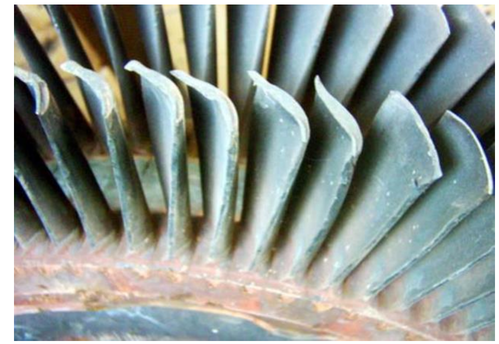
Non-Recoverable Degradations

https://preciseflight.com/article/aviation-bird-strikes-solutions/

Foreign Object Damage (FOD)

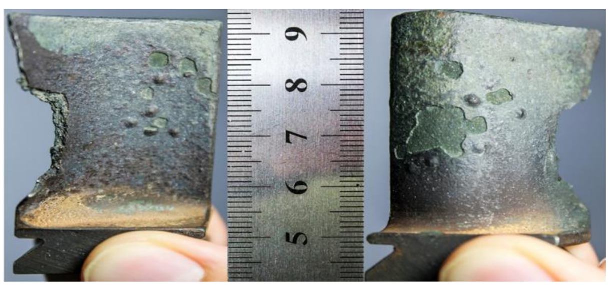
<<International Turbomachinery>> Vol.45 No.5, Sep./Oct. 2004

Domestic Object Damage (DOD)



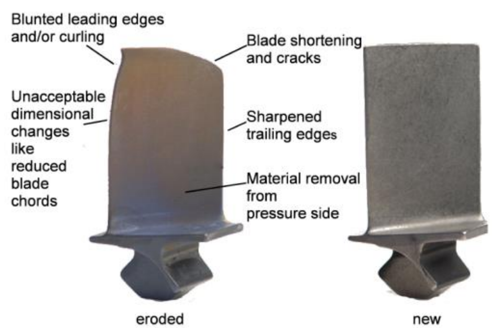
("Failure analysis of gas turbine blades" by Naeem, Jazayeri, Nesa Rezamahdi & Toosi, 2005)

Creep



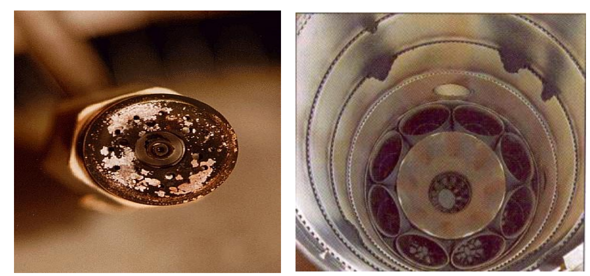
Corrosive Damage

Salehnasab B., Poursaeidi E., Mortazavi SA., Farokhian GH. Hot corrosion failure in the first stage nozzle of a gas turbine engine. EFA. Elsevier Inc.; 2016;



(Schrade & Staudacher, 2014)

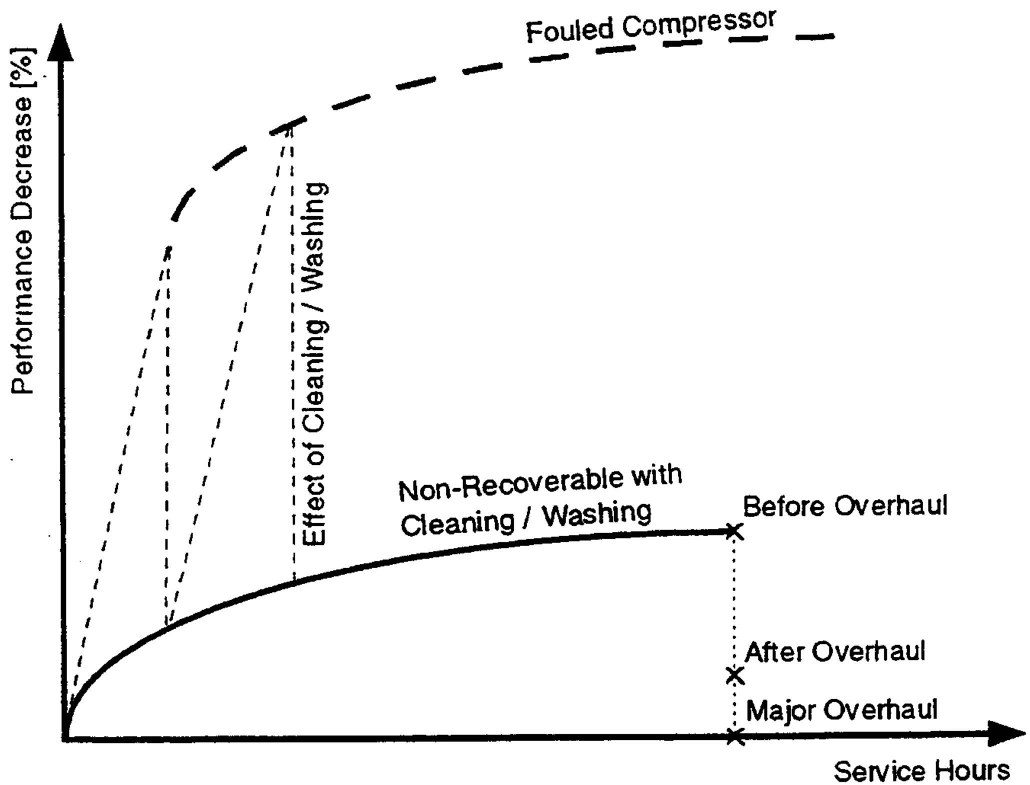
Erosion



<<International Turbomachinery>> Vol.45 No.5 Sep./Oct. 2004

Combustion system deterioration

Phenomena of GT degradations



- Recoverable
- Non-recoverable
- Cumulative effect

Health Parameters

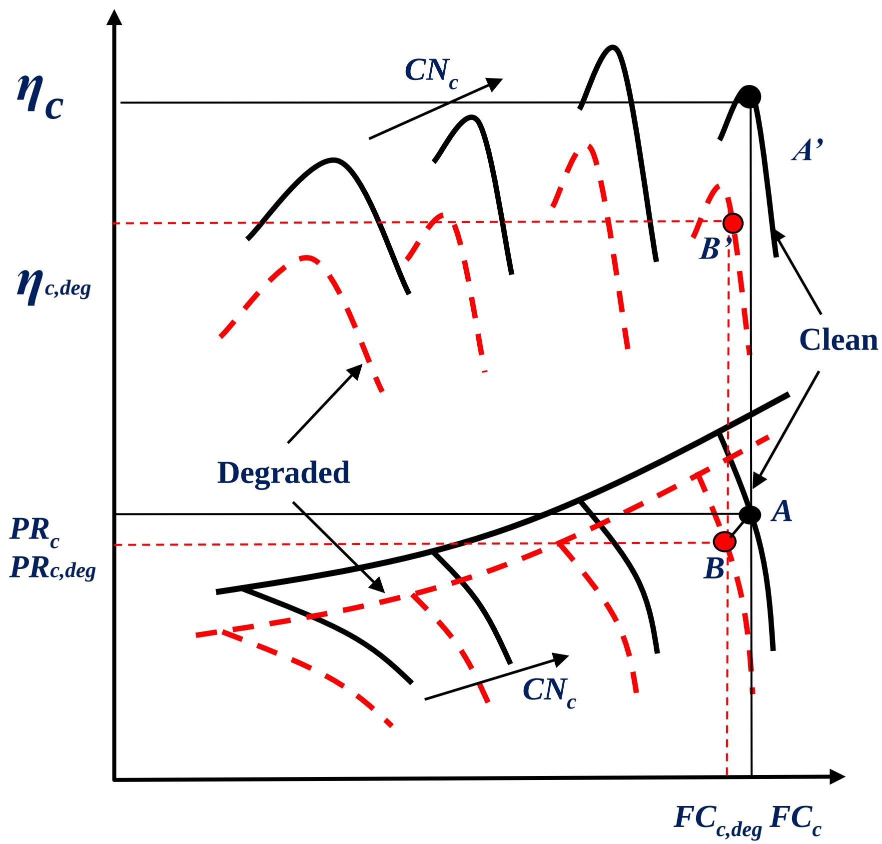
COMPRESSOR:

Flow Capacity Index/Scaling Factor
Efficiency Index/Scaling Factor
Pressure Ratio Index/Scaling Factor

$$SF_{c,FC} = FC_{c,\deg} / FC_c$$

$$SF_{c,Eff} = \eta_{c,\deg} / \eta_c$$

$$SF_{c,PR} = PR_{c,\deg} / PR_c$$



ASSUMPTION:

$$SF_{c,FC} = SF_{c,PR}$$

Health Index = SF - 1

Health Parameters

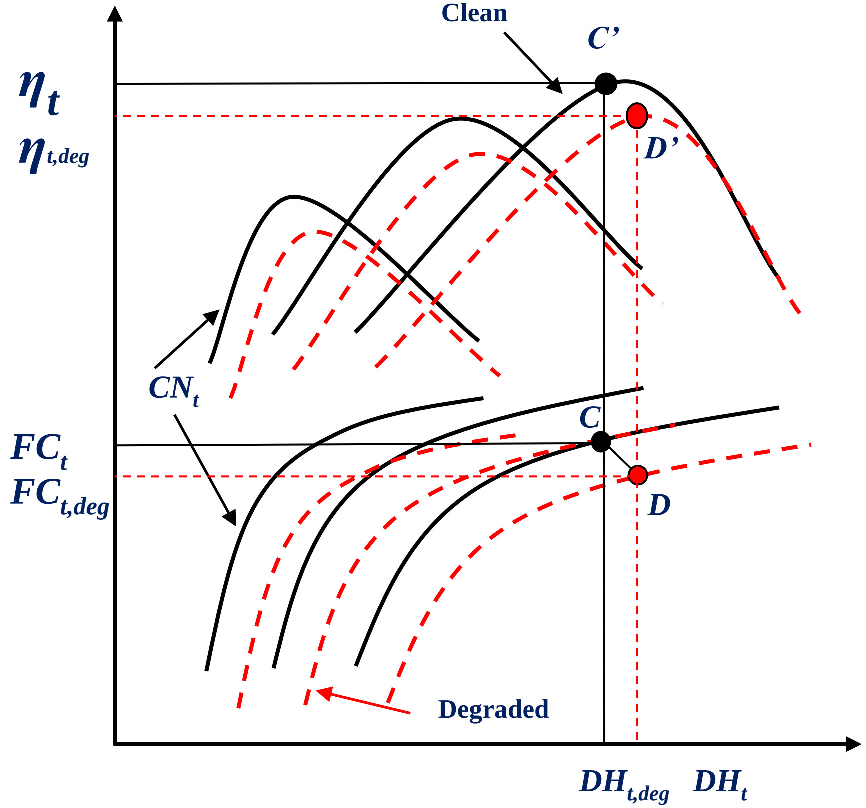
TURBINE:

Flow Capacity Index/Scaling Factor
Efficiency Index/Scaling Factor
Enthalpy Drop Index/Scaling Factor

$$SF_{t,FC} = FC_{t,\deg} / FC_t$$

$$SF_{t,Eff} = \eta_{t,\deg} / \eta_t$$

$$SF_{t,DH} = DH_{t,\deg} / DH_t$$



ASSUMPTION:

$$SF_{t,FC} = -SF_{t,DH}$$

Health Index = SF - 1

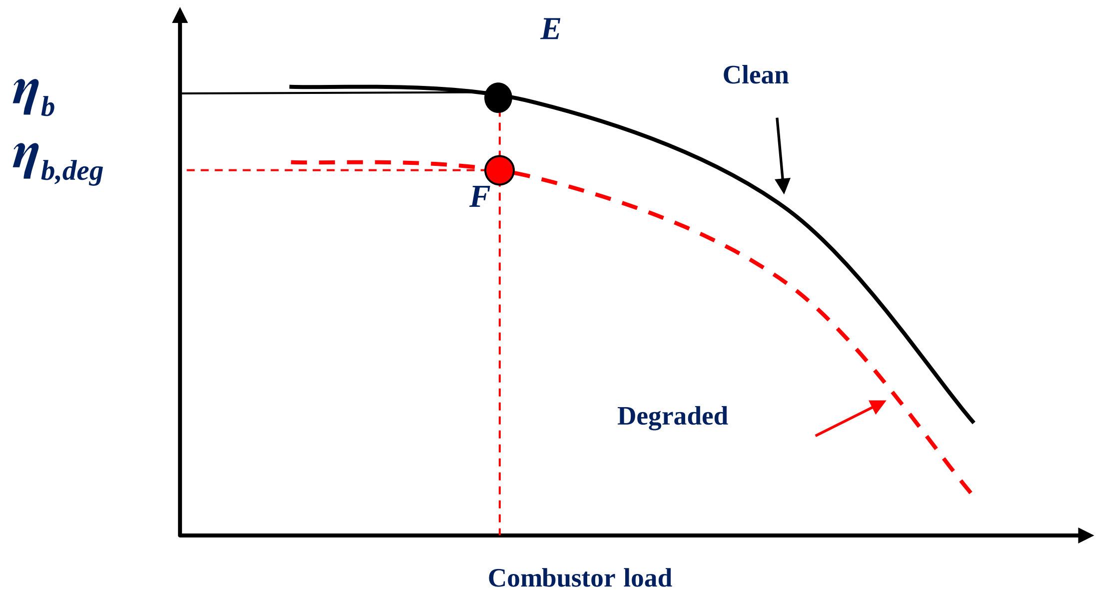
Health Parameters

COMBUSTOR:

Efficiency Index/Scaling Factor

$$SF_{b,Eff} = \eta_{b,\deg} / \eta_b$$

Health Index = SF - 1



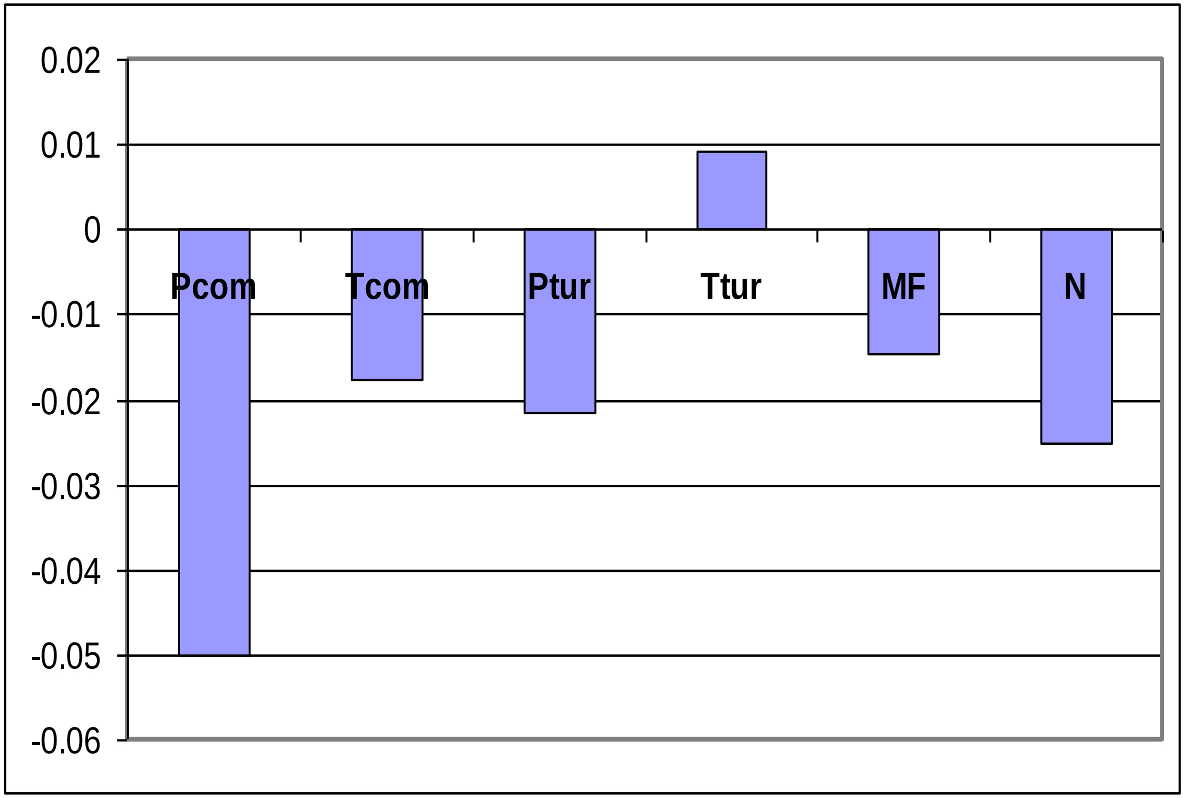
$$Combustor\_Load = f\left(P_b, \Delta T_b\right)$$

Fault Signature

Fault Signature:

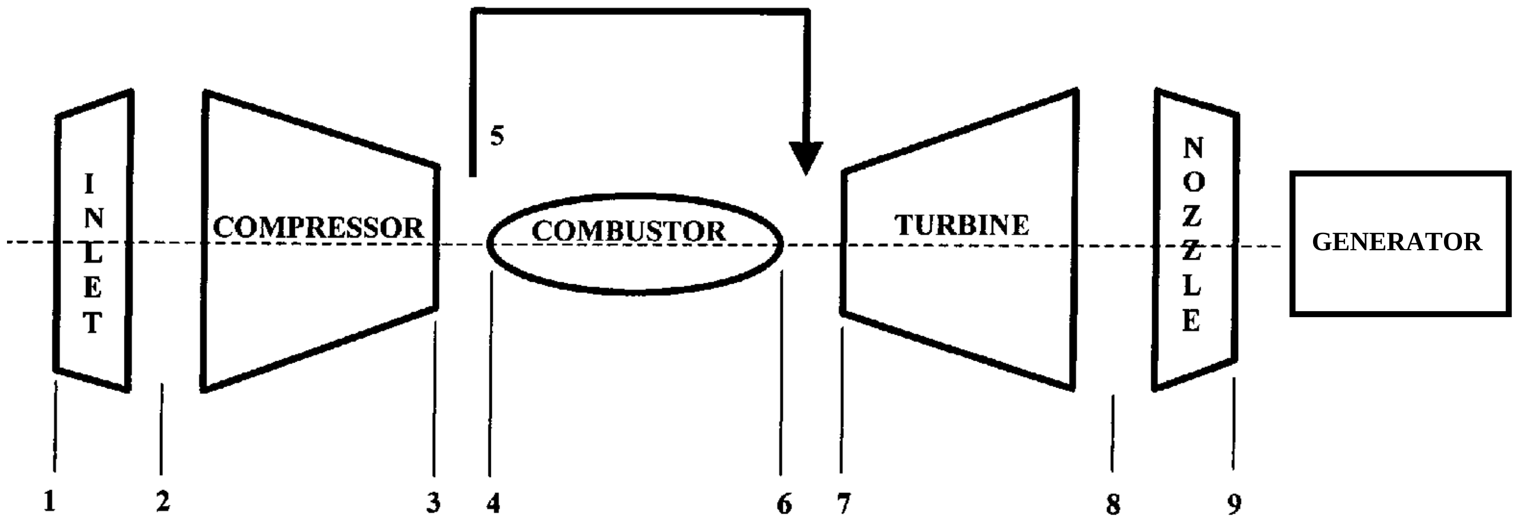
Measurement Deviation

$$\Delta X = \frac{X_{actual} - X_{ideal}}{X_{ideal}}$$



Fault signature of a single shaft industrial engine

Example of Performance Degradation

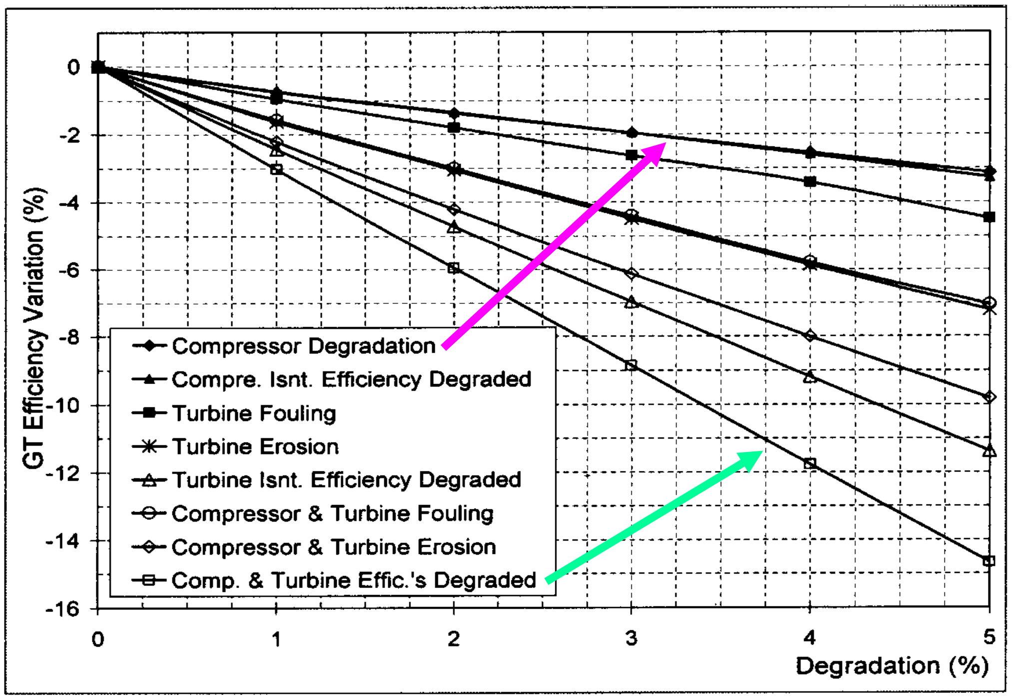


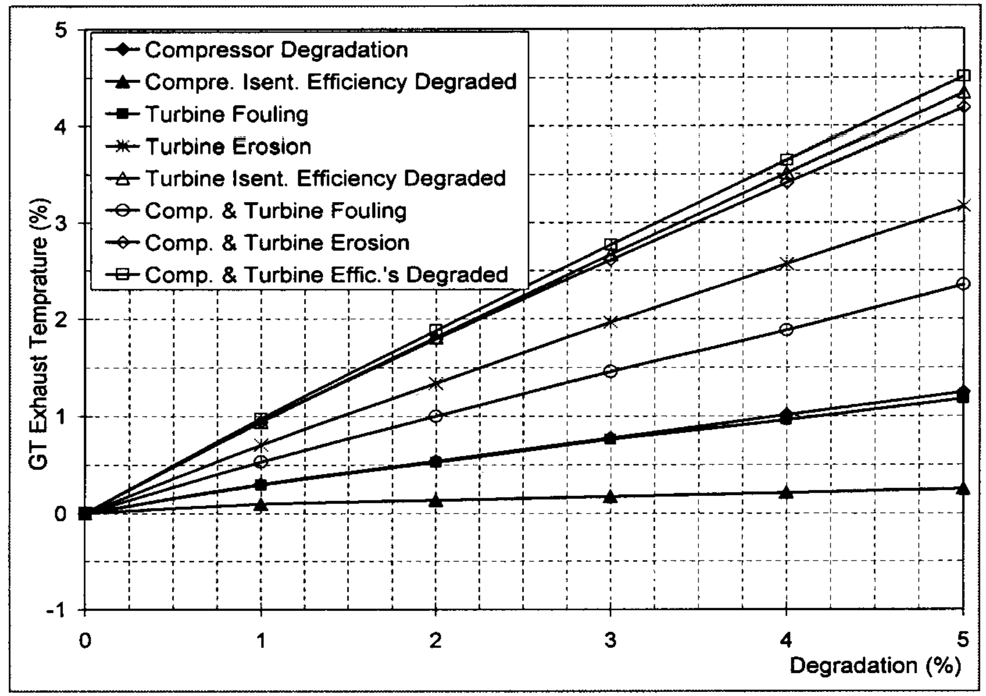
Inlet mass flow:	**408.66 kg/s**
Compressor pressure ratio	**15.2**
Turbine entry temperature	**1697.8 K**
Exhaust temperature	**871.24 K**
Net power output	**165.93 MW**
Overall thermal efficiency	**35.57 %**

Example of Performance Degradation

Fault	Represented By	Range
Compressor Fouling	Drop in Γ Drop in η_C	0.0 – (-5.0%) 0.0 – (-2.5%)
Compressor Erosion	Drop in Γ Drop in η_C	0.0 – (-5.0%) 0.0 – (-2.5%)
Turbine Fouling	Drop in Γ Drop in η_T	0.0 – (-5.0%) 0.0 – (-2.5%)
Turbine Erosion	Rise in Γ Drop in η_T	0.0 – (+5.0%) 0.0 – (-2.5%)
FOD	Drop in η_C and η_T	0.0 – (-5.0%)

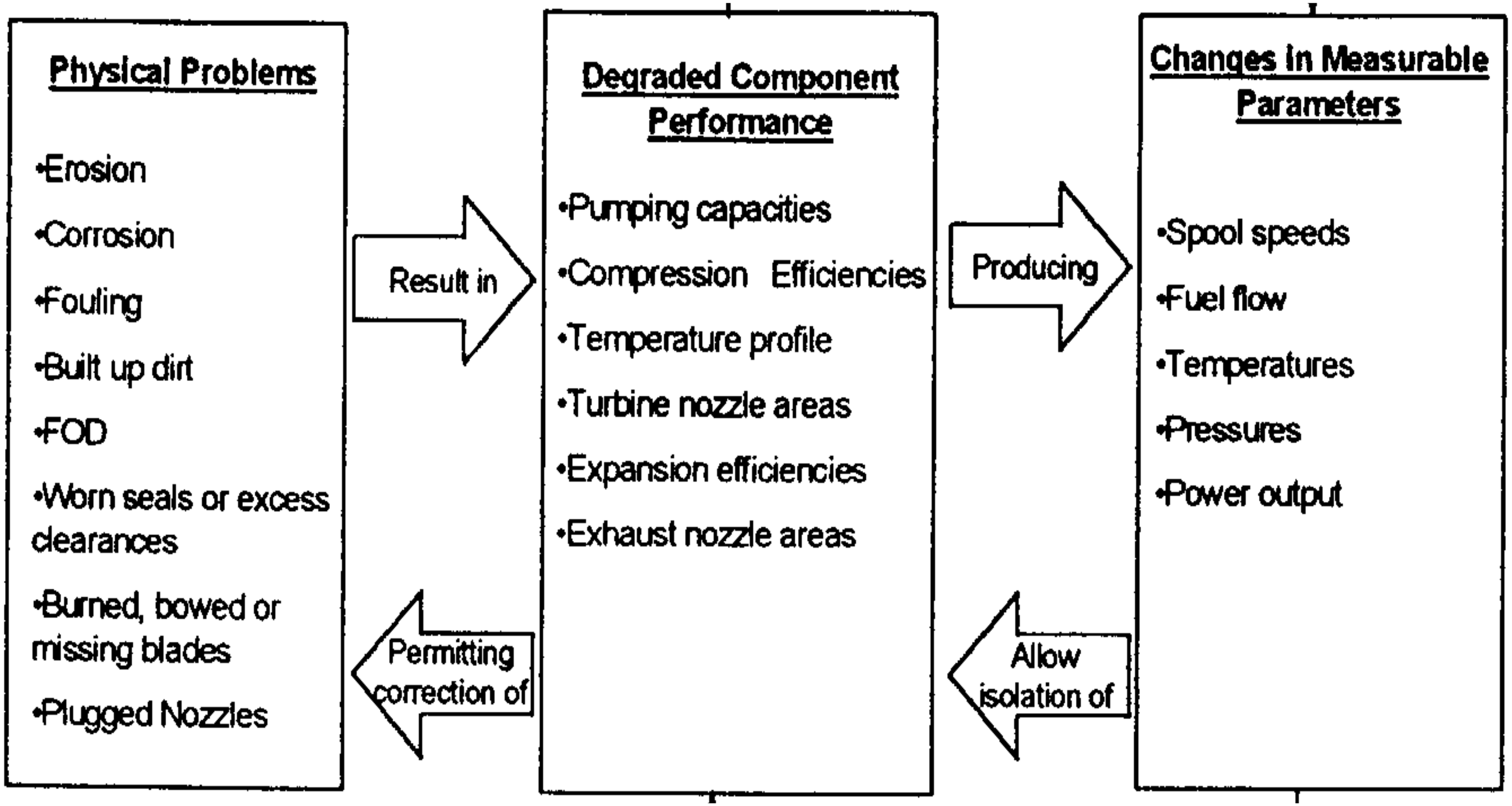
Example of Performance Degradation





Gas Path Analysis (GPA)

Gas Path Analysis (GPA)



Engine fault and parameter relationship (Urban, 1975)

Direct matrix inverse approach

Engine model: $\vec{z} = h(\vec{x})$ 0 – Nominal diagnostic point

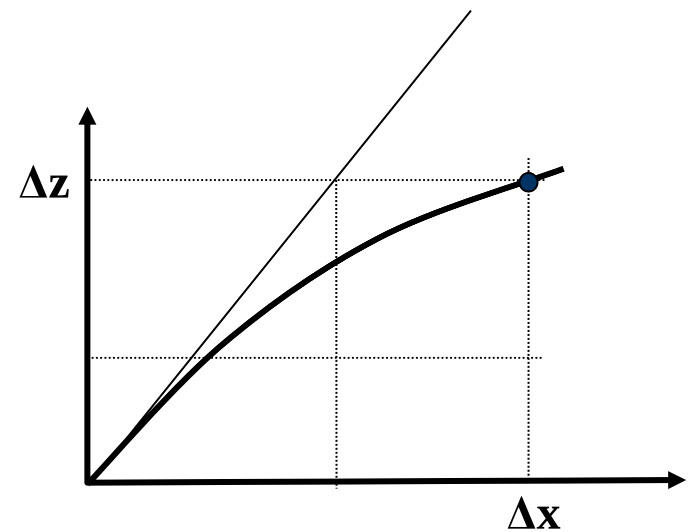
Expansion: $\vec{z} = h(\vec{x}_0) + \frac{\partial h(\vec{x})}{\partial x}(\vec{x} - \overrightarrow{x_0}) + \text{HOT}$

Linear engine model: $\Delta\vec{z} = H \cdot \Delta\vec{x}$

(ICM)

Linear GPA model: $\Delta\vec{x} = H^{-1} \cdot \Delta\vec{z}$

(FCM)



Gas Path Analysis (GPA)

$$\Delta\vec{z} = H \cdot \Delta\vec{x}$$

Assumptions for GPA:

- **A set of accurate measurement deltas (Δz) is available**

  - repeatable, free of measurement noise & bias

- **The linear model represents engine performance accurately around a reference point**

- **The ICM (*H*) is invertible**

Potential capabilities of linear GPA:

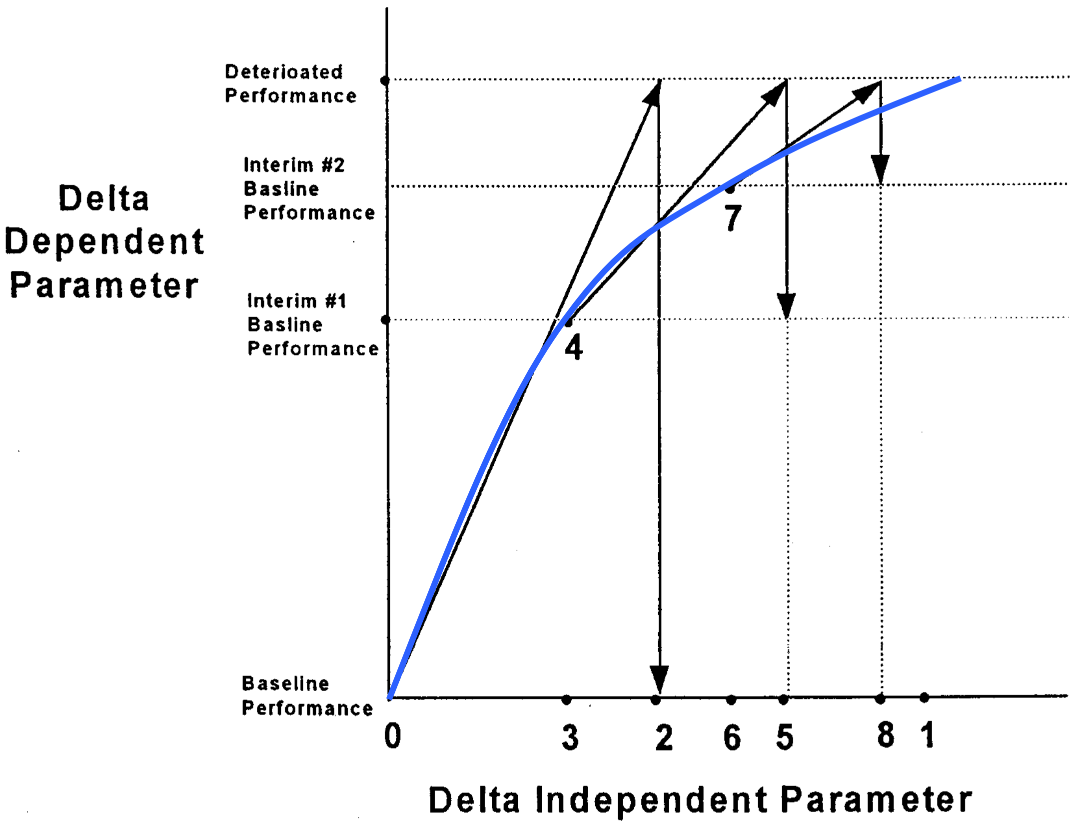
- Simple
- Fast
- Fault detection
- Fault isolation
- Fault quantification
- Deal with multiple faults

Challenges of linear GPA:

- Non-linearity
- Data repeatability
- Selection of measurements
- Smearing effect

Non-Linear Gas Path Analysis (GPA)

Non-linear GPA



Convergence of non-linear GPA:

- Under-relaxation
- Convergence criteria:

$$\Delta\vec{z}_{sum}=\sum_{j}^{M}\left|\Delta z_{meas_j}-\Delta z_{cal_j}\right|<\delta$$

Data Pre-Processing

Data Repeatability - Measurement Noise and Noise Filtering

Noise filters

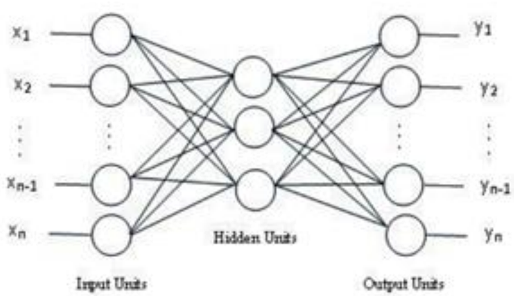
- **Rolling average**

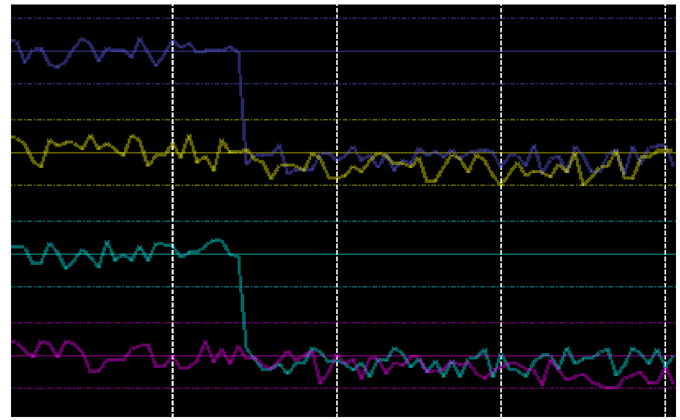
$$\bar{x}_t = \frac{1}{I}\left(x_t + x_{t-1} + \dots\dots + x_{t-I+1}\right)$$

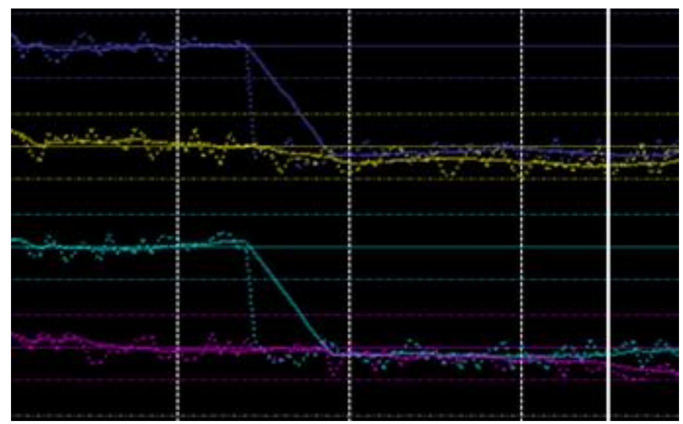
- **Exponential average**

$$\bar{x}_{t10} = \bar{x}_{(t-1)10} * 0.85 + x_t * 0.15$$

- **Artificial Neural Networks**





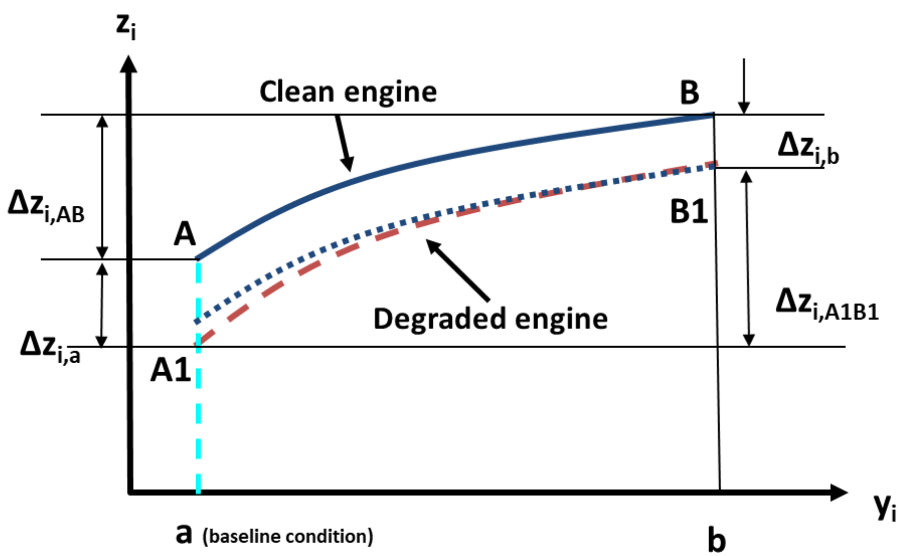


Data Pre-Processing

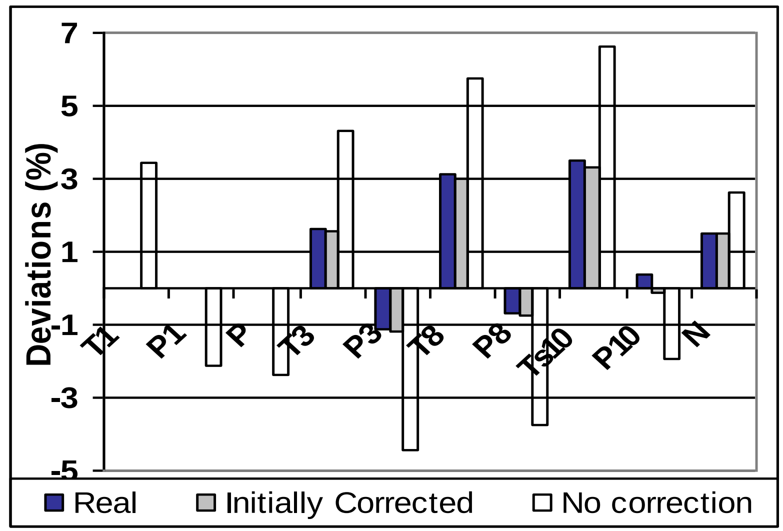
Data Repeatability - Data Corrections

Using referred parameters (based on θ=T/288.15 & δ=P/101.325 corrections) is not accurate

(Such as $N^* = N/\sqrt{\theta}, W^* = W\sqrt{\theta}/\delta, T^* = T/\theta, P^* = P/\delta$)



$$\Delta z_{i,a} = \Delta z_{i,b} - \left(\Delta z_{i,AB} - \Delta z_{i,A1B1}\right)$$



Comparison of data (fault signatures) before and after data correction

Measurement Selection

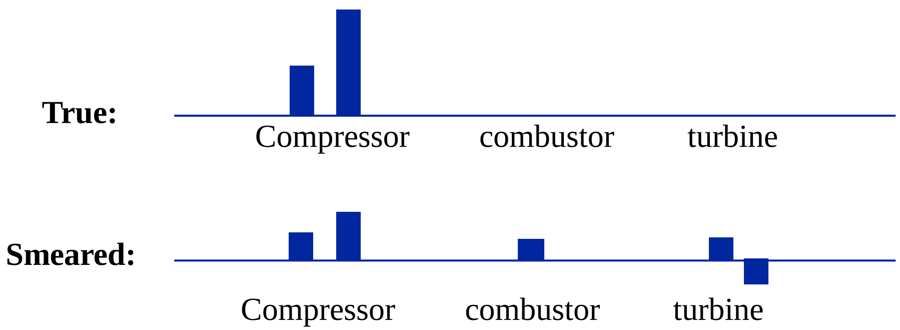
Measurement Selection Criteria

- Availability
- Number of sought faults & health parameters
- Sensitivity
- Correlation
- Sub-sets and global set
- Redundancy

Fault Isolation

Smearing Effect & CFC

- **Smearing effect:**



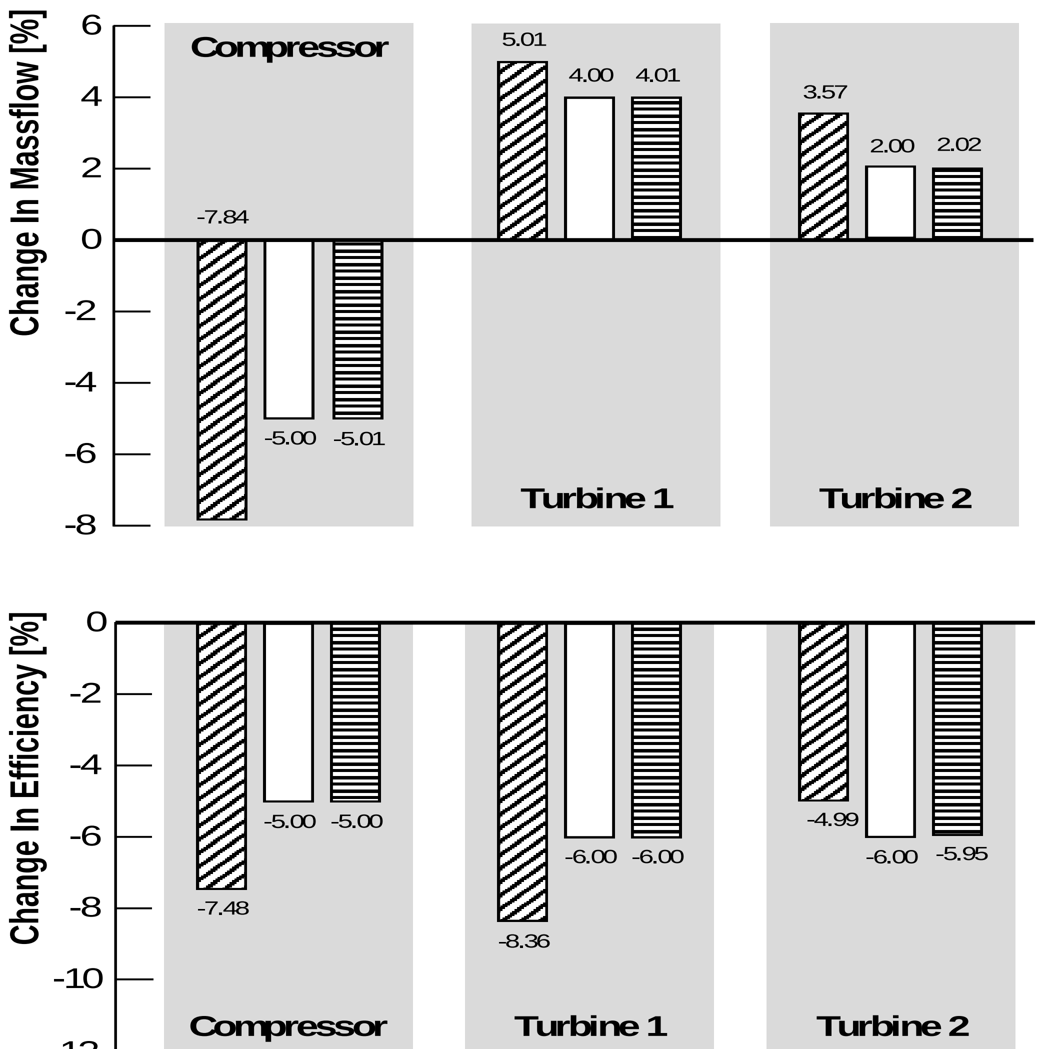
- **Component Fault Cases (CFC)**

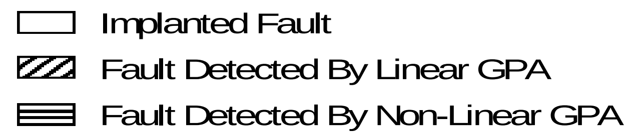
Component Fault Case	Pre-defined faulty components
CFC1	Compressor
CFC2	Burner
CFC3	Turbine 1
CFC4	Turbine 2
CFC5	Compressor + Burner
CFC6	Compressor + Turbine 1
CFC7	Compressor + Turbine 2
CFC8	Burner + Turbine 1
CFC9	Burner +Turbine 2
CFC10	Turbine 1 + TURBINE 2

Comparison between linear & non-linear GPAs

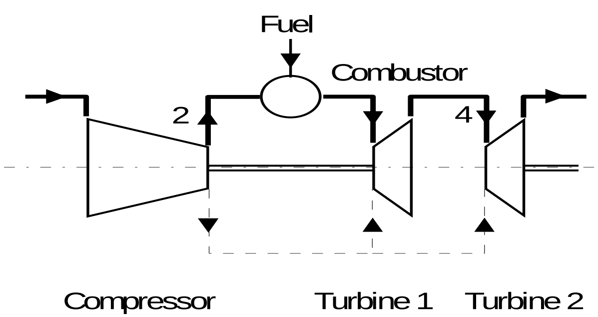
	Linear GPA	Non-linear GPA
Accuracy:	Low	Higher in general
Computation time:	Short	Slightly Longer
Convergence	No problem in general	May diverge

Well defined GPA

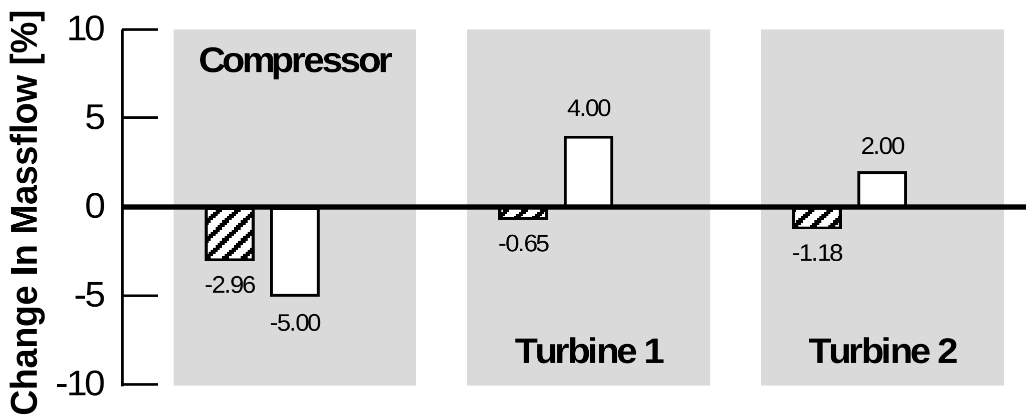




Monitored Parameters (where T is total temperature and P is total pressure):
Rotational Speed of Compressor, P_2, T_2, Fuel Flow, P_4, T_4



Poorly defined GPA

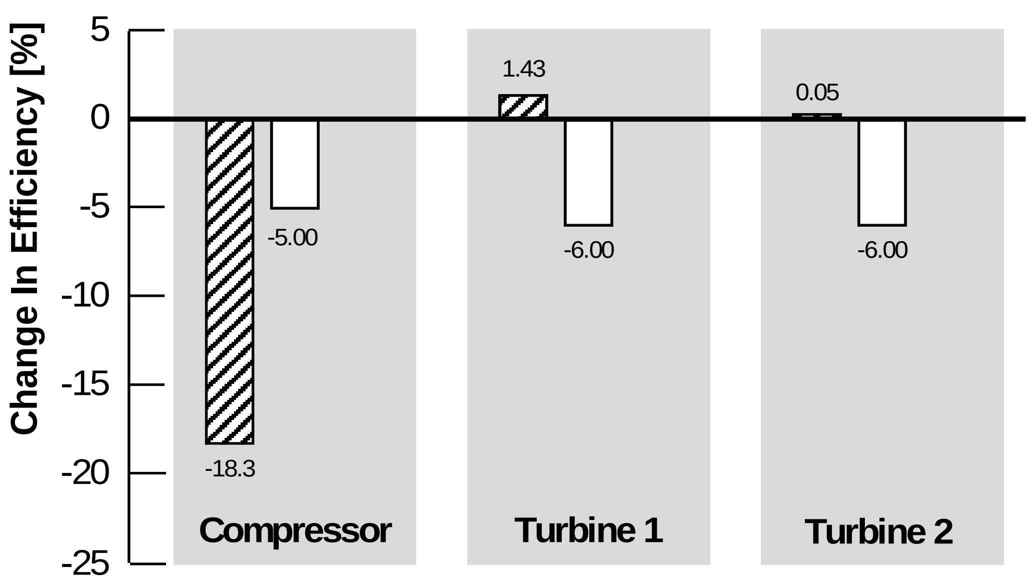


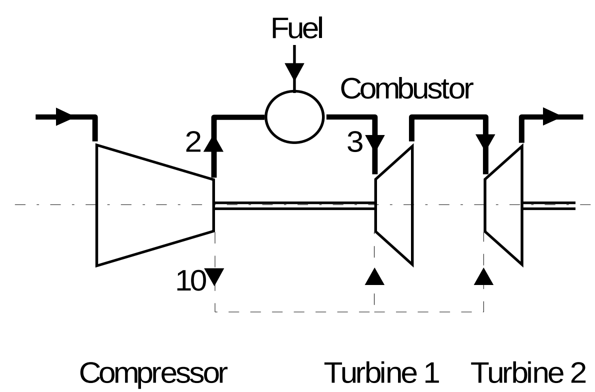
Implanted Fault

Fault Detected By Linear GPA

Fault Detected By Non-Linear GPA (Calculation did not converge!)

Monitored Parameters (where T is total temperature and P is total pressure): **P_2, T_2, P_{10}, T_{10}, P_3, T_3**





Demonstration of GPA diagnostic Application

Gas Path Diagnostics Methodology

Step 1: Performance Model Setup

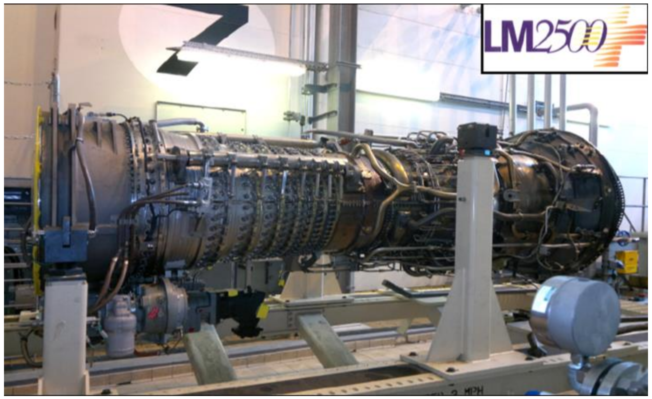
Step 2: Data Acquisition & Corrections

Step 3: Data Pre-processing

Step 4: Measurement Selection

Step 5: GPA Diagnostic Analysis

Step 1: Gas Turbine Model Sep Up & Adaptation

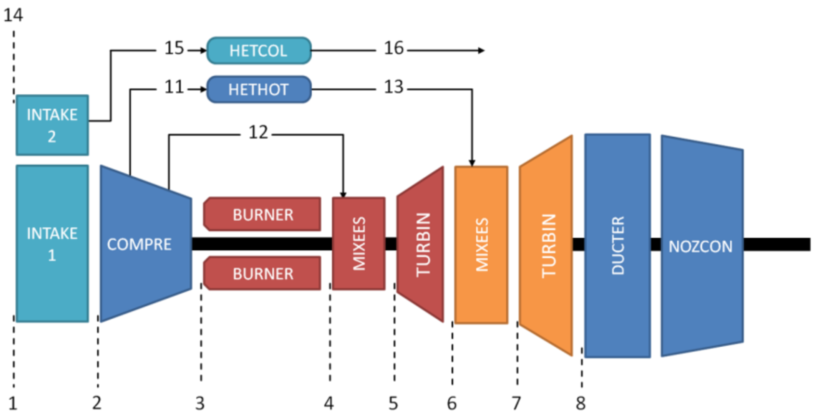


https://www.manxutilities.im/media/1138/welcome-to-pulrose-power-station.pdf

GE2500+ Engine

Performance Specification:

- **Power output:** **29 MW**
- **Thermal efficiency:** **38.8%**
- **Total pressure ratio:** **23.1**
- **Exhaust gas flow rate:** **83 kg/s**



Performance Model

Step 2: Data Acquisition & Correction

Measurement Data Selection

Make ensure that the selected data are at steady state conditions.

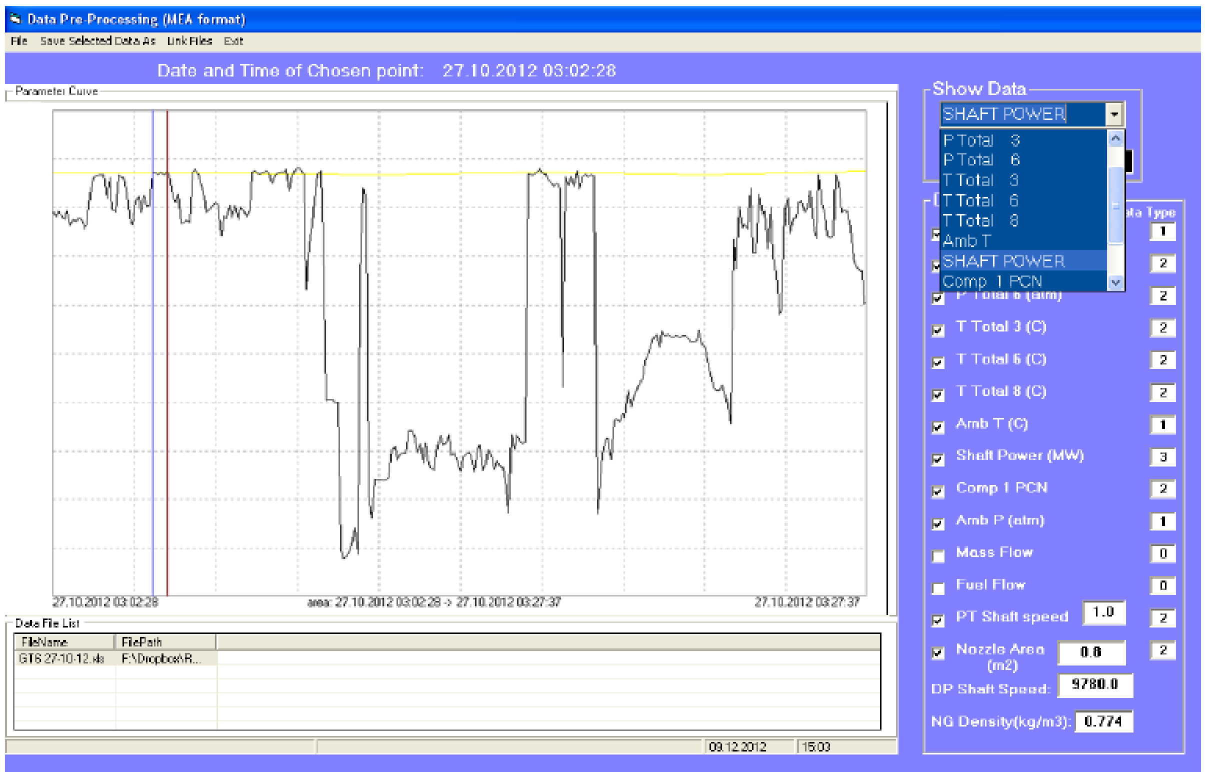
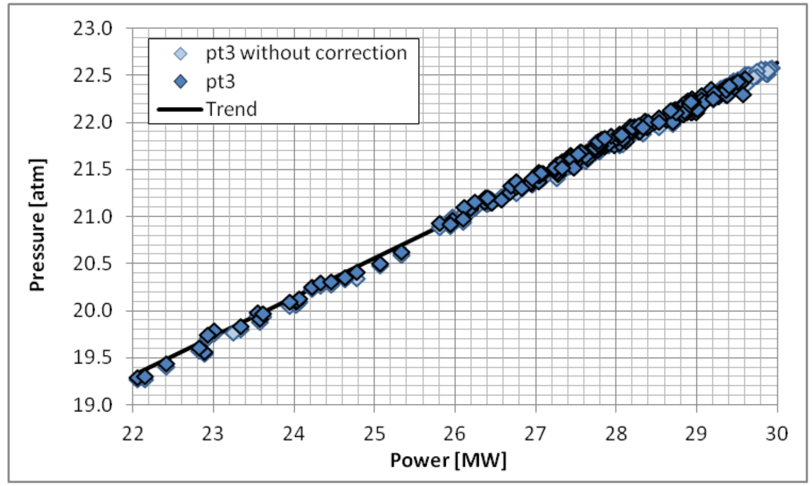
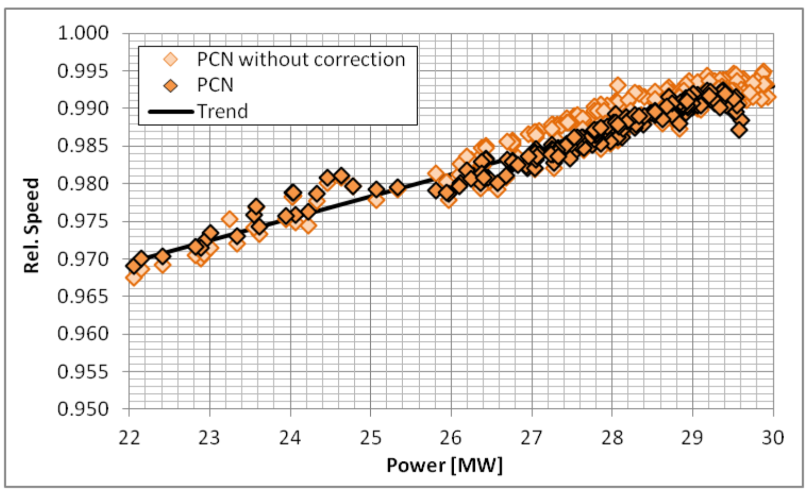


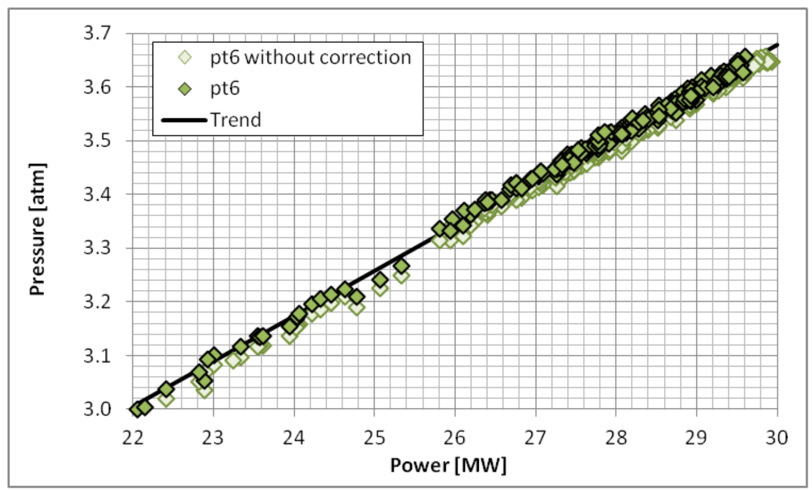
Fig. 8-21: PYTHIA data pre-processing

Step 2: Data Acquisition & Correction

No major changes in pressures and PCN after data corrections

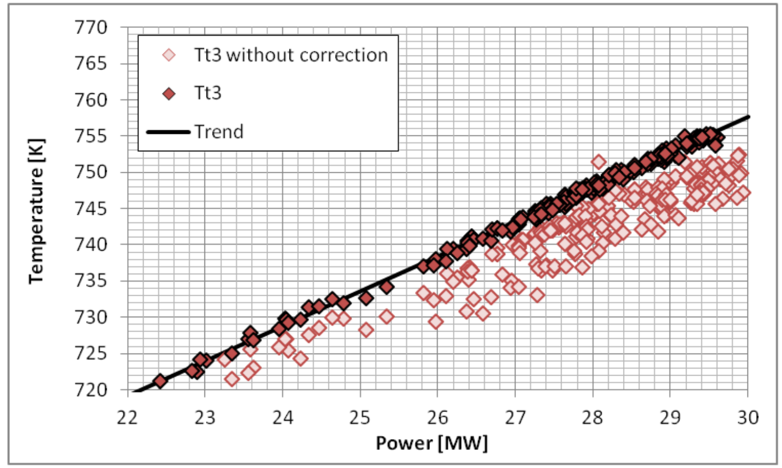


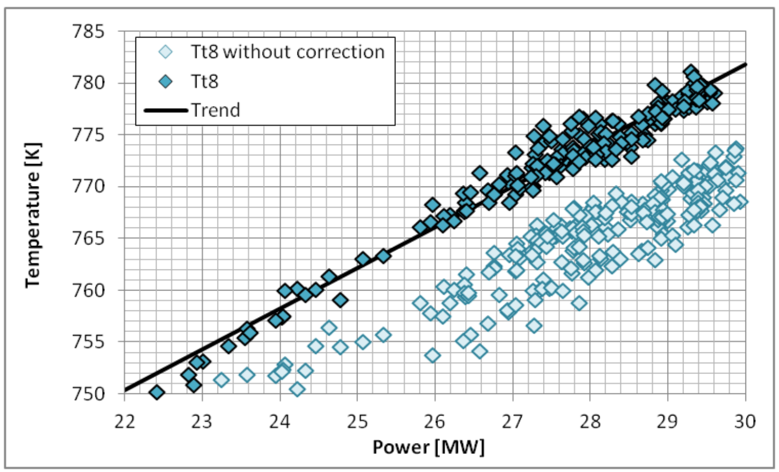




Step 2: Data Acquisition & Correction

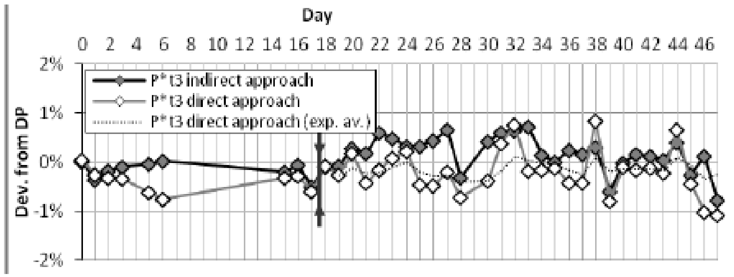
More corrections to temperature measurements



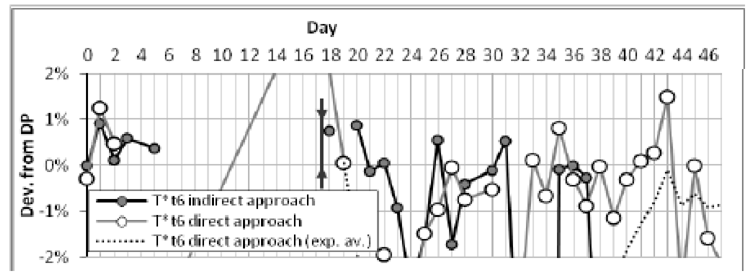


Step 3: Data Pre-processing

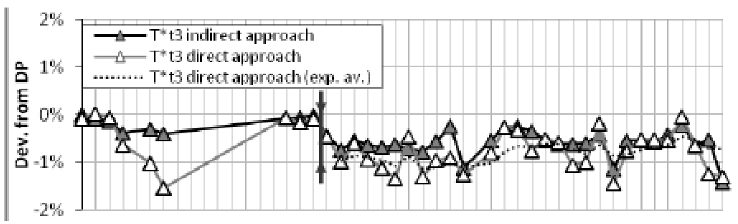
Data After Pre-Processing using Three Pre-processing Methods



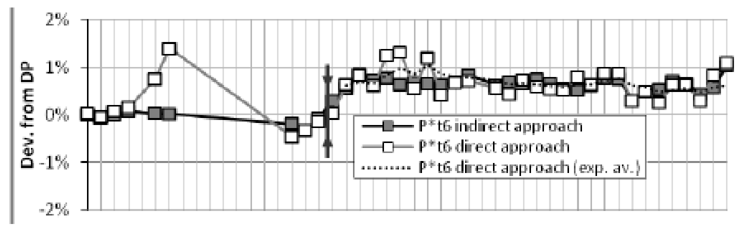
Compressor exit P_{t3}



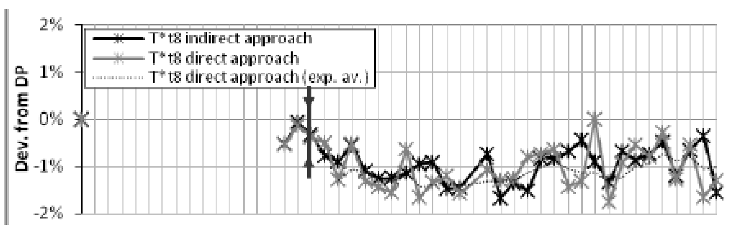
Compressor turbine exit T_{t6}



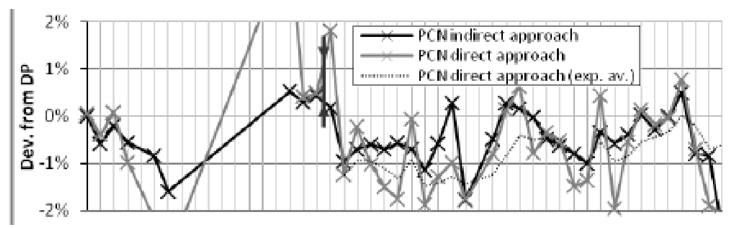
Compressor exit T_{t3}



Compressor turbine exit P_{t6}



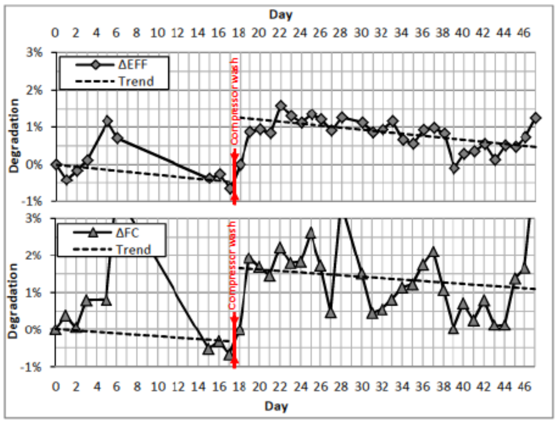
Power turbine exit T_{t8}



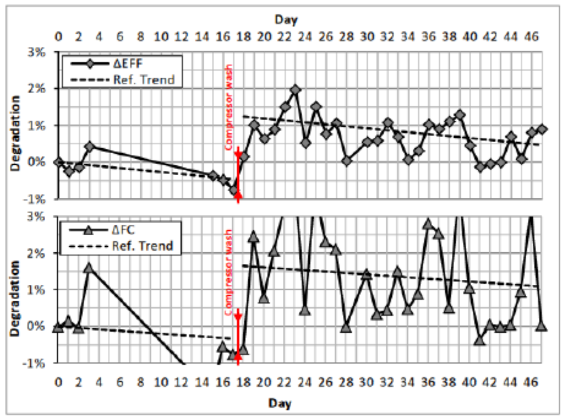
Compressor shaft speed PCN

Step 5: GPA Diagnostic Analysis

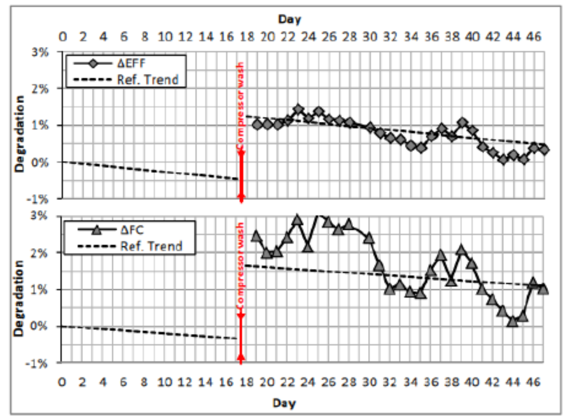
Comparison of Predicted Compressor Fouling



(1) Indirect Approach



(2) Direct Approach



(3) Direct Approach + Exponential Average

- **Indirect approach (1) provides smooth results**
- **Direct approach (2) is more convenient, but with more scattering**
- **Direct method + Exponential average (3) further reduces scattering (2)**
- **Trend line and the rate of degradation can be identified**
- **Compressor washing is clearly identified**

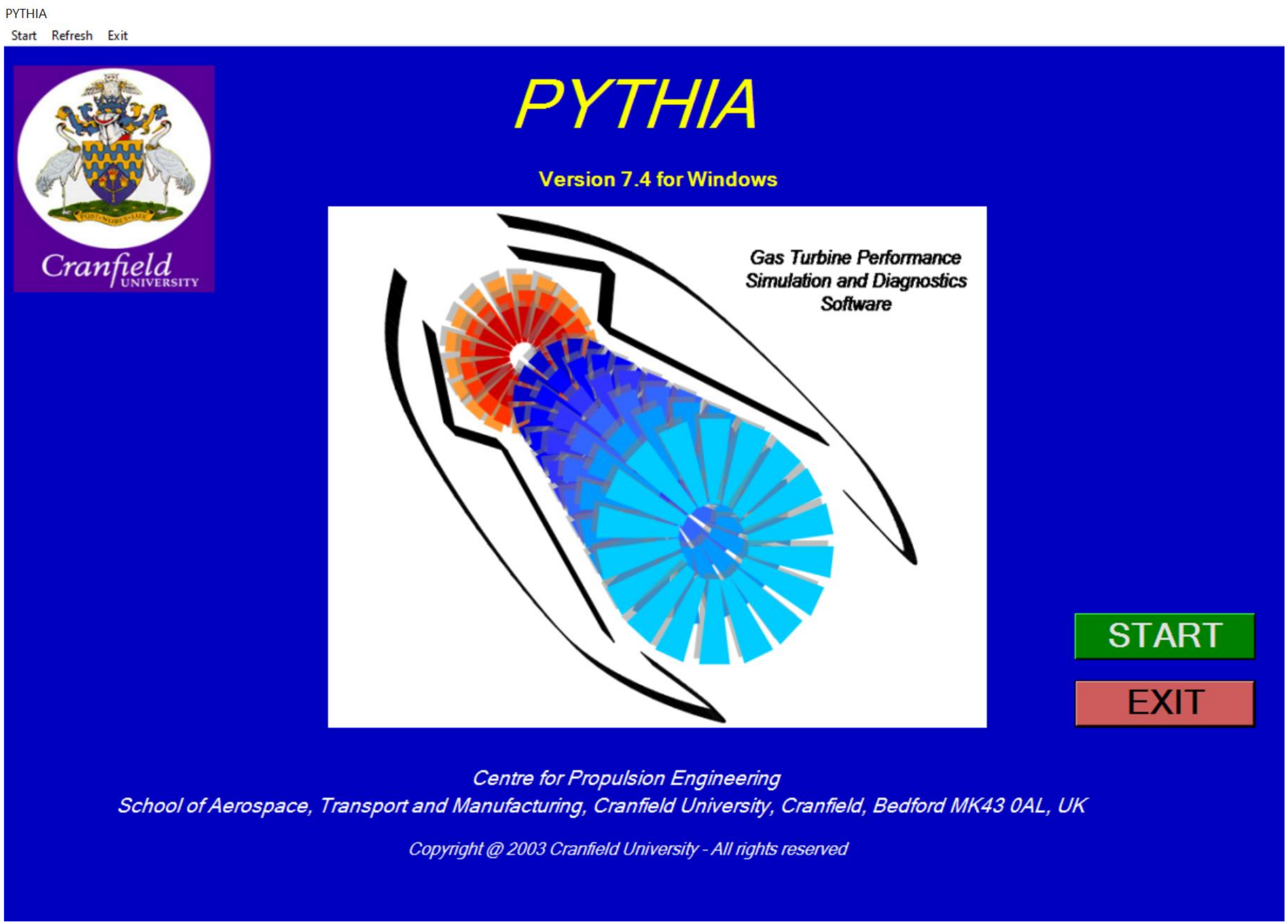
Summary of Diagnostic Analysis

- Fouling results in
  - ✓ 0.02% loss per day in flow capacity index
  - ✓ 0.02% loss per day in efficiency index

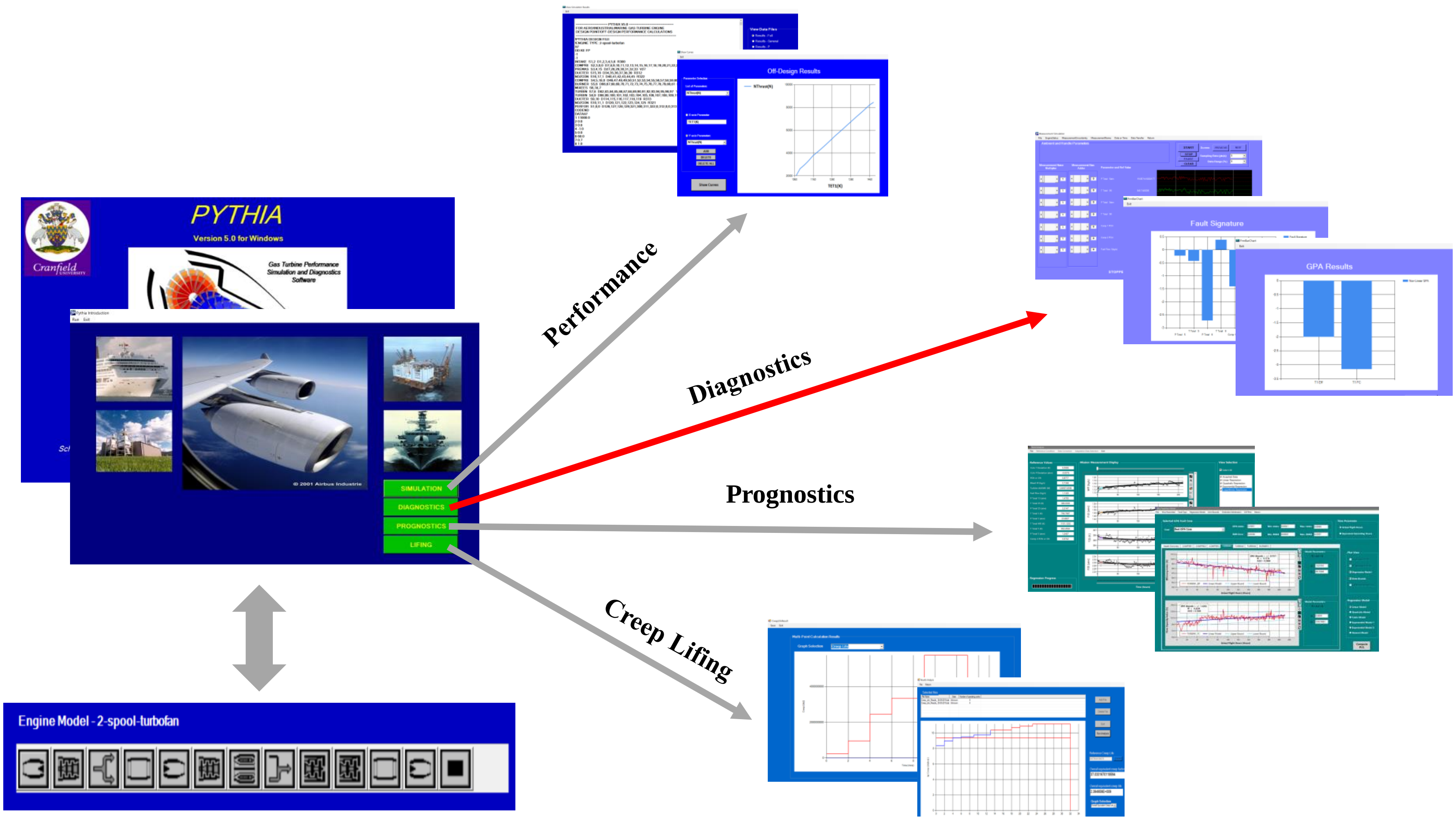
- Off-line compressor washing results in
  - ✓ 1.5% gain in flow capacity index
  - ✓ 1.0% gain in efficiency index

Demonstration of GPA diagnostics using digital twin Platform PYTHIA

Demonstration of GPA Diagnostics

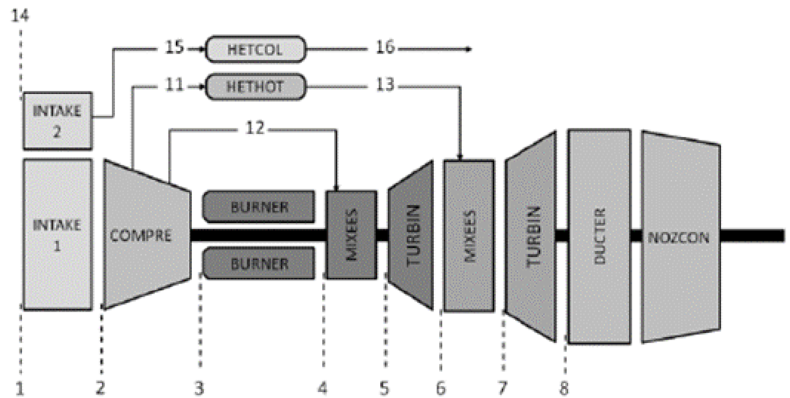


Demonstration of GPA Diagnostics



Engine Model

Demonstration of GPA Diagnostics



Configuration of a 2-shaft gas turbine model

Performance Specification (Sea Level Static ISA condition)

▪ Compressor pressure ratio:	21
▪ Turbine entry temperature:	1,550 K
▪ Exhaust gas flow rate:	80 kg/s
▪ Power output:	30 MW
▪ Thermal Efficiency:	39.8%

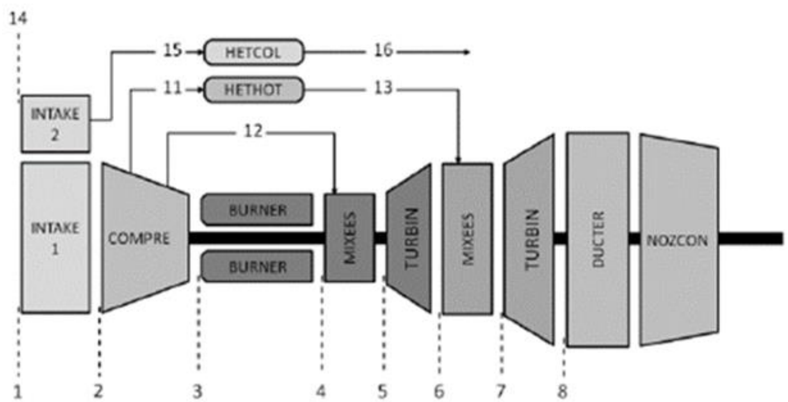
Demonstration of GPA Diagnostics

Faulty Component: turbine

Health parameters:

η_{c1} η_{b1} η_{t1} η_{t2}

Γ_{c1} Γ_{t1} Γ_{t2}



Measurement parameters:

PCN P_3 T_3 m_f $P6$ $T6$ $P8$ $T8$

Demonstration of GPA Diagnostics

Demo Phase 1
Simulation of Measurement Samples

- Implementation of degradation
- Measurement setting
- Run engine model and record measurement data

Demonstration of GPA Diagnostics

Demo Phase 2
Diagnostics Using Gas Path Analysis (GPA)

- **Upload measurement samples and select a sample**
- **GPA setting**
- **Run GPA to predict engine degradation**
- **Run GPA to predict a sensor fault**