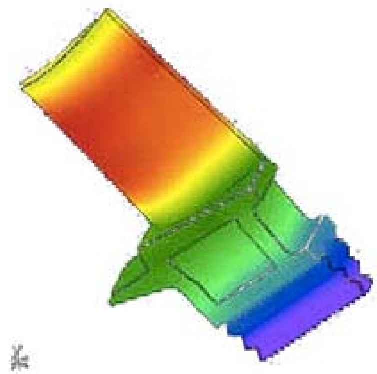
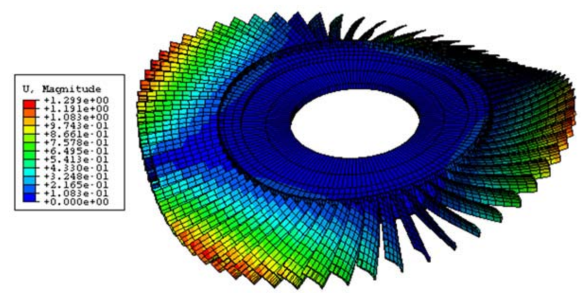
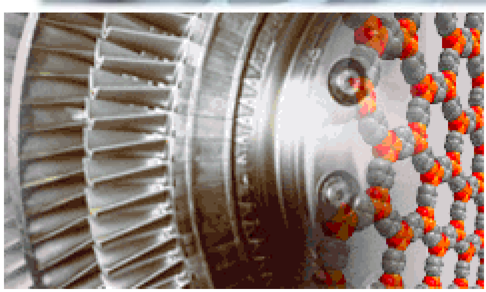
LIFE PREDICTION TECHNOLOGIES, INC

Unit 23, 1010 Polytek Street, Ottawa, ON, K1J 9J1 Canada.
Tel: 613-744-7574; **Fax**: 613-744-5278; www.lifepredictiontech.com

Validation of XactLIFE Prognostics (predictive maintenance) System for Gas Turbine Components

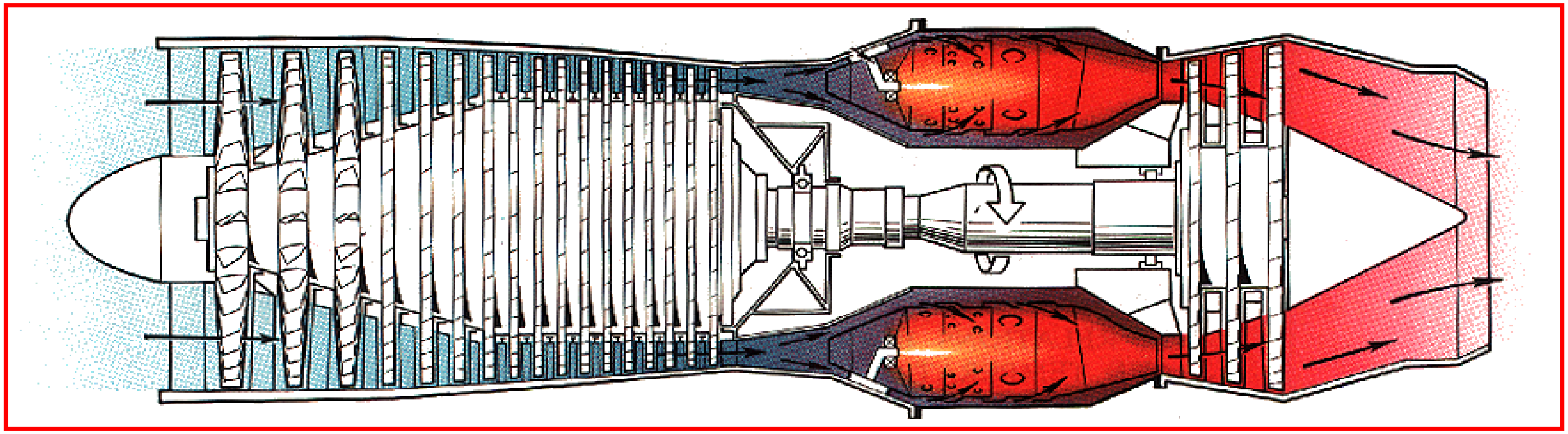






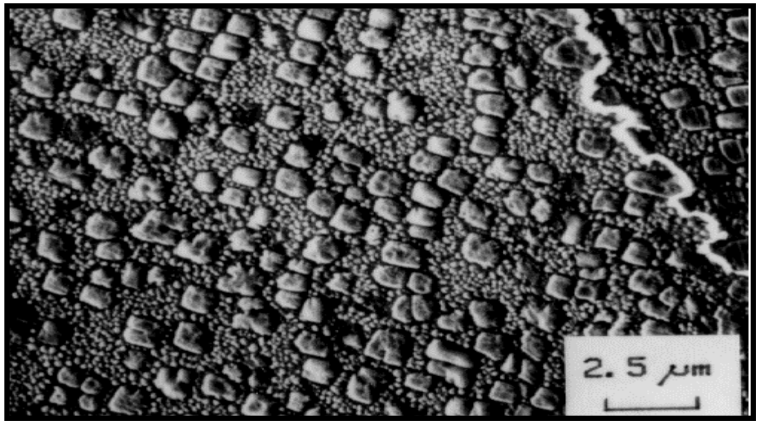
LPTi delivers world-class prognostics systems and services for turbines and other mechanical structures to dramatically reduce the cost of engine fleet ownership through exact and reliable life assessment, life extension, optimized overhaul intervals, health management and engine efficiency. Our products and services are useful for repair and overhaul facilities, operators, third party parts manufacturers, OEM's and the consultants in the aerospace sector, petro-chemical industries, gas & oil and marine applications.

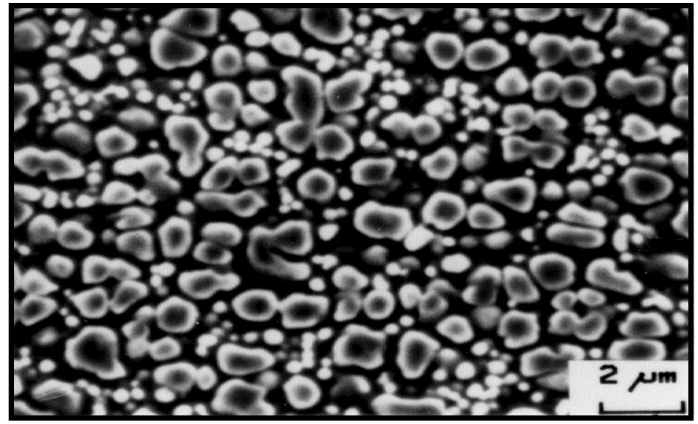
Damage Modes in Engines

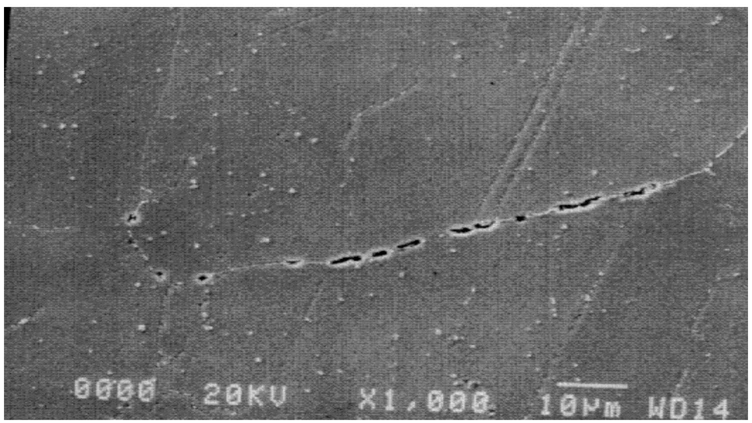


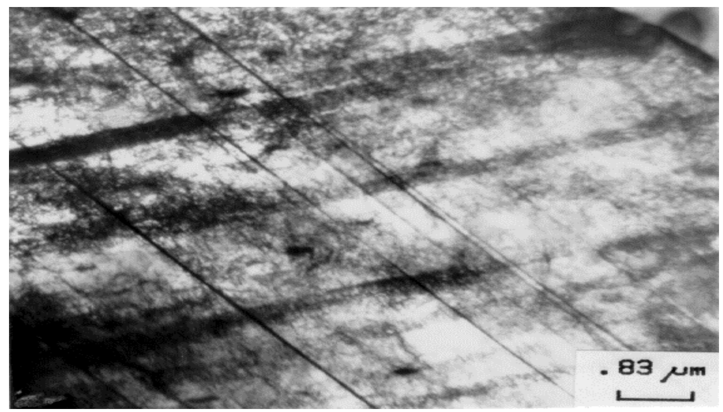
Erosion, Corrosion	**Oxidation, Hot Corrosion**
Fretting Wear	**Thermal Fatigue, TMF**
HCF	**Fretting, Creep, HCF, LCF**
LCF	**Microstructural Aging**

Internal Damage (Microstructural Aging)



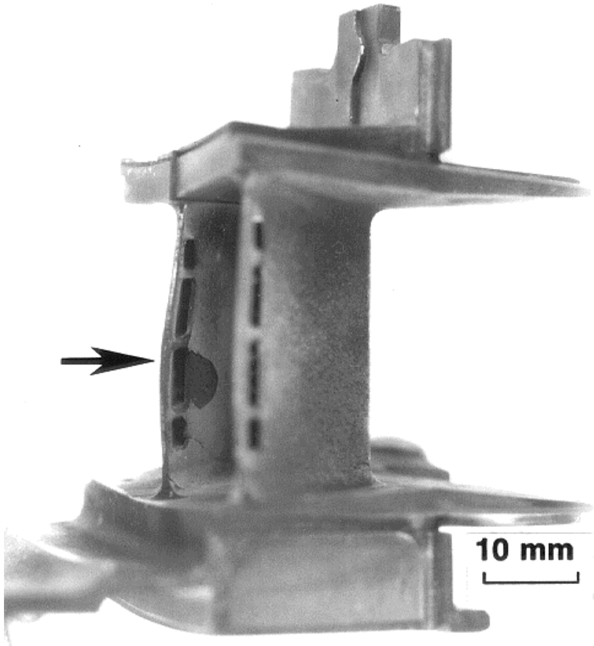






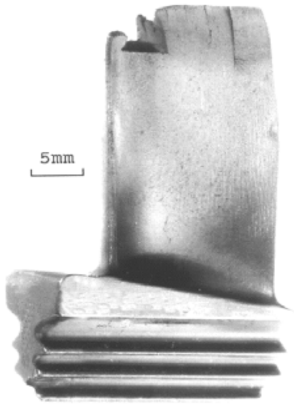
- Precipitate reactions and aging
- Cavitation and LCF-PSBs

Distortion and Cracking



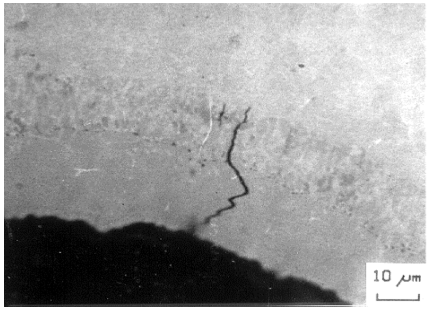
Bowing and crackingof NGV airfoil

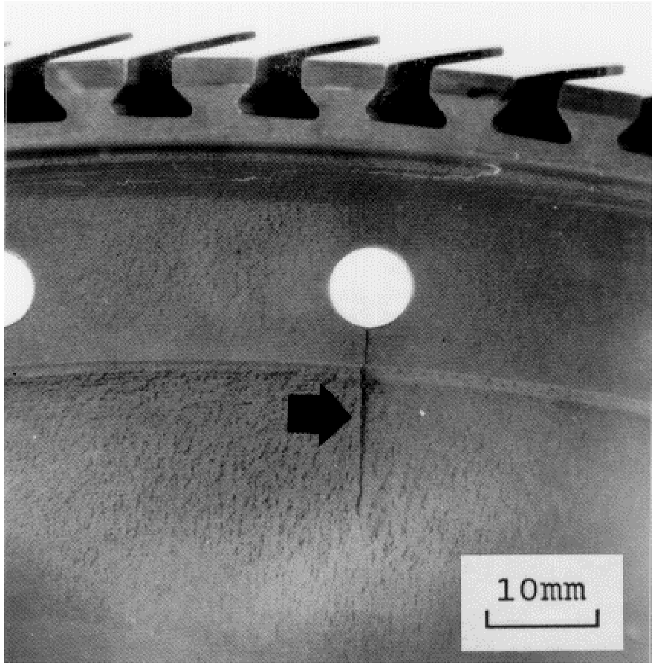
Loss of protective coating



Blade tip cracking

Coating crack



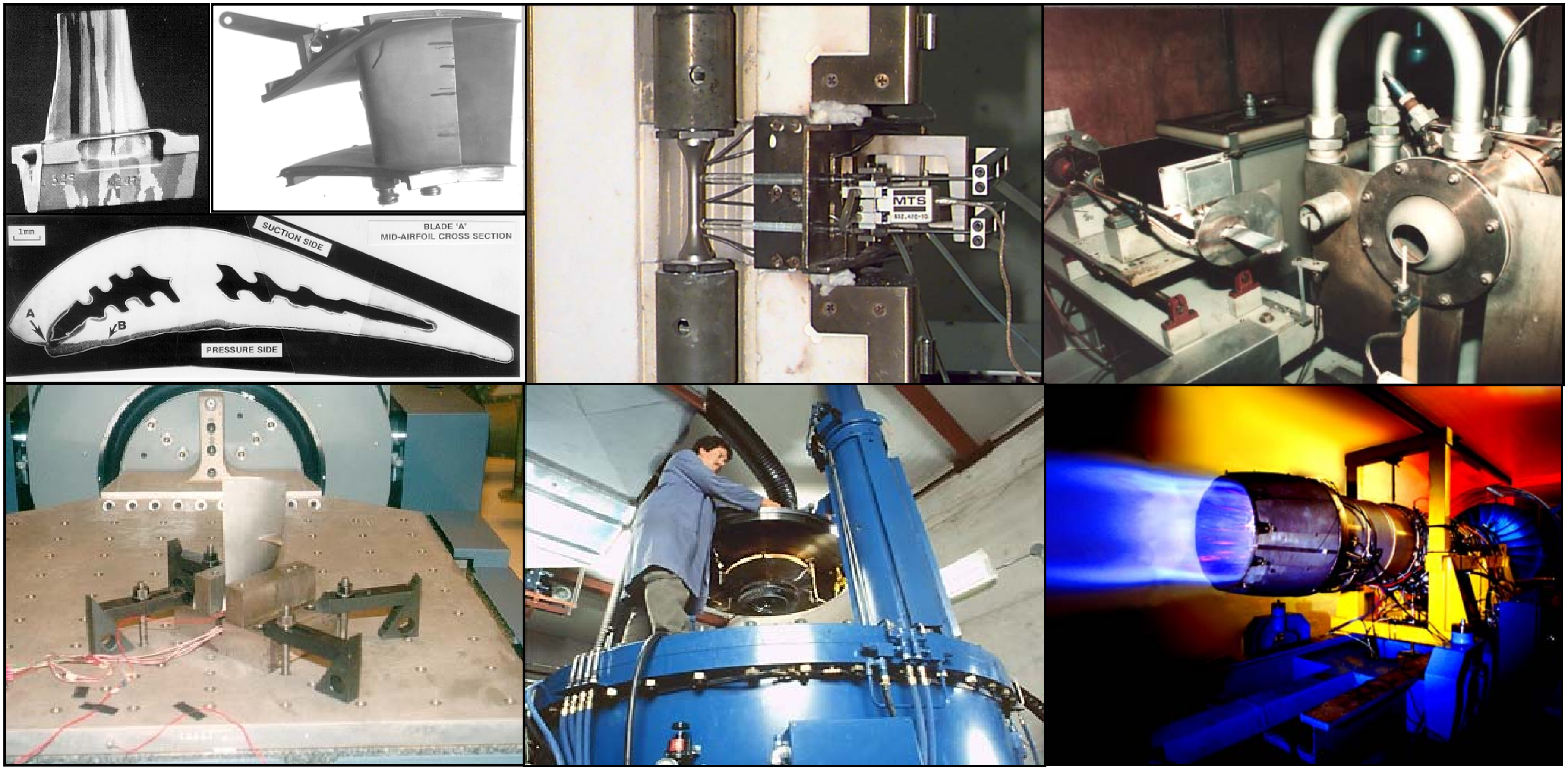


LCF crack in compressor disc initiating at bolt hole

Engineering Requirements (ENSIP Guide)

- Component level design, durability and damage tolerance assessment including design margins
- Component level life cycle management of both durability critical and fracture (safety) critical parts and parts life tracking
- Repair and overhaul (*ERSIP*)
- Qualification or verification testing
  - Qualification through analysis
  - Qualification through testing (coupon level, parts level, rig level and full scale engine testing)
- Reliability

Qualification Testing



Limitation of Qualification Testing

- In Burner Rig tests on blades, temperature profile can be duplicated but centrifugal loads can not be applied
- In Spin Rig tests on discs, temperature profile can not be duplicated and the test is carried out in vacuum
- In Shaker Rigs, neither the effect of centrifugal loads nor the influence of temperature profile on blades can be duplicated
- In AMT such as ASMET, cyclic effects can be duplicated but the time dependent damage accumulation is limited
- In AMT conducted at higher TIT, precise time dependent effects can not be duplicated

Analytical Life Prediction Techniques

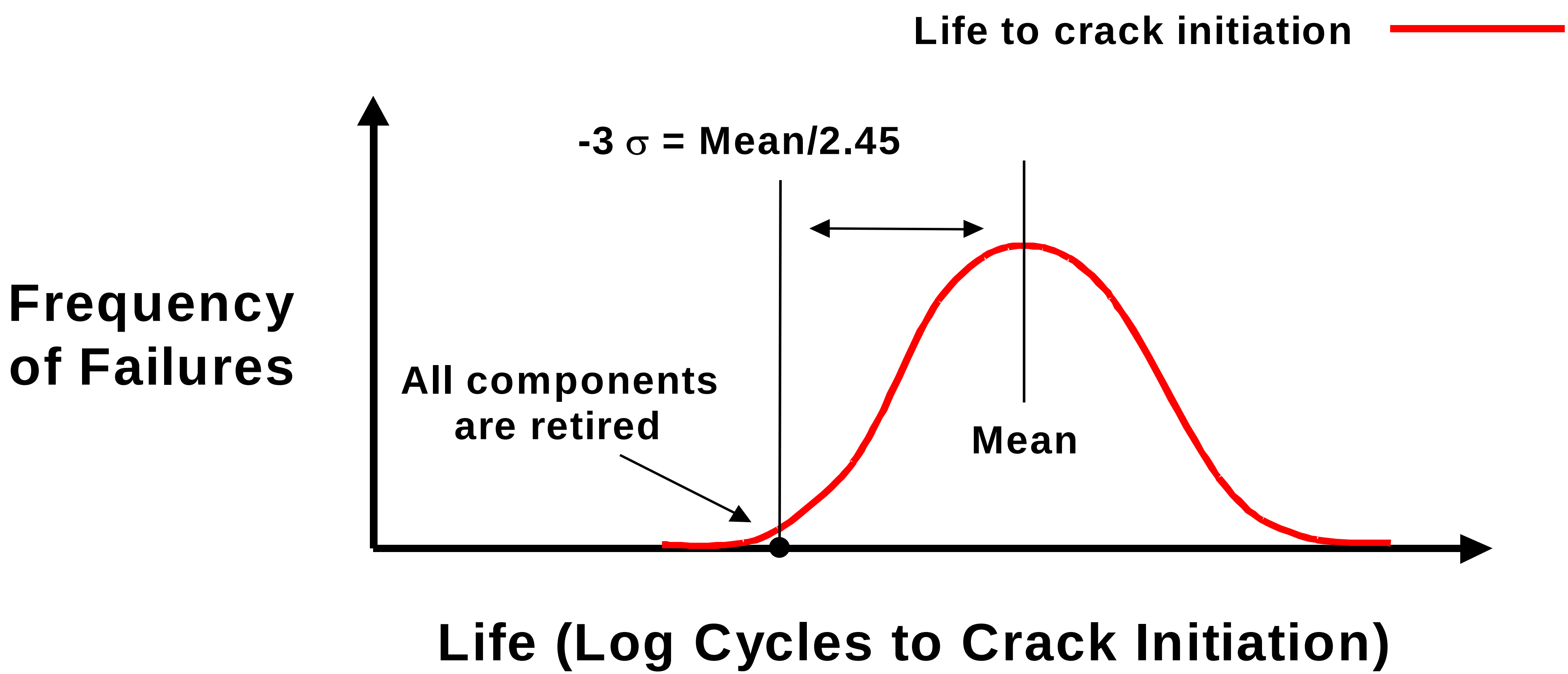
Empirical Models

- Creep
  - Larson Miller Parameter
  - Monkman Grant Type Relationships
- Low Cycle Fatigue or TF or TMF
  - Manson Coffin Type Relationship
  - Frequency Modified Approach
  - Energy Approaches
- Crack Growth
  - Paris Relationship
  - Forman Type Relationships
  - Short Crack Growth Models
  - Thresholds

Limitations

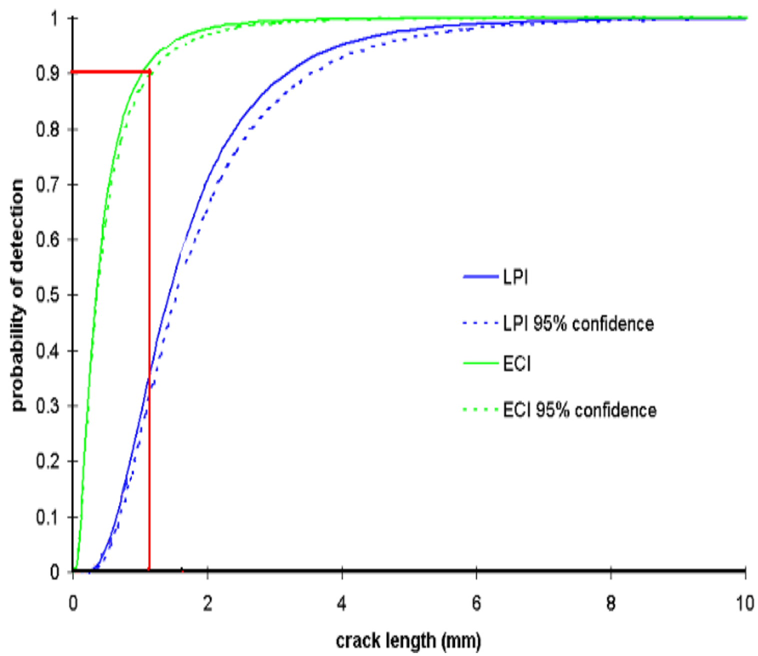
- Material treated as a continuum (GB, IPB, IDB, Hard Particles should be treated as material discontinuities)
- Test data intensive models
- Microstructure evolves during service

Economic Life Parts LCMM Philosophy



Physics Based Modeling -Assumptions and Definitions

Safe Life based on life to form an 0.8 mm surface crack and this definition is arbitrary. Using a crack depth of 0.8 mm is more Realistic.



In physics based modeling

Life = $t_{N} + t_{SCG} + t_{LCG}$

In the case of forgings

t_{N} – 1 to 3 Grain Diameters, t_{SCG} is 3 to 10 Grain Diameters and t_{LCG} is beyond 10 grain diameters. An 80 μm grain size yields a crack size of 0.8 mm within 10 grain diameters

In castings, t_{SCG} is negligible due to their large grain size

XactLIFE System

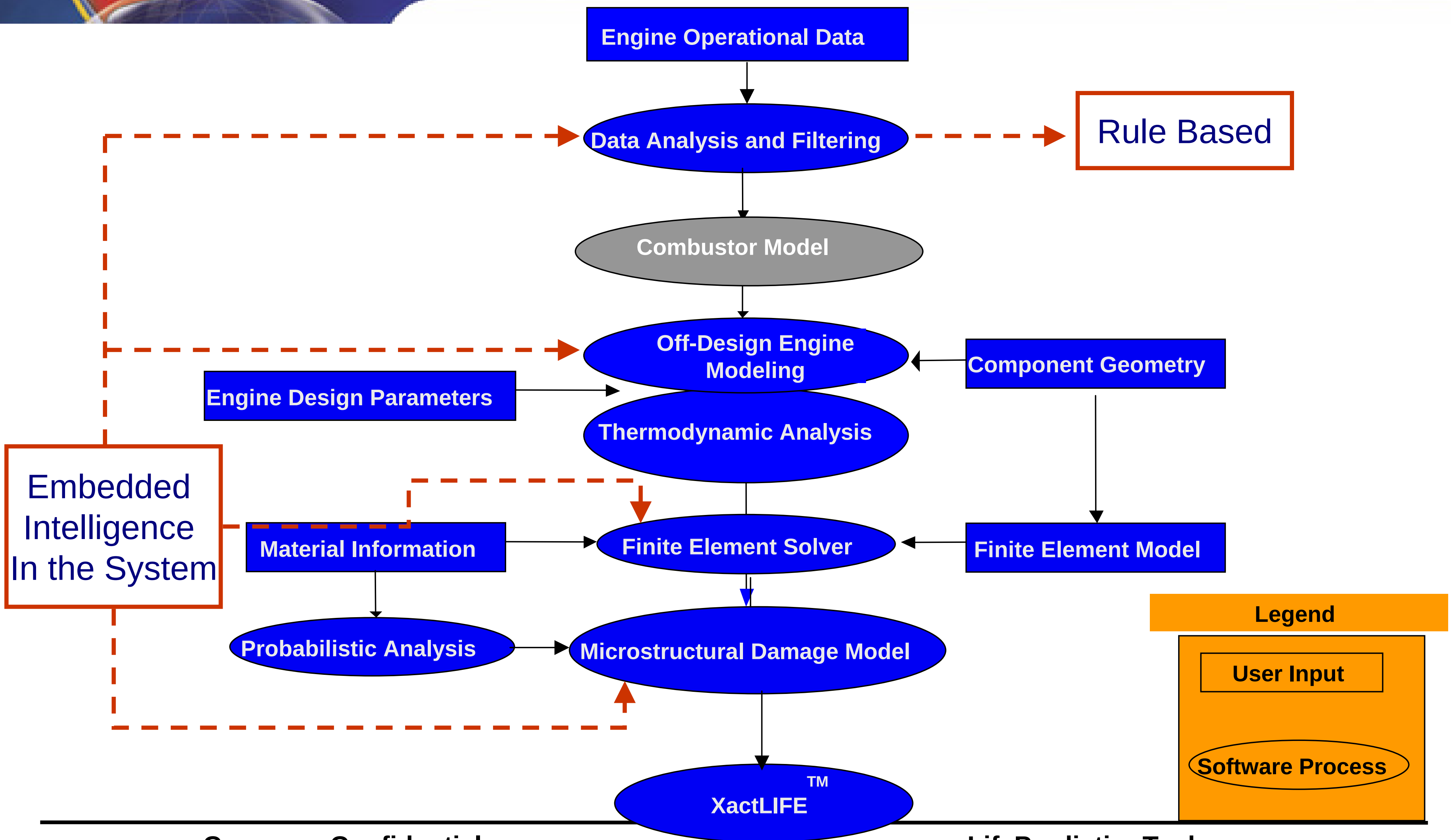
Software verification and validation (IEEE STD 610)

Verification: ***The process of evaluating software to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase.***

Validation: ***The process of evaluating software during or at the end of the development process to determine whether it satisfies specified requirements.***

XactLIFE™ System Architecture

(US Patent No. 8,116,990 B2 & Canadian Patent No. 2,604,118)

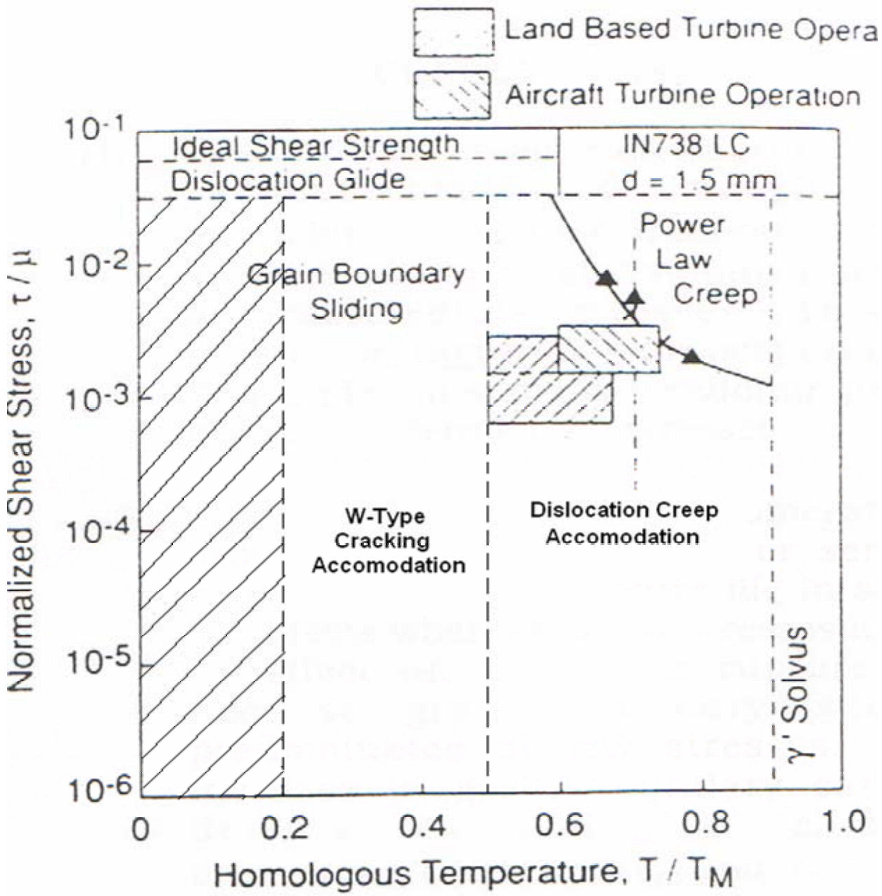


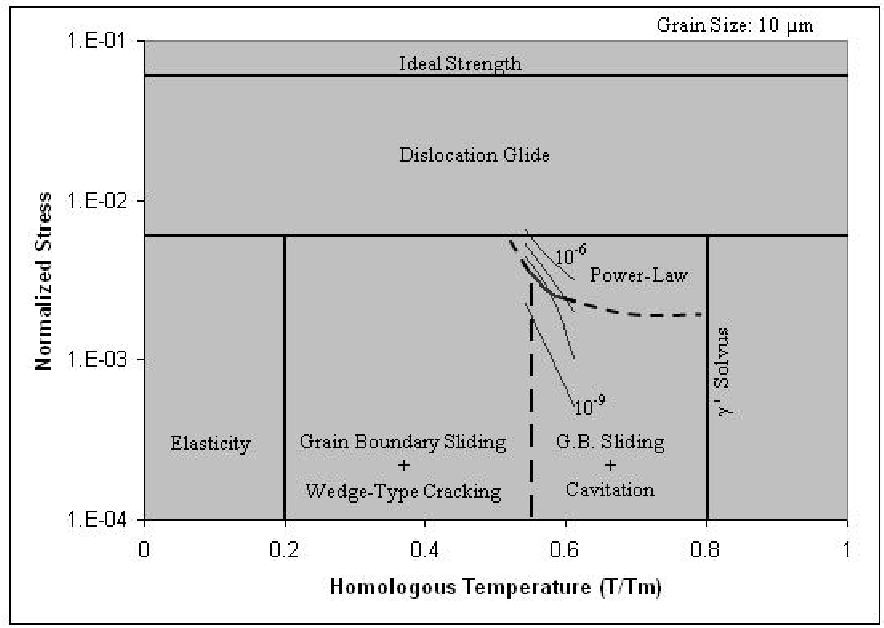
Operational Data Filtering

Material engineering based fuzzy logic by which creep and LCF 'load segments' are filtered from raw operational data

- Filter out: fatigue reversals, plastic fatigue cycles and creep loading
- Remove non-damaging loads
- Maintains order of load segments as this can affect damage accumulation.
- Parameter limits defined to ensure incoming data is acceptable. If exceeded, will store data for future review. E.g. Bad data due to defective sensor

Basis for Embedded Intelligence





IN738LC

DA 718

Physics Based Damage Models

- Low Cycle Fatigue (LCF)
  - Transgranular
  - Intergranular
- Thermal Mechanical Fatigue (TMF)
- Creep Damage in Hot Section Parts
  - Forged Components
  - Conventionally Cast Components
  - DS/SX Components
- Damage Tolerance (FCGR, CCGR)
  - SGR
  - LCG
- Coating Damage Models
  - Aluminides
  - MCrAlY
  - TBC

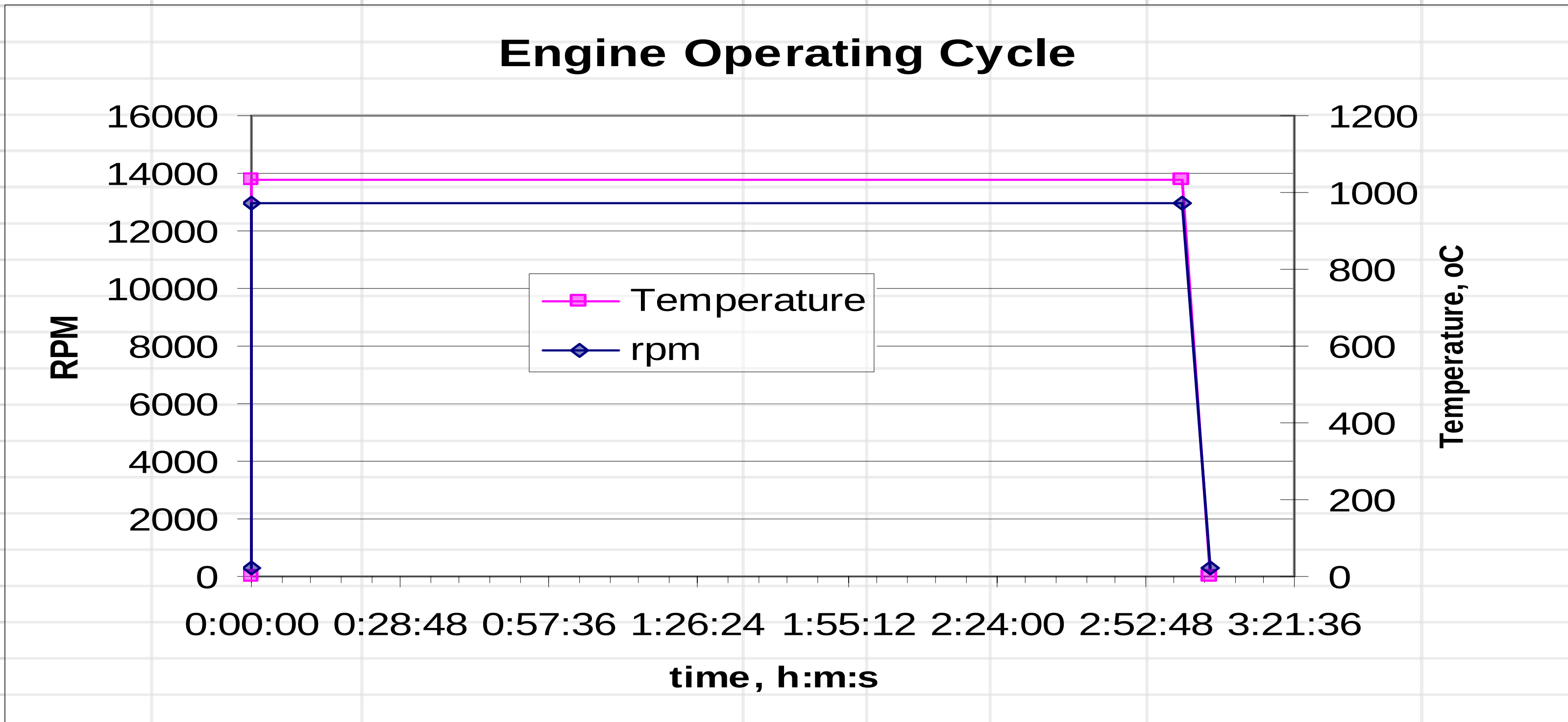
Verification Testing of a Feature and Its Documentation

Feature	Engineering Testing (LPTi)	Software Testing (Third Party)
Damage Model	Unit	Unit
Damage Module	Module	Module
GUI	Some	Extensive
System	Extensive	Extensive

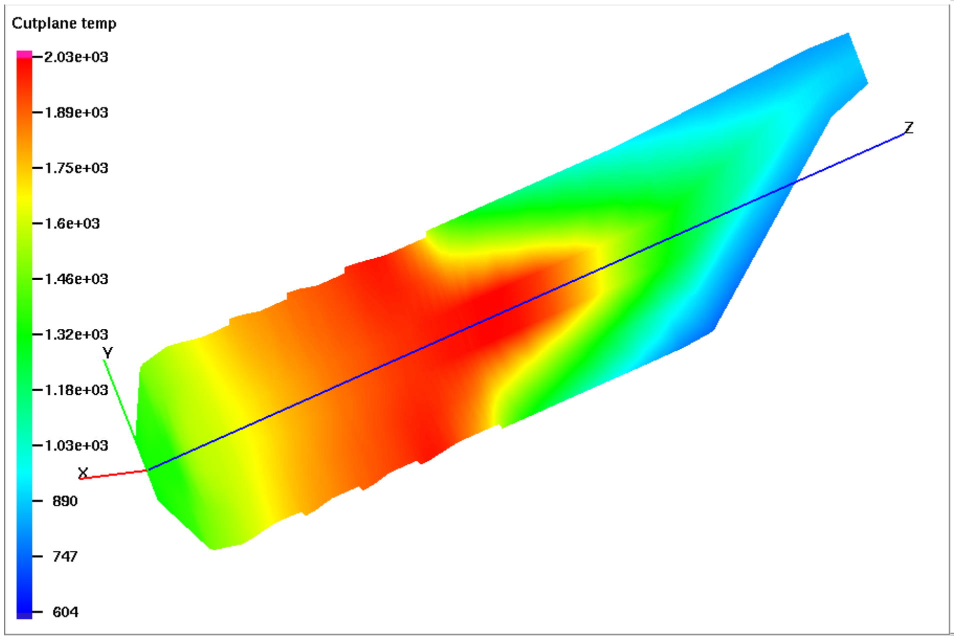
1. Bugs, 2. Crashes, 3.Accuracy, 4. Repeatability

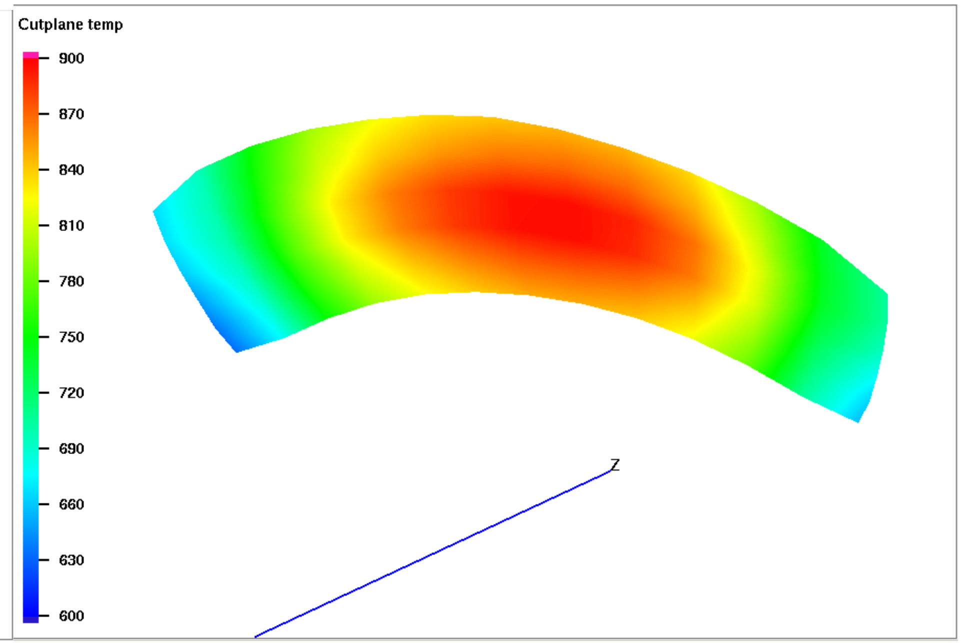
Mission Profile T56 blade

time, sec		incremental, dd/mm/yyyy h:mm:ss	rpm	Temp. , oC	Altitude, m	Forward Speed, m/s	
cumulative	incremental	time	rpm	temperature	altitude	forward speed	Comments
0:00:00	0:00:00	05/01/2004 0:00:00	0	25	0	0	shut down
0:00:10	0:00:10	05/01/2004 0:00:10	13810	971	9144	172	t/o
3:00:10	3:00:00	05/01/2004 3:00:10	13810	971	9144	172	cruise
3:05:10	0:05:00	05/01/2004 3:05:10	0	25	0	0	shut down



Combustor Model



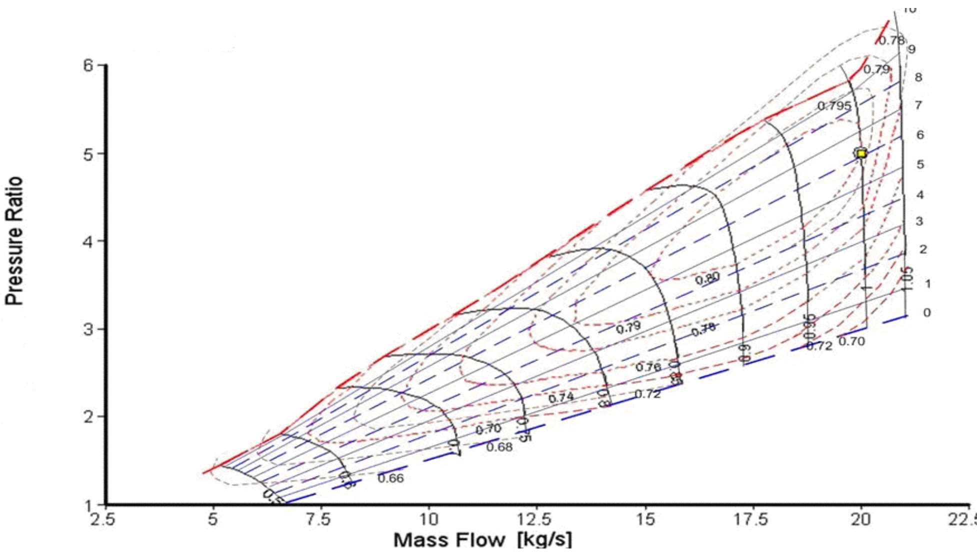


Embedded Off-design Engine Modeling

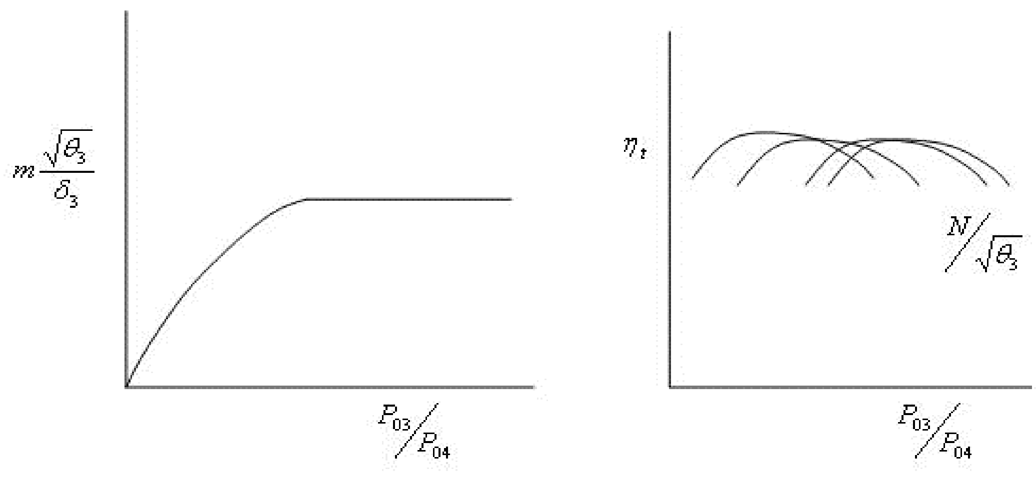
Accommodate full range of engine operating conditions

- Calculates input parameters to the turbine model by an iterative algorithm which matches compressor and turbine turbomachinery maps

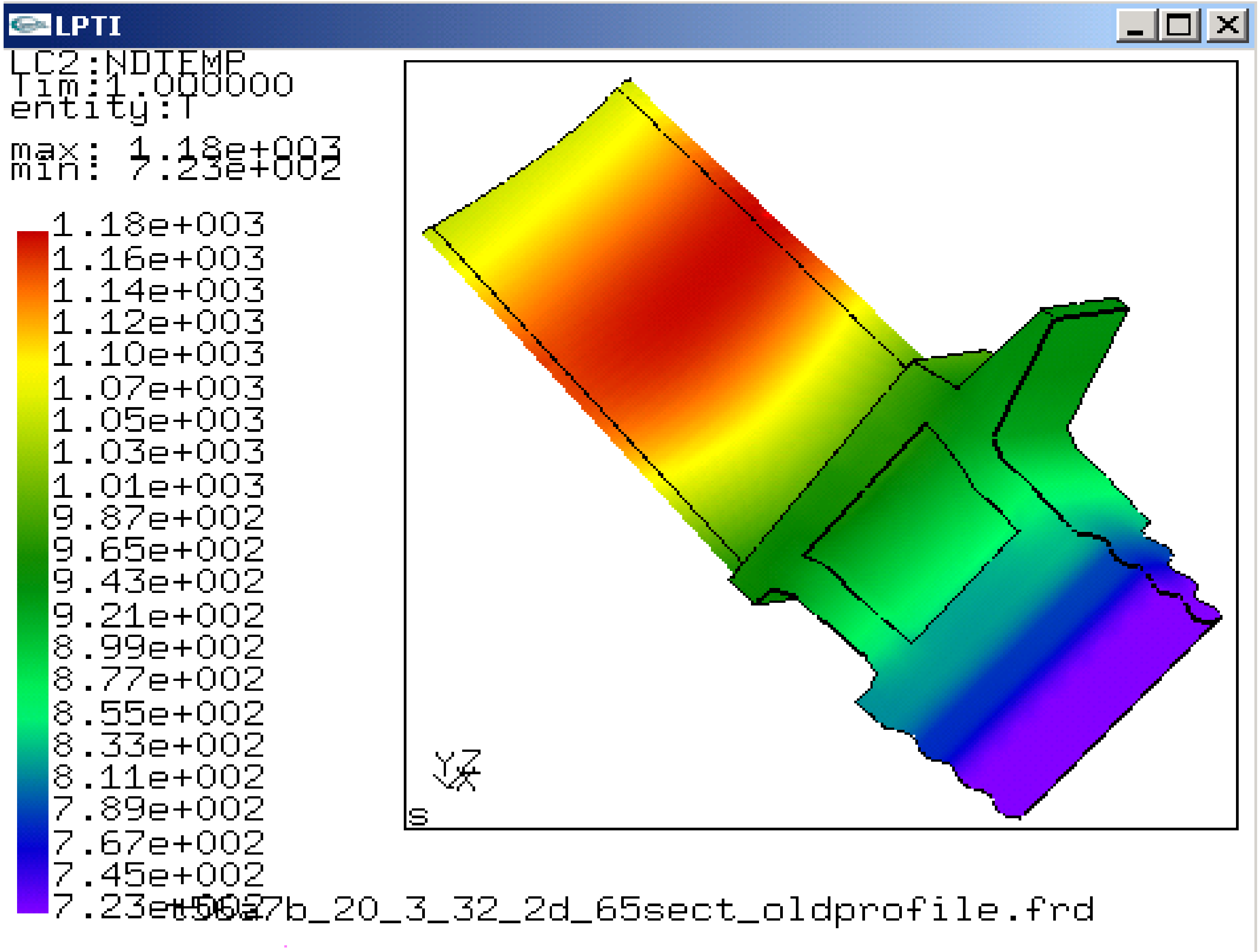
Sample Compressor Map



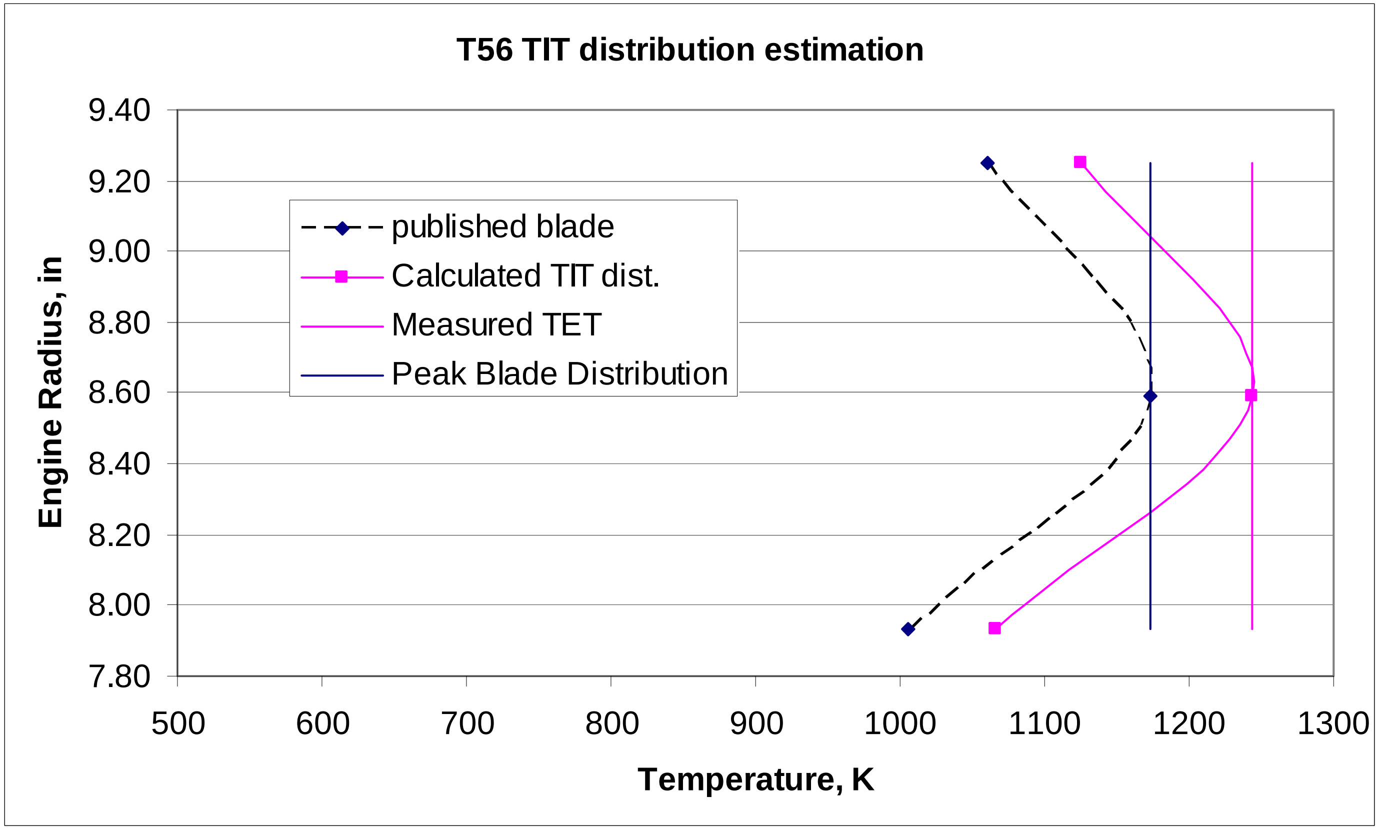
Sample Turbine Maps



Temperature distribution along the pressure (concave) side of the T56 A7B blade



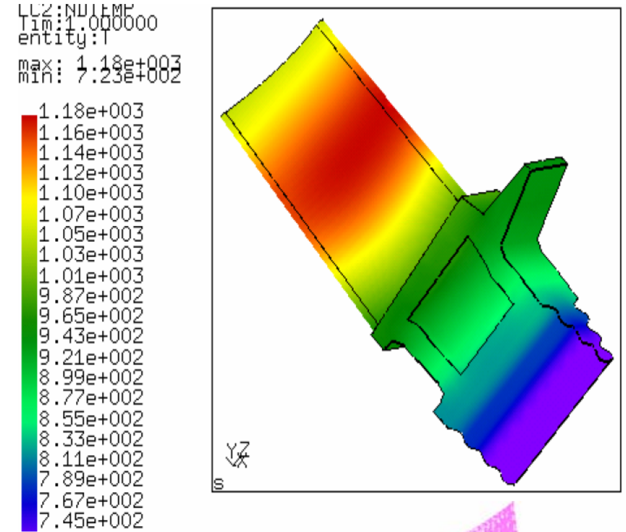
Computed TIT distribution and chord-wise blade temperatures



Validation Test case1

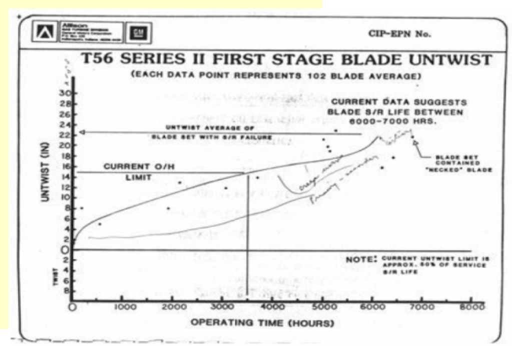
Project: Safe Life analysis of 1st stage Turbine Blade

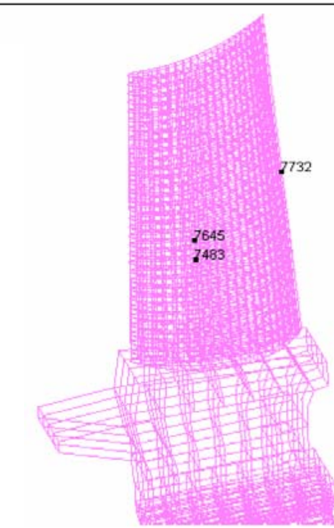
- **Client:** DND, Canada
- **Engine:** T56 A7B
- **Highlights of the Project:**
  - XactLIFE™ Creep life analysis predicted the safe life to be around 6000 hrs
  - The creep life with the Larson-miller analysis is 184,000 hrs compared to the LPTi life prediction of 5,900 hrs
  - CIP data available indicates the blade necking occurs at approximately 7000 operating hrs thus substantiating the XactLIFE™ damage modeling capabilities

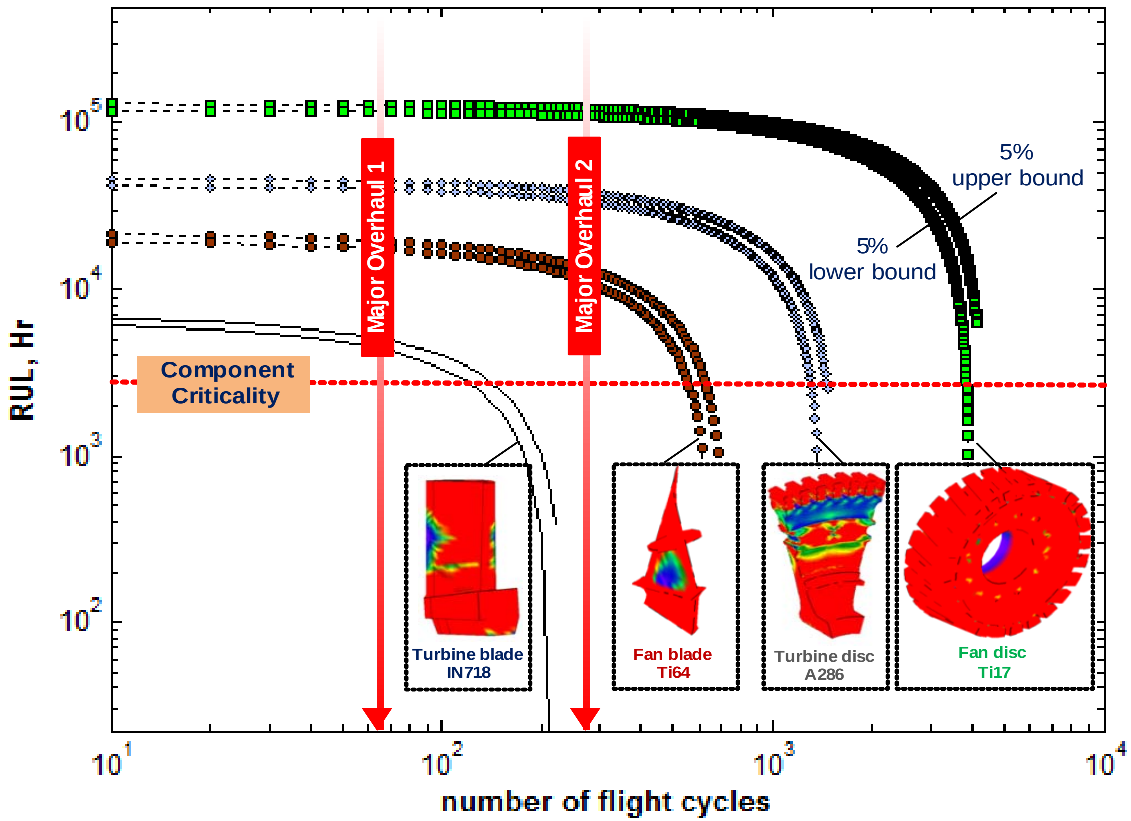


Results:

	Larson Miller	LPTi microsturctural creep model
Model input	50	7% failure strain
Creep Rupture life, hrs	184,198	5,932







RECOMMENDATIONS BASED ON ANALYSIS

- Typical overhaul interval of 1600 hours is used for aero-engine operating in theatre, so RUL should be at least equal to this interval
- Engine core comprising of disc, spacer, cooling plates and shaft should have considerably larger RUL in them, and these components can be maintained with ENSIP based LCM methodology
- It is observed that the turbine blade is most fracture prone and overhaul intensive component, which should be refurbished with recoating and other rejuvenation techniques to last till the second Major Overhaul and reduce ownership cost

Importance of Analysis & Physics Based Prognostics

- Prediction of a potential problem under exact engine operating conditions

- Prediction of future fault progression under exact engine operating conditions

- Recommendations of actions using reliability analysis and CBM