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Gas Turbine Materials/Components Life Evaluation & Extension Programs

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Presentation Outline

- Introduction to NRC Programs on GT
- GT Component Life Estimation and Extension
- Capability Guide
- Surface Modification Programs at NRC
- Some Examples of recent initiatives
- Concluding Remarks

NRC Key Sectors

Criteria

- **Important, or will be important, to the Canadian economy**
- **R&D and knowledge-intensive - innovation plays a key role to their success**
- **Ones in which NRC's innovation impact can make a significant positive contribution to Canada's economy**

Aerospace ☆

Agriculture

Automotive

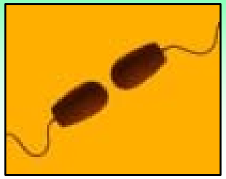
Manufacturing ☆

Bio-Pharma ☆

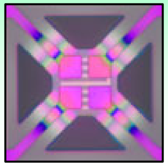
Chemicals

Construction ☆

ICT ☆



Electronic Instruments



NRC-IAR structure

Director General

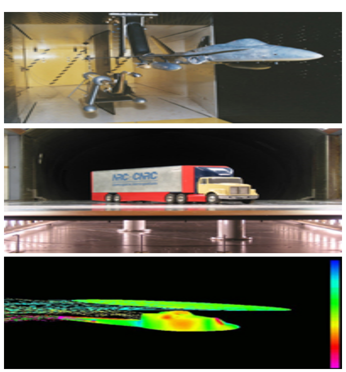
Aerodynamics Laboratory
- Fixed-wing Aerodynamics
- Rotary-wing Aerodynamics
- Surface Vehicles and Structures
- Montreal Road Wind Tunnel Facilities
- Uplands Wind Tunnel Facilities

Aerospace Manufacturing Technology Centre
- Automation & Intelligent Manufacturing
- Forming & Joining of Metallic Products
- Fabrication & Joining of Composite Structures
- Material Removal

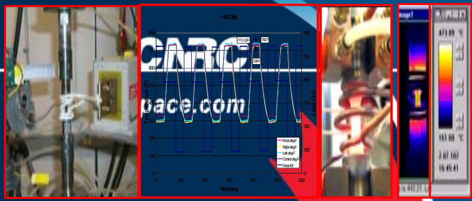
Flight Research Laboratory
- Airborne Research
- Flight Mechanics & Avionics
- Flight Recorder Playback Centre

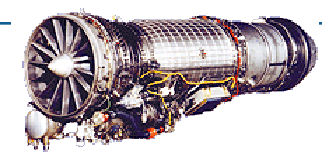
Gas Turbine Laboratory
- Internal Aerodynamics & Combustion
- Propulsion Performance and operability assessment
- National Facilities - Icing, Altitude, Compressors and Exhausters
- Lubrication Tribology

Structures & Materials Performance Laboratory
- Aeroacoustics & Structural Dynamics
- Metallic and Ceramic Materials
- Non-Destructive Evaluation
- Structures
- Composites & Novel Airframe Materials









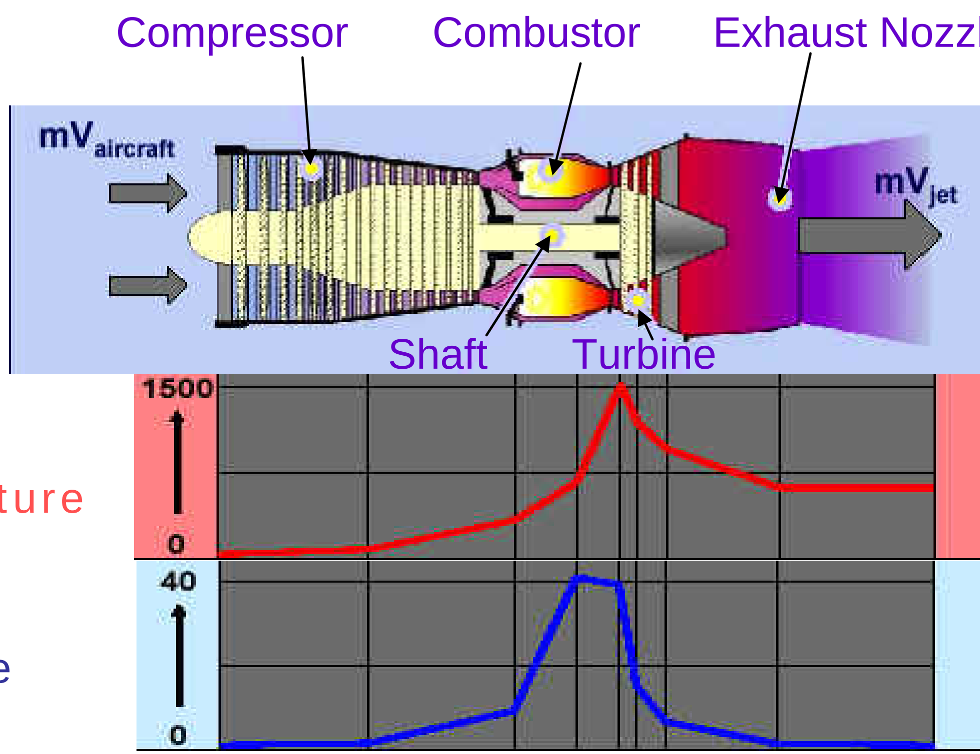
Gas Turbine Engine Life Cycle

•Manufacturing Processes/Materials

- –Forging
- –DS/Single Crystal Processing
- –Fabrication/Joining (FSW,LW & EBW)
- –Compressor Coatings
- –HSM of Ti Alloys
- –Nano-materials
- –Sensing Devices MEMS
- –Hot Section Coatings
  - •EB-PVD, TBCs
  - •HVOF& Plasma Coatings
  - •CVD Coatings

•Repairs/Reworks

- –Single Crystal and DS Turbine Blade & Vane Repair (EBW, LW, HVOF)
- –FOD Repair/Rework
- –Fatigue Damage Repair
- –Advanced Coatings
  - •TBCs
  - •CFG coatings
  - •Erosion Resistant
- –HIP Rejuvenation
- –Diffusion Brazing

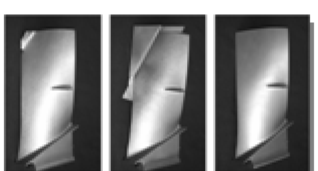


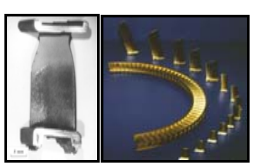
Temperature

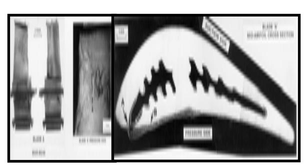
Pressure

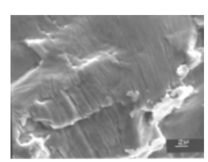
•Failure Modes

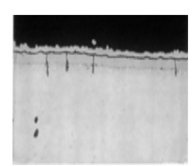
- –Fatigue (LCF,HCF , Fretting & TMF)
- –Hot Corrosion
- –Cyclic Oxidation
- –Fretting/Wear
- –Erosion/Corrosion
- –Creep
- –Failure Mode interaction











Current Gas Turbine Program At NRC-IAR

Gas Turbine Lab(GTL)

- Performance
- DPHM
- Internal Aerodynamics
- Combustion
- Instrumentation
- Icing Certification
- Tribolgy of Bearings
- Weight Reduction
- Emission Low NOx

Structures & Materials Performance Lab(SMPL)

- Component Design & Analysis(FEM),DT Analysis
- Materials for GT
- Coatings for GT
- GT Repair Technologies
- Sensors & MEMS
- Physics of Component Failure
- Coupon Testing
- Component Testing (Vibration HCF, Spin pit, Burner rig)
- ND Inspection
- Modeling & Simulation(HPC)
- Qualification and Certification

Aerospace Manufacturing Technology Centre (AMTC)

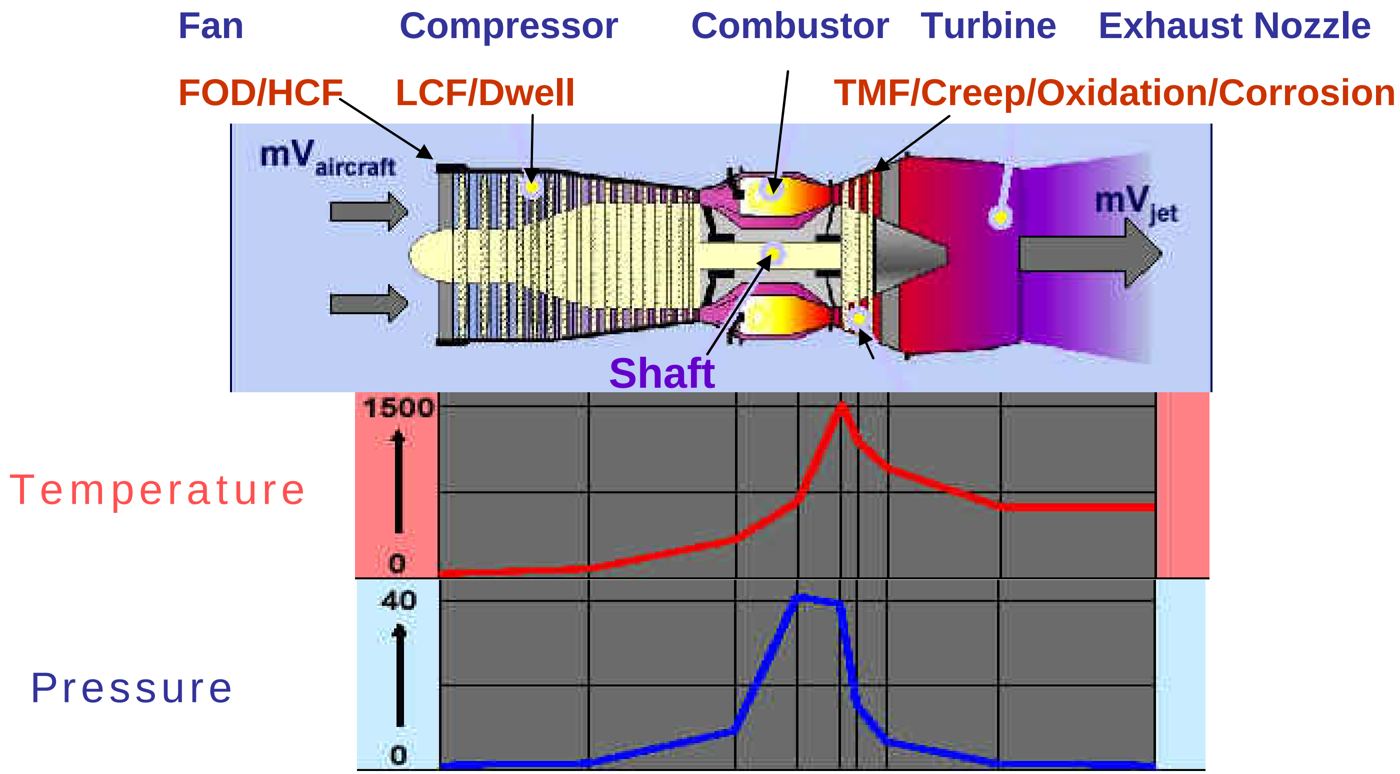
- Forming & Joining
- Automation & Robotics
- High Speed Machining
- Composite Structures

Industrialization of GTs

- Design Change- Materials, Coatings, Surface Modifications
- Relifing-design duty Cycle
- Change of Failure Modes LCF/TMF to Creep
- Hot Corrosion as Primary Failure Mode due to fuel derating

Physics Based Failure Mechanisms

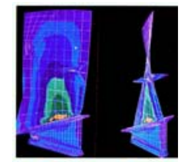
- Understanding engine component failure mechanisms
- Develop physics-based damage accumulation models
- Model Holistic Method for life prediction

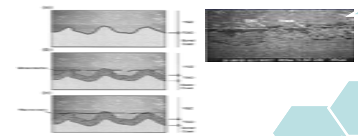


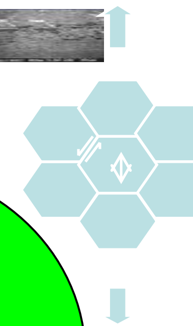
Physics of Failure & Lifing

- FOD induced HCF failure
- FEM models for vibration analysis.
- Modeling Creep fracture (for single crystal materials)
- Modeling LCF, TMF and Fretting Fatigue
- Modeling Erosion/Corrosion in the LPC
- Modeling High Temperature Erosion in the HPC
- High Temperature Oxidation Model
- High Temperature Corrosion Model for marine/industrial Environment
- Operating Mission Analysis
- Development of Life consumption rules under multiple Failure Mode conditions
- Degradation of Coating impacting bulk material properties
- Degradation of TBCs

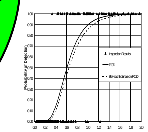
Holistic Modeling of Gas Turbine Component Life at NRC

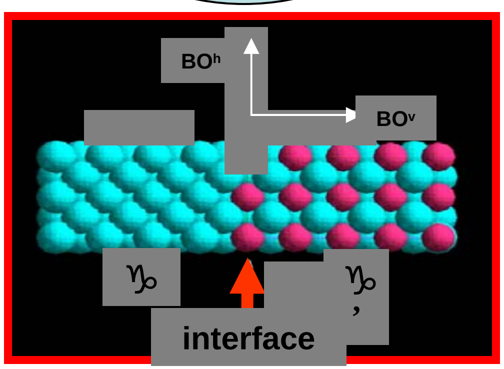


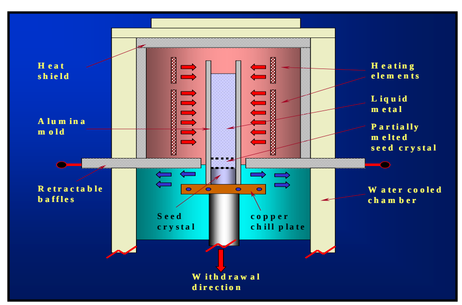


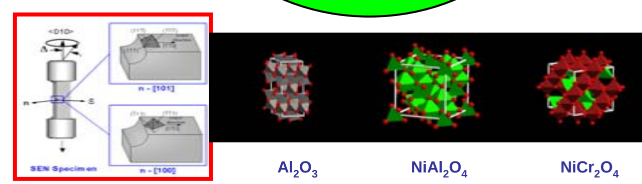


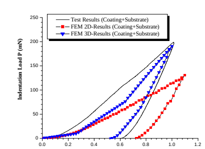
First Principle Modeling (Materials Design) → **Process Modeling (Chemical/Mechanical)** → **Durability Modeling**

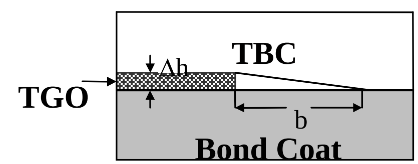




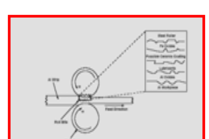


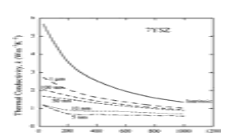






A schematic of TBC fracture.





$$\sum_{N=1}^{N_f}\left[\left(1-\frac{\varepsilon_r}{\varepsilon_f}\right)\left(\frac{W_N}{W_c}\right)^m+\frac{\varepsilon_r}{\varepsilon_f}\right]^b=1 \qquad K=\frac{Eh}{\sqrt{2\pi b}}$$

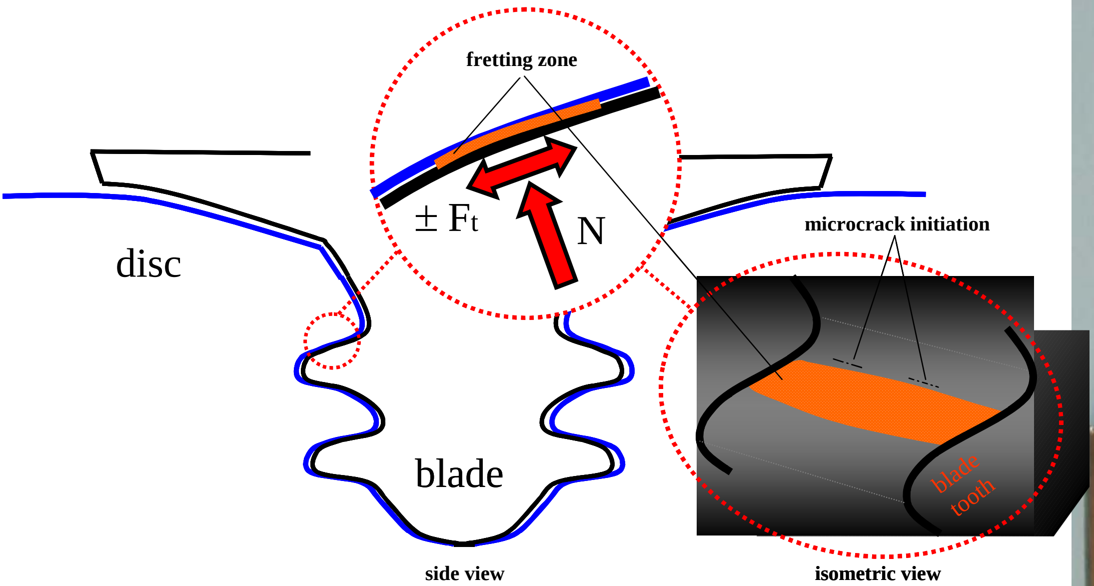
High Temperature Materials Testing-Test Standards

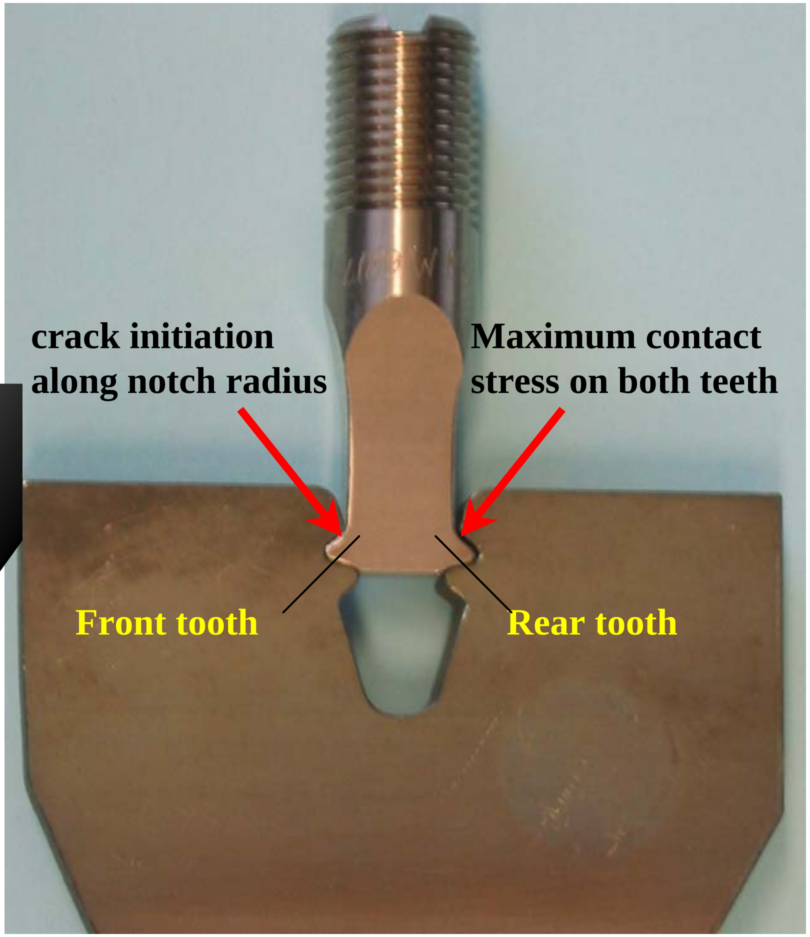
Conform to ASTM Standards with modifications to procedures as per customer requests:

	Examples:
• Tensile - Ambient Temperature	**ASTM E8**
• Tensile - Elevated Temperature	**ASTM E21**
• Stress Rupture	**ASTM E139**
• Creep Strain	**ASTM E139**
• Load Control Low Cycle Fatigue	**ASTM E466**
• Strain Control Low Cycle Fatigue	**ASTM E606**
• Crack Propagation	**ASTM E647**
• Fracture Toughness (Plane-Strain)	**ASTM E399**
• Axial High Cycle Fatigue	**ASTM E466**
• Thermo mechanical Fatigue	**ASTM E2368**
• Test Frame Alignment (Calibration)	**ASTM E1012**
• Force Verification (Calibration)	**ASTM E4**
• Verification of Extensometry	**ASTM E83**

Fretting/Fatigue Effects on LCF life of SX Superalloys

- Some examples of our work …





Quantification of Peening Credit on Blade Fixing by OEM

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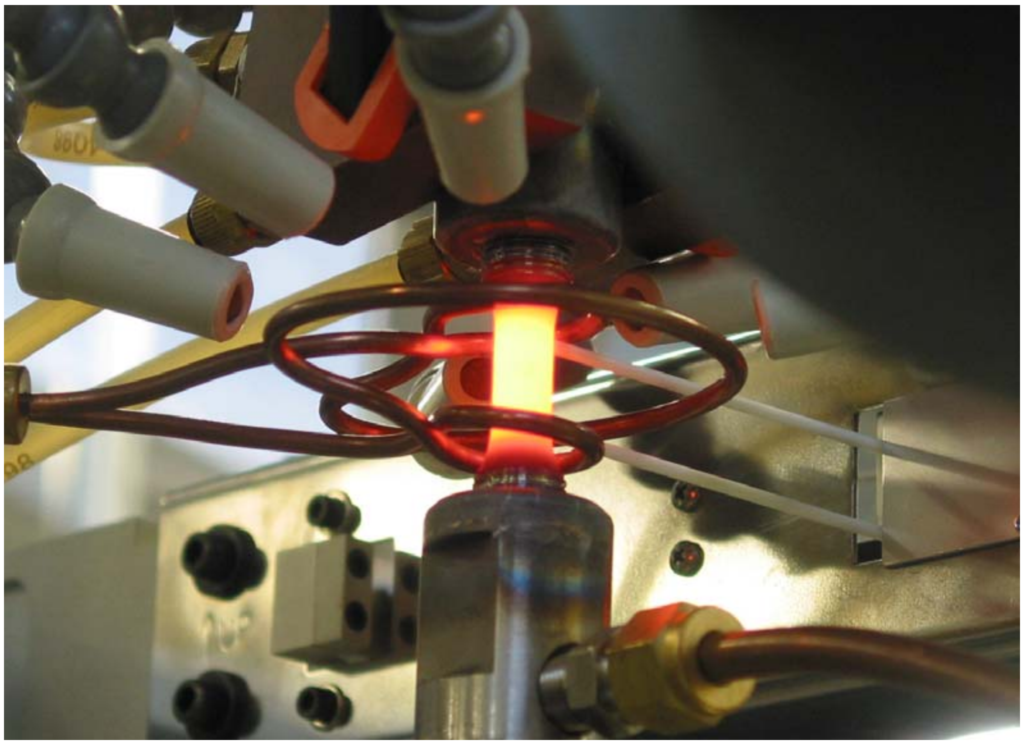
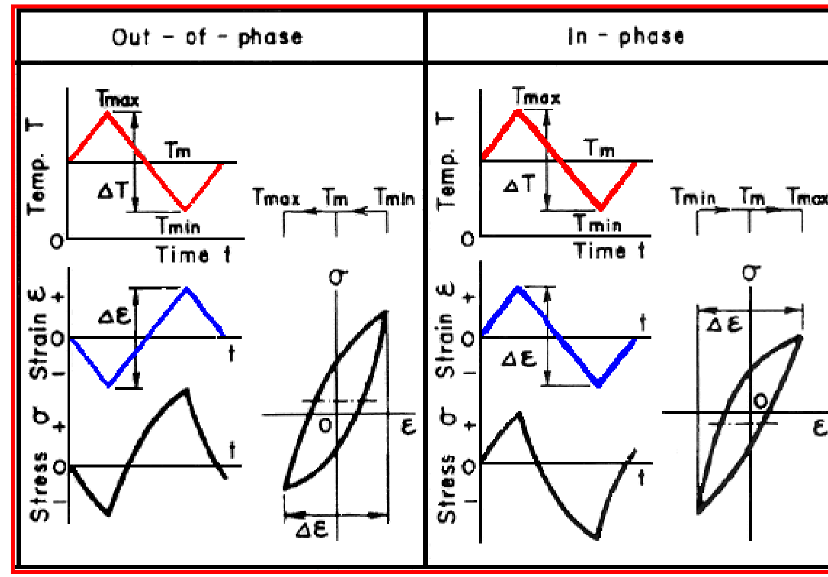
TMF Initiation Life of SX Superalloys

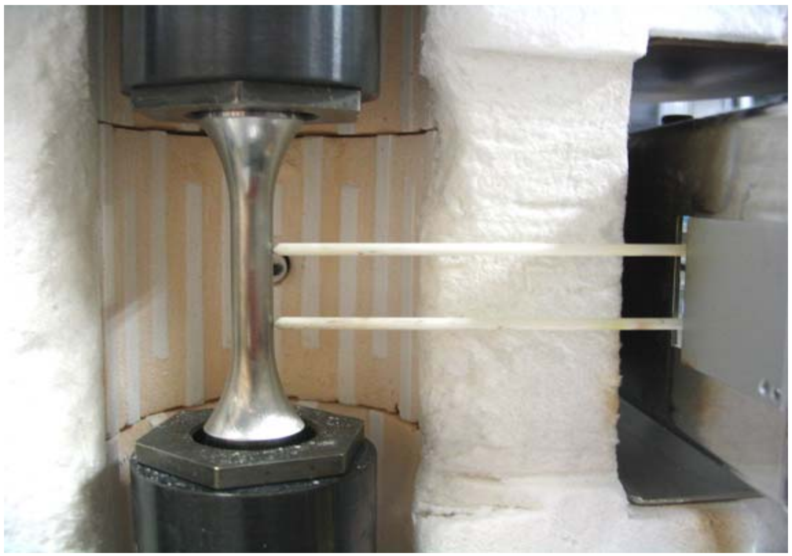


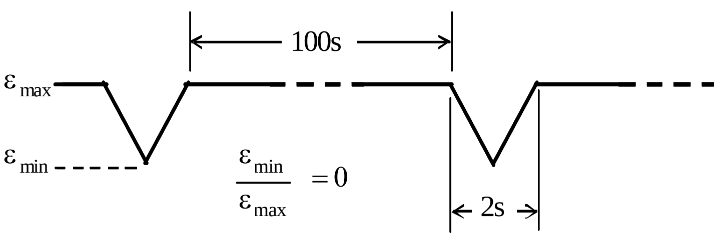
TMF Testing Programs (For Canadian & US Engine OEM's)

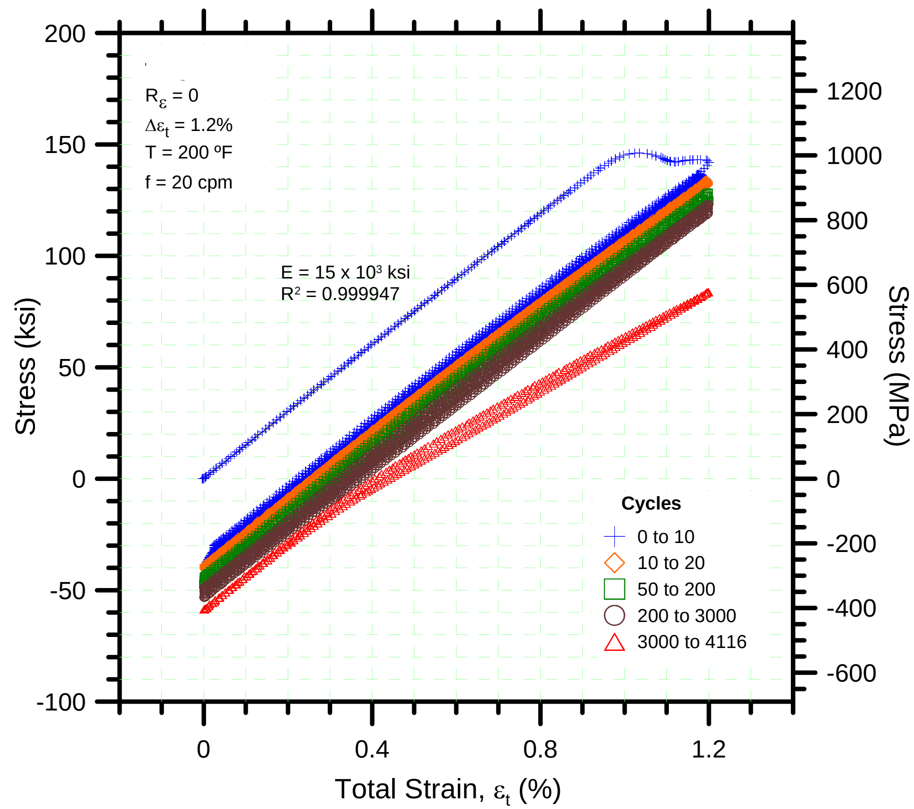


* Note: IAR has been requested to partake in TMF inter-laboratory Round Robin Program

Strain Control LCF Dwell Test for a New Superalloy







NRC Capabilities in Surface Technologies

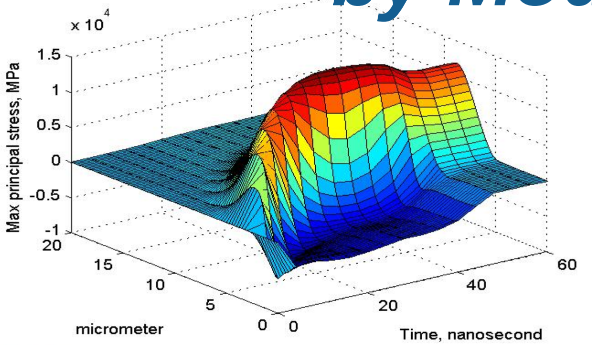
- **IAR-Ottawa/Montreal :** Process Development & Certification Testing
  - Magnetron sputtering
  - Vacuum Arc
  - EB-PVD
  - Shot Peening
  - Laser Alloying

- **IMI- Montreal :**Thermal spraying
  - Plasma, HVOF, arc, flame, cold spray
  - Suspension/solution plasma spraying
- **IMI-London:** Laser processing
  - Pulse laser deposition
  - Laser cladding, laser transformation hardening, laser glazing, laser alloying, laser gas nitriding
  - Laser-assisted plasma spraying
- **IFCI-Vancouver: Wet processing:**
  - Chemical surface modification, sol gel, spray pyrolysis,
  - Reactive spray deposition technology

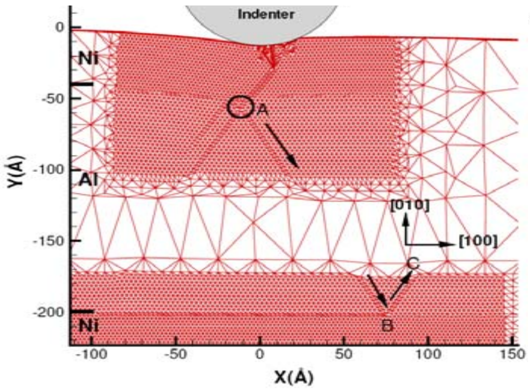
NRC Capabilities in Surface Technologies

- Modeling & Design
  - **Coating Design**
  - **Coating Process simulation**
  - **Coating durability simulation**
- Testing & Evaluation
  - **Erosion, abrasion, hardness, cyclic oxidation, fretting**
  - **Thermal properties, mechanical properties**
  - **Burner rig**
  - **Engine**
- Characterization, non-destructive evaluation
  - **SEM, AFM, X-ray diffraction, Nano Hardness**
  - **Laser-ultrasonics**
  - **Neutron reflectometry**

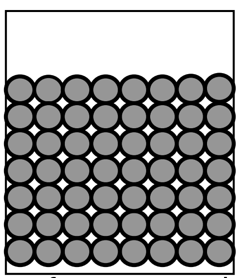
Coating Design by Modeling



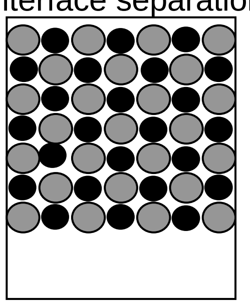
Coating-particle interactions by dynamic FEM modeling

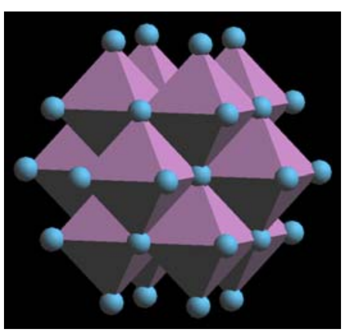


Coating indentation deformation by MD/FEM simulation



Interface separation

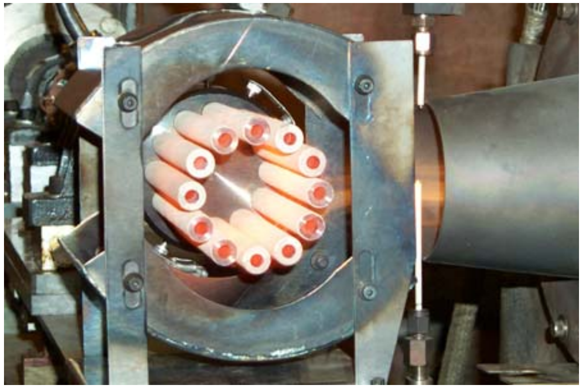




Materials properties prediction by first-principle DFT calculation

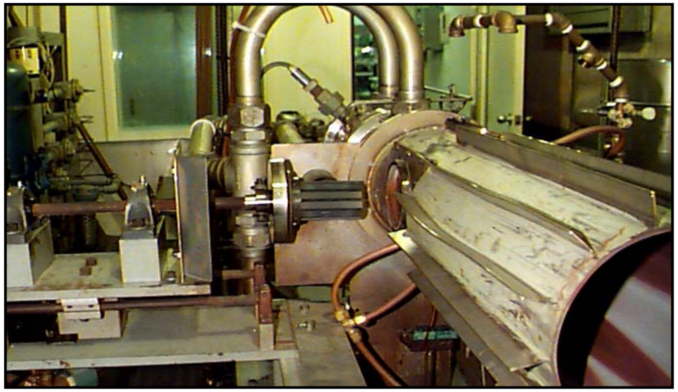
Oxidation/Corrosion Testing

Internally cooled TBC pins

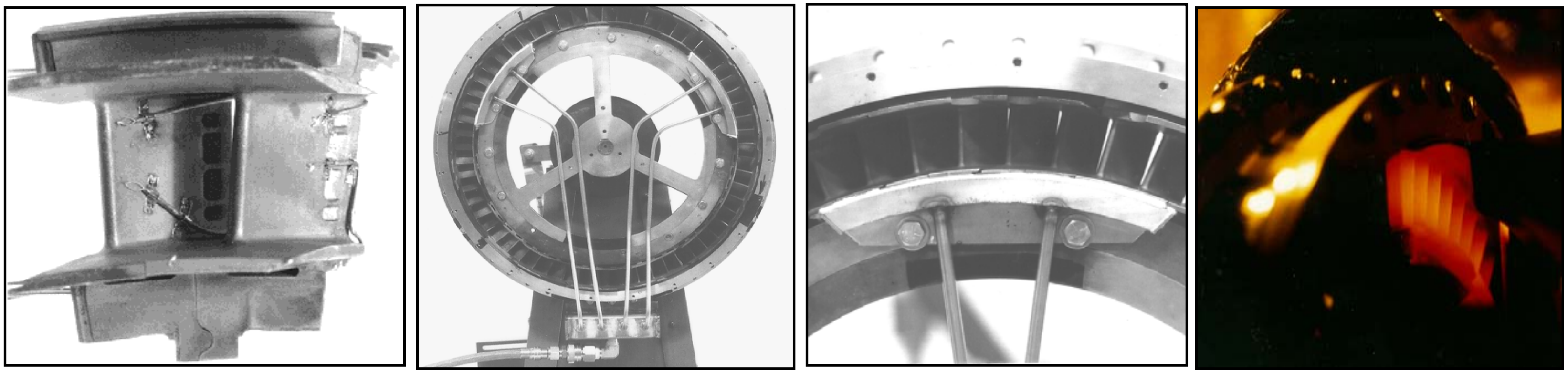


Solid Pt-Al coated pins

Hot corrosion with retort



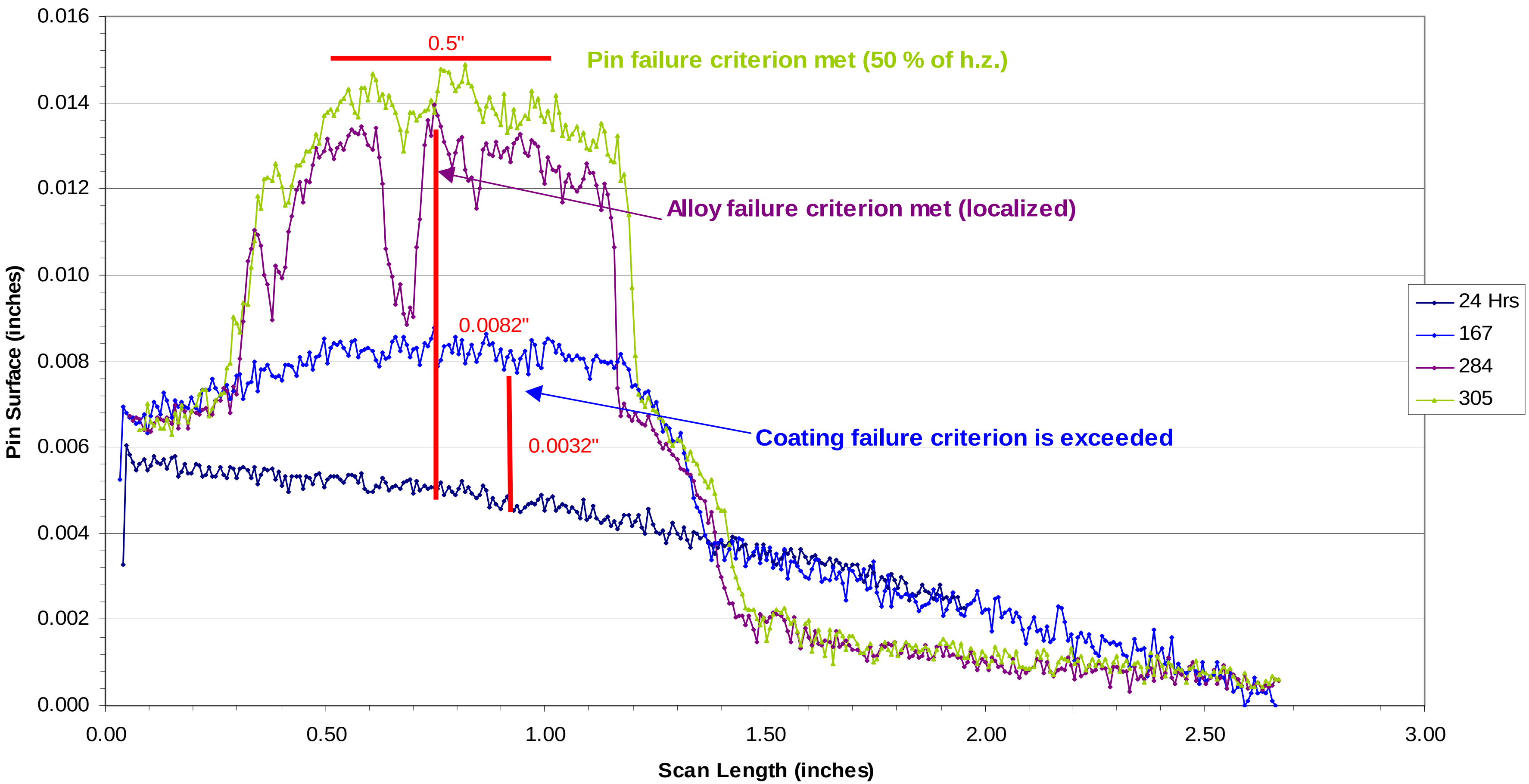
T56 1st stage nozzle guide vanes



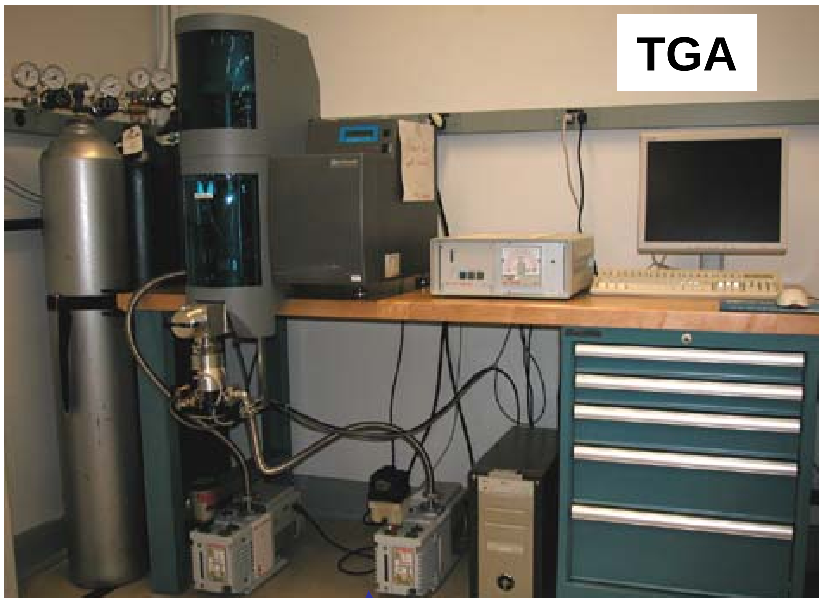
Burner Rig Test Facilities

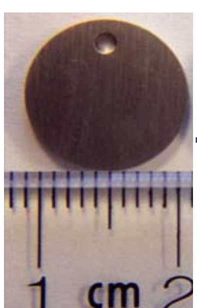
Damage Progression in Substrate & Coatings

Laser measurements quantifying coating loss

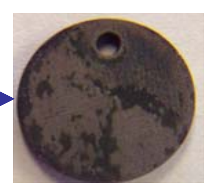


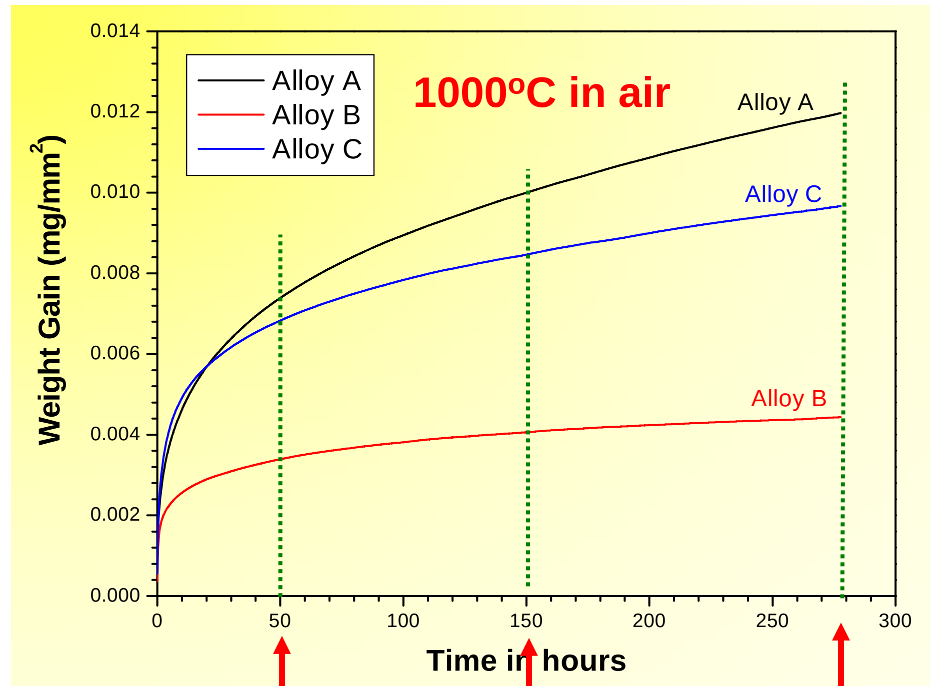
Oxidation/Corrosion Testing





TGA





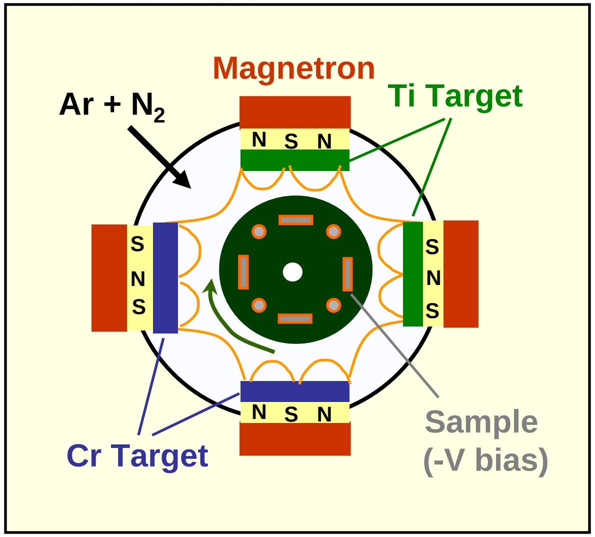
Simple Oxidation Test Facilities

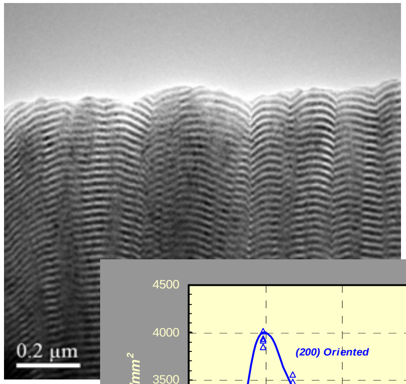
Magnetron Sputtering & Cathodic Arc Coating Processes for Gas Turbine Component Life Extension

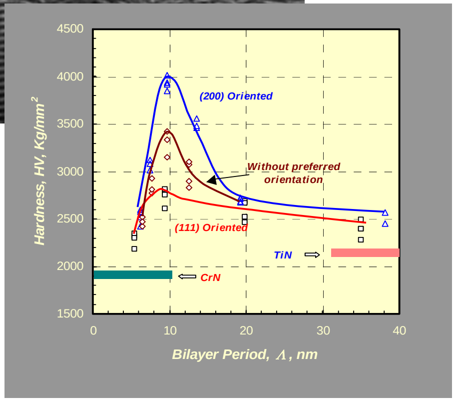
Magnetron Sputtering PVD

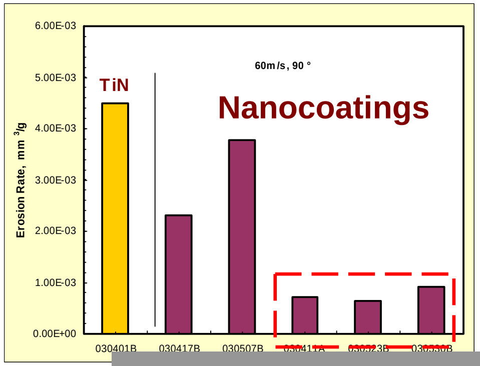
Cathodic Arc PVD

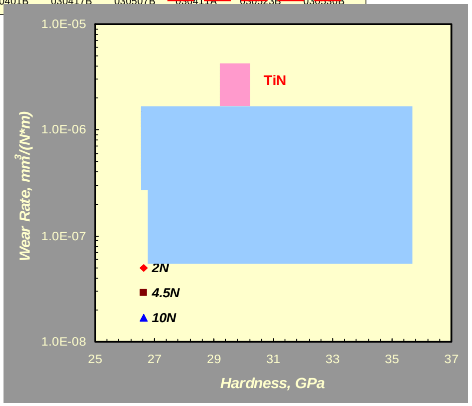
Nanostructured Superhard Coatings











PVD Processing

Plasma etching

Substrate bias

Working pressure

Temperature

Fixturing

Properties:

Thickness: 0.5 – 10 µm

Hardness: 30 – 40 GPa

Good thermal stability

Low coefficient of friction

High adhesion strength

Performance:

Excellent wear resistance

Superior erosion protection

Hot Corrosion

Type I hot corrosion —high temperature reaction between a coating, a molten deposit of alkaline salts, and sulfur-containing combustion gas. It includes basic fluxing, acidic fluxing, and alloy-induced acidic fluxing.

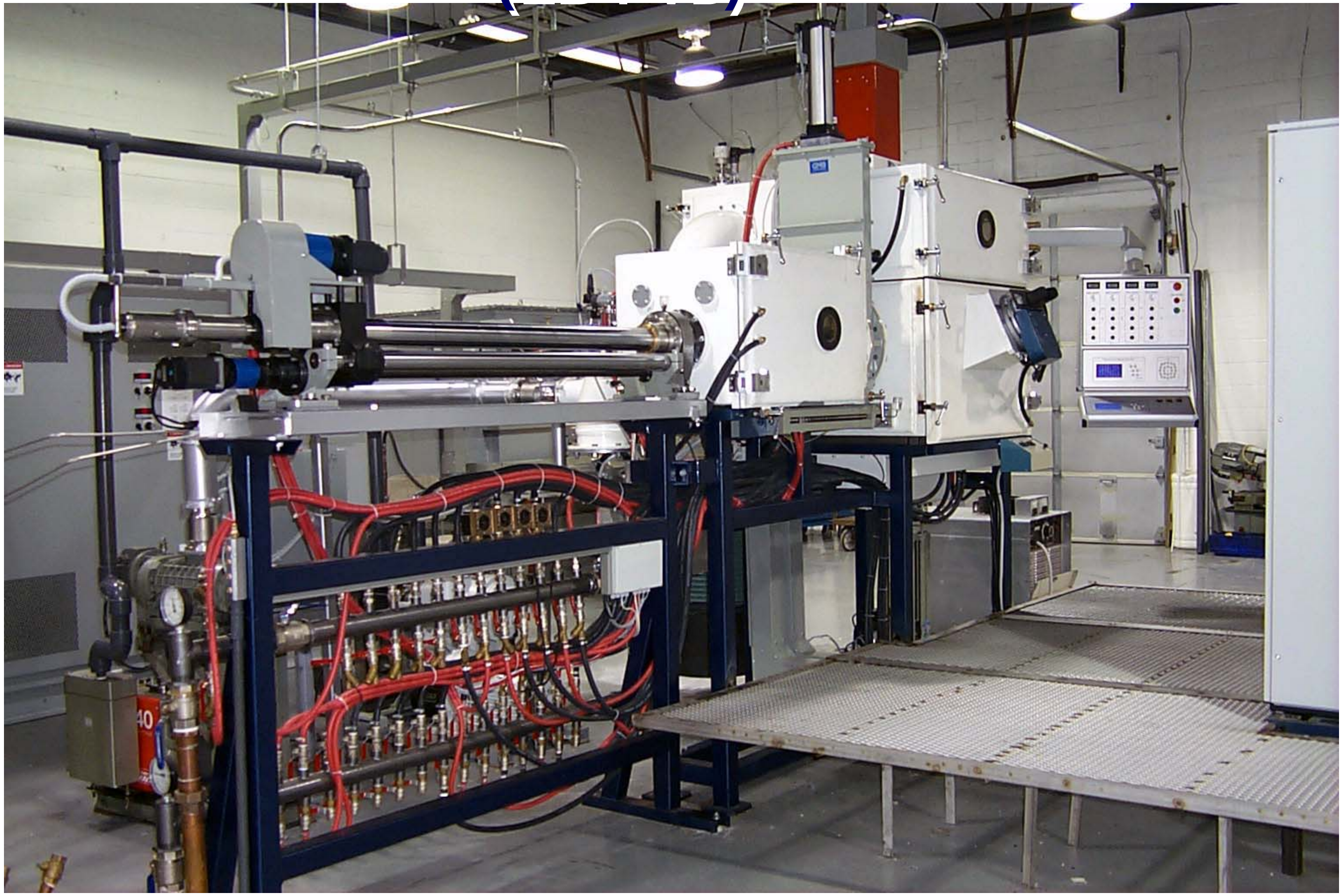
Type II hot corrosion — low temperature reaction between a coating, a solid deposit of alkaline salts, and sulfur-containing combustion gas. This corrosion produces low-point-eutectic phases of Ni and Co which become molten at 650-800°C.

Combating Hot Corrosion

For Industrial/Marine Gas Turbines:

- **Diffusion Coatings**
  - **Si-modified slurry coating**
  - **Pt-modified CVD coating**
  - **Cr-modified pack coating**
- **Overlay Coatings**
  - » **MCrAlY by EB-PVD**
  - » **MCrAlY by APS, LPPS, and VPS**
  - » **MCrAlY by HVOF**
- **Thermal Barrier Coatings (TBC)**
  - » **YSZ + MCrAlY bond coating by EB-PVD**

High-Rate Electron-beam Physical Vapor Deposition (EB-PVD)



Multipurpose NTI High-Rate EB-PVD Coater with reactive plasma-assisted deposition capability

NRC-NTI Aerospace Coatings Development Center (NRC-NTI-ACDC)

National Research Council of Canada – Institute for Aerospace Research

- **Structures and Materials Performance Laboratory**
- **Gas Turbine Laboratory**

↓

NRC-NTI Aerospace Coatings Development Centre (NRC-NTI-ACDC)

↑

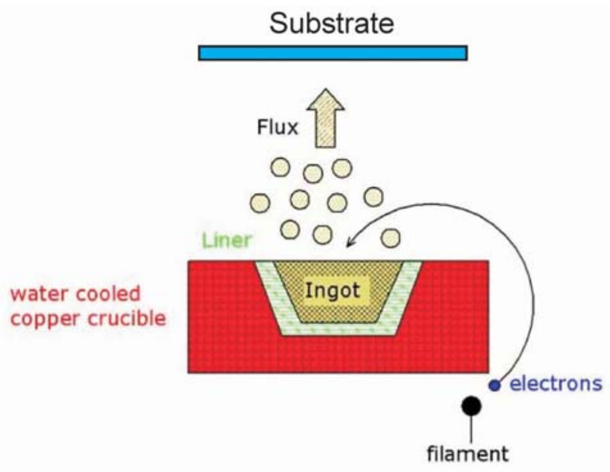
Newman Technologies Inc.

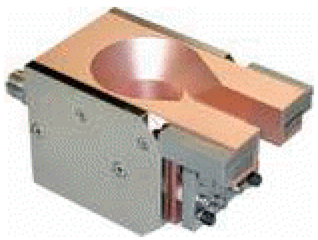
Objectives of NRC-NTI-ACDC

- Design & fabrication of novel Gas Turbine materials.
- Design & Fabrication of advanced Gas Turbine protective coatings.
- Design of new PVD-based coating processes.
- Design of customized PVD-based coating equipment.
- Ideal tool for addressing Coatings for Marine Applications
- Assistance in Technology Transfers to Clients & Partners.

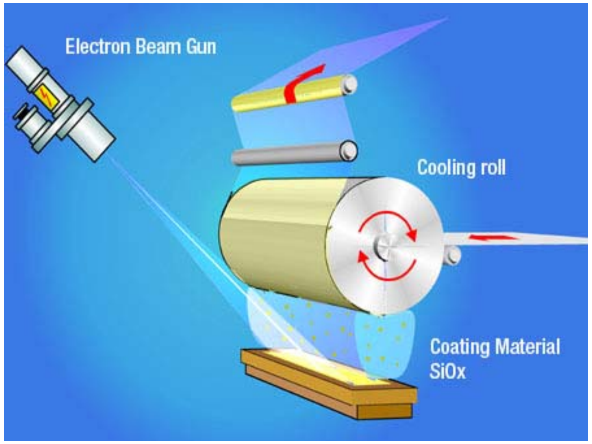
Comparison of Traditional and High-Rate EB-PVD

Traditional EB-PVD
(e-gun power is below 30 kW, deposition rate below 0.1 μm/min)

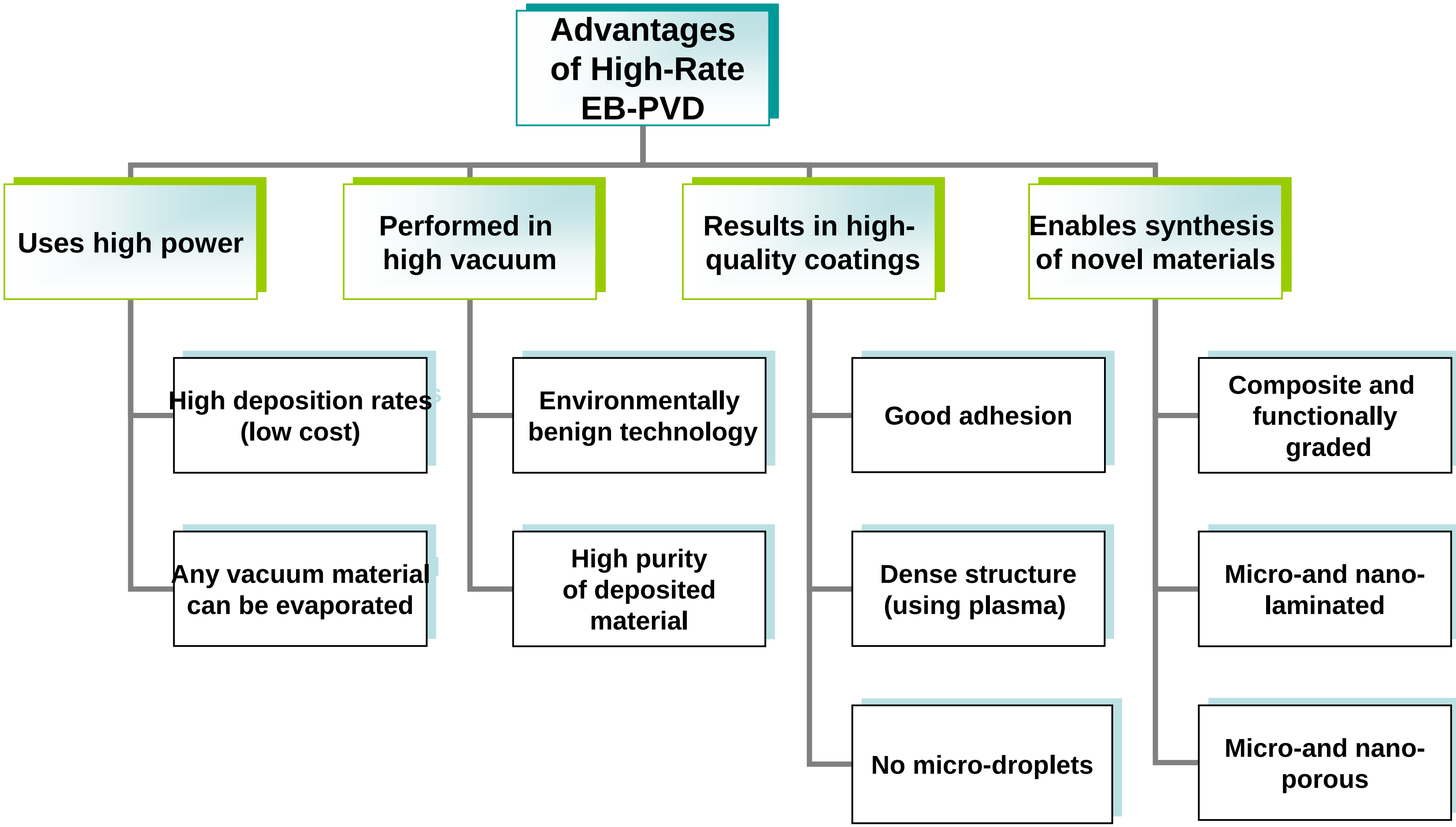




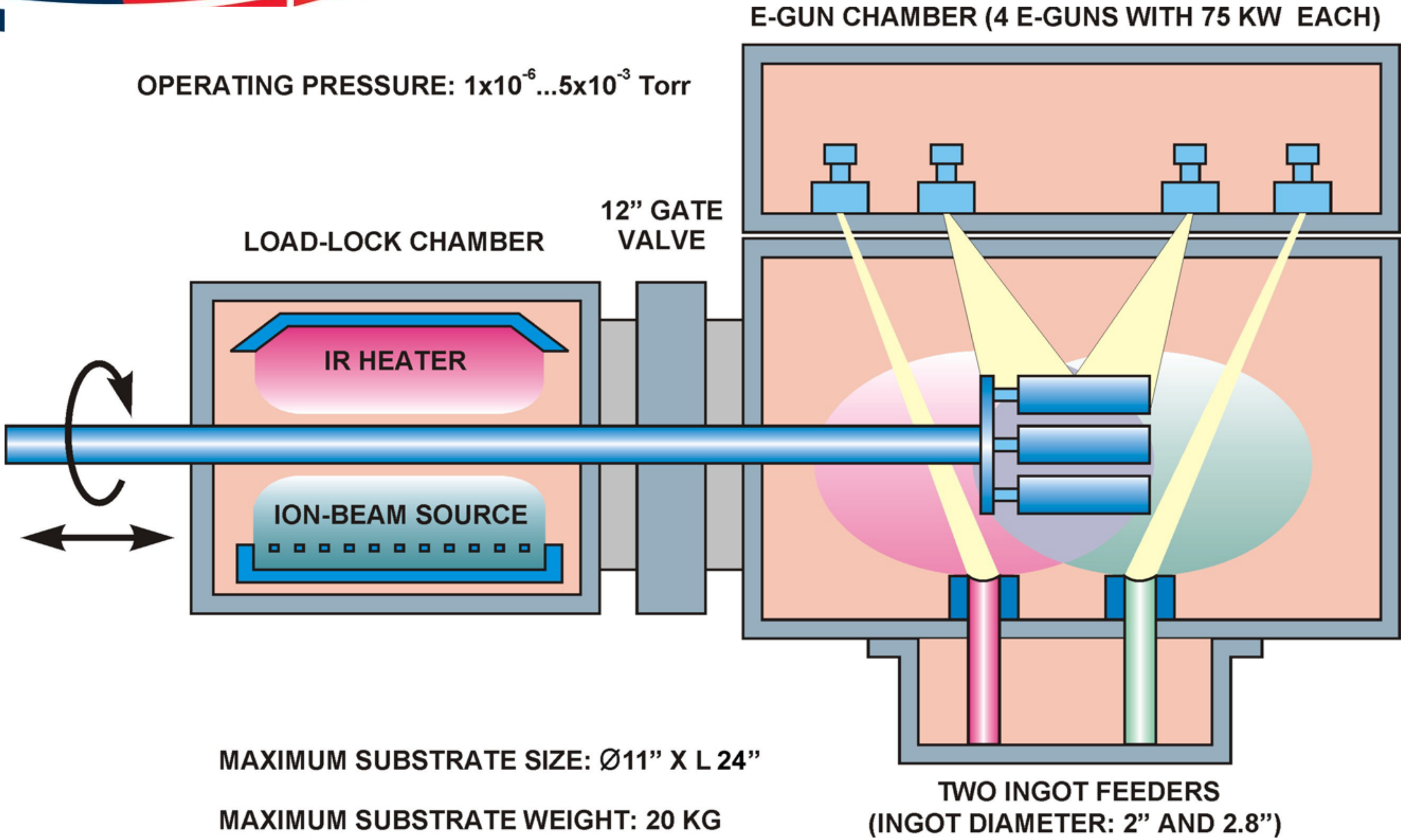
High-Rate EB-PVD
(e-gun power exceeds 60 kW, deposition rate exceeds 10 μm/min)



Advantages of High-Rate Deposition EB-PVD Technology



General Design of The EB-PVD Coater



Synthesis of Composite and Graded Materials by Reactive Plasma-Assisted High-Rate EB-PVD

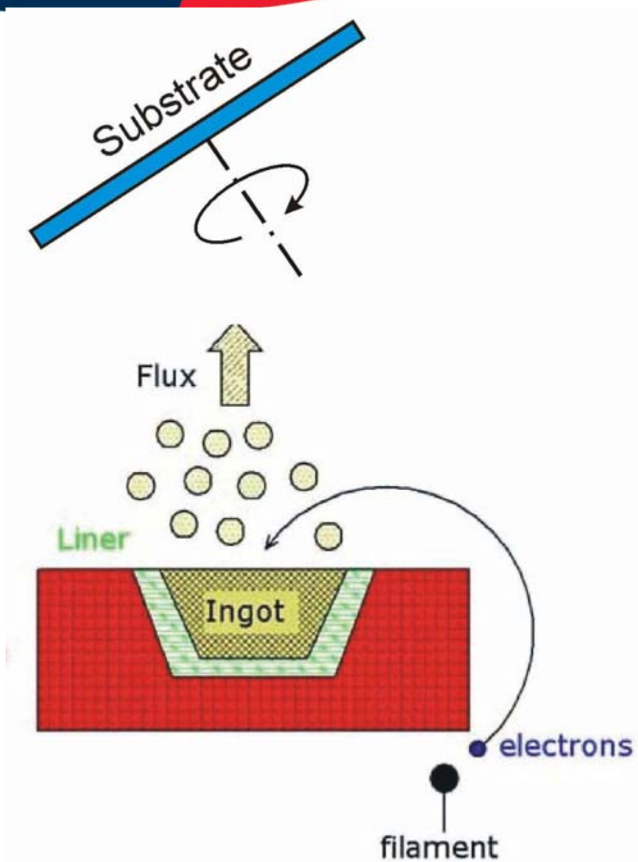
EB-PVD without plasma assistance

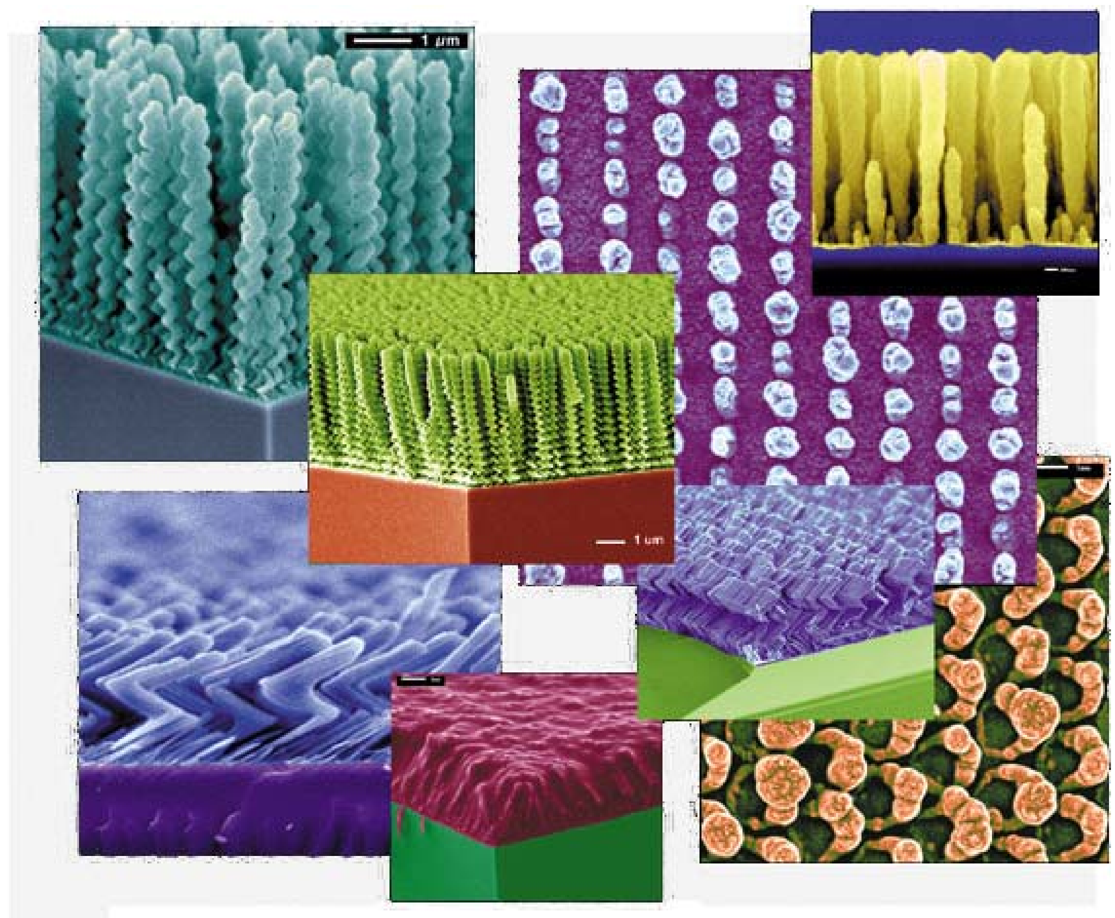
EB-PVD with plasma assistance

The effect of plasma assistance:

- densifies coating microstructure;
- improves coating adhesion;
- stimulates chemical reactions;
- enables control of intrinsic stress.

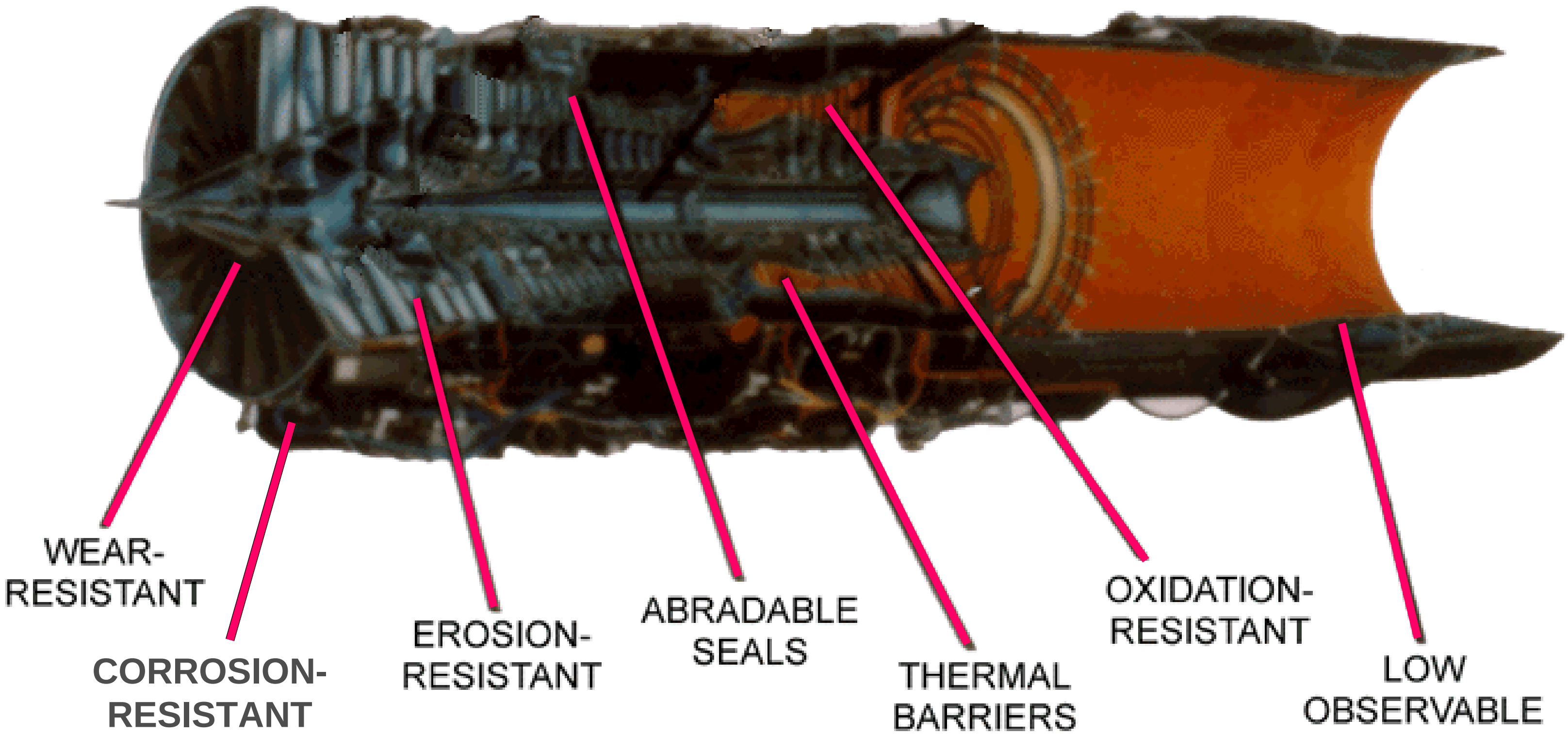
Glancing Angle Deposition of Materials with Highly Developed Morphology





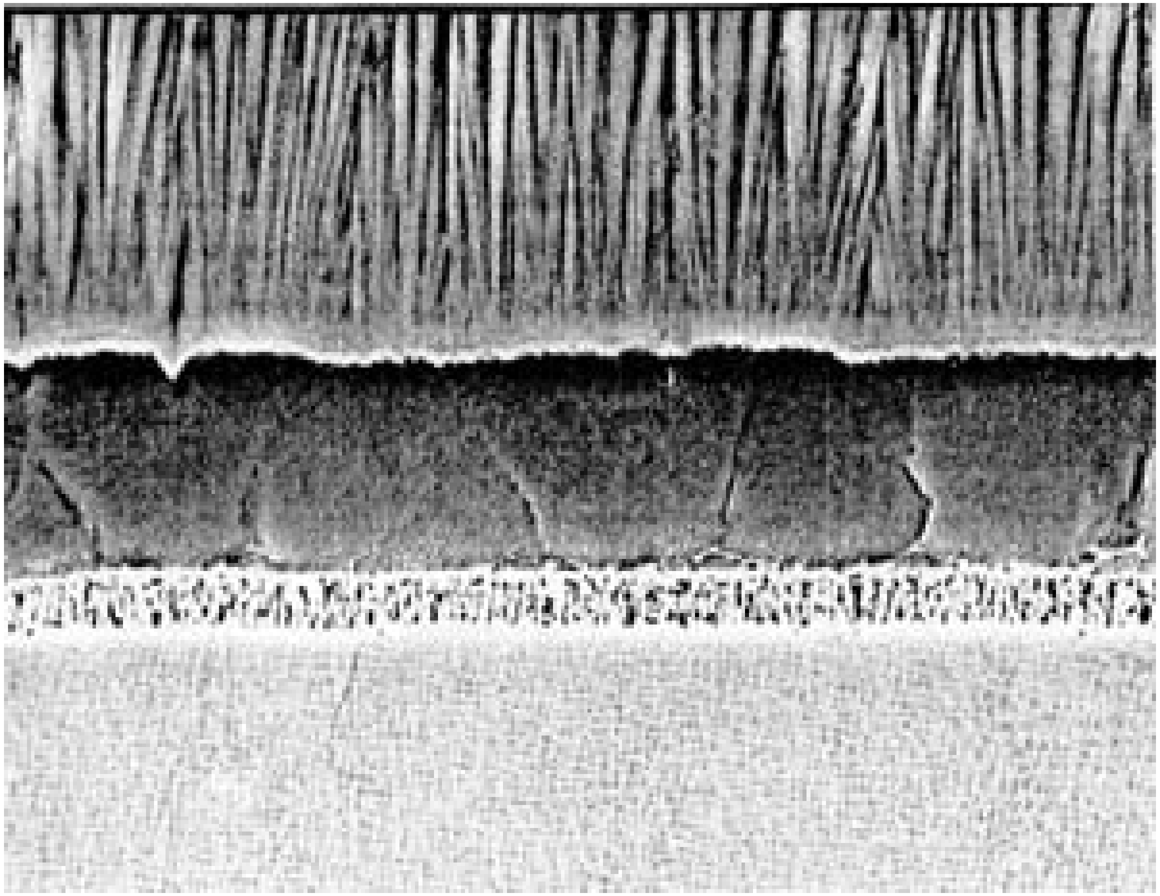
Examples of sculptured coatings with helicoidal and nematic microstructure

Fabrication of Advanced Gas Turbine Protective Coatings



Fabrication of Duplex Thermal Barrier Coatings with Improved Properties

Duplex (Two-Layer) Thermal Barrier Coating fabricated by two-step process



YSZ ceramic top coat applied by EB-PVD

MCrAlY bond coat applied by thermal spray or EB-PVD

Substrate

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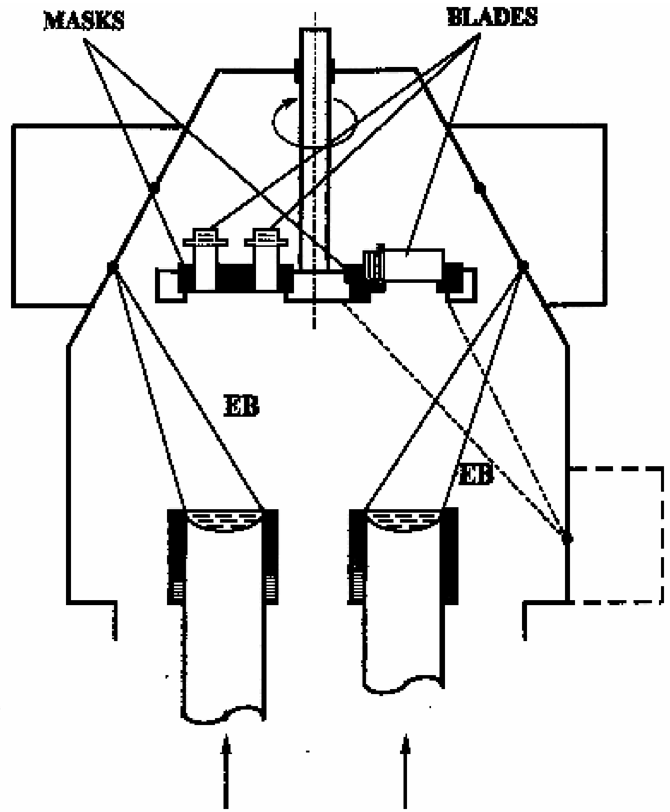
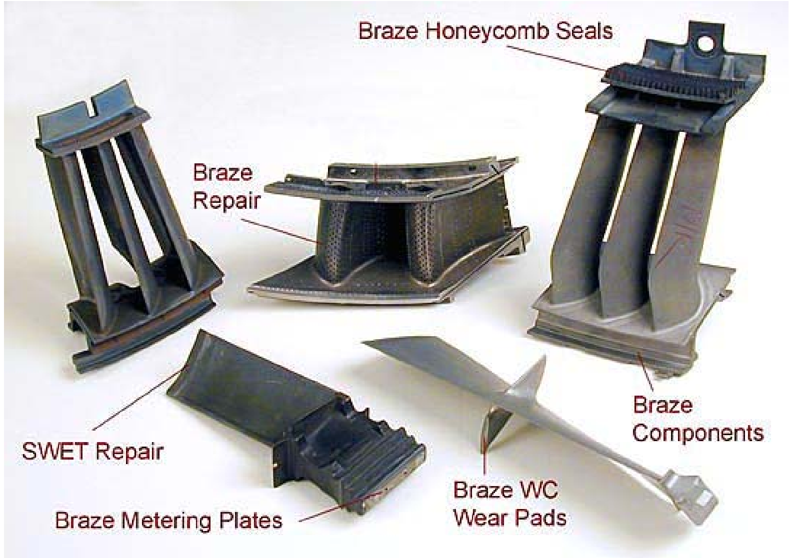
Dimensional Restoration of Turbine Blades Using EB-PVD

Typical arrangement for blade repair



- Blade tips can be repaired by positioning the blades vertically with tips facing the vapour stream
- Airfoils can be repaired by positioning the blades horizontally



Degradation of TBCs by CMAS Attack

- Airborne sand turns into Calcium-Magnesium-Alumino-Silicate when reacts with TBCs
- CMAS attacks the TBC and degrades it
- CMAS impregnated TBC has low strain-tolerance and highly susceptible to TMF loading
- Addition of Alumina and Rutile to TBC has resulted some success but alumina raises the conductivity of the TBC

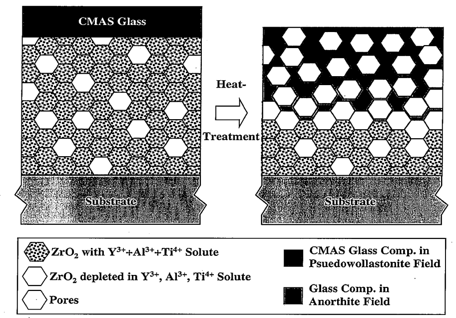


Fig. 14. Schematic illustration (not to scale) of the proposed mechanism of CMAS-attack mitigation in SPPS(YSZ+Al+Ti) TBCs.

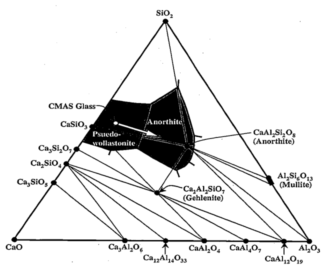


Fig. 15. Redrawn $CaO–Al_2O_3–SiO_2$ (wt.%) ternary phase diagram (after [28]) showing composition of the simulated CMAS glass, and the psuedo-wollastonite and anorthite fields. The arrow indicates composition shift in the CMAS glass.

Hutchinson [37] analyzed the thermomechanical failure of CMAS-penetrated TBC in a thermal gradient, and indicated that as the CMAS-penetration depth increases the propensity of thermomechanical failure of the top-coat increases in a complex way. A critical CMAS-penetration depth could be defined and compared with the actual CMAS-penetration depth of 60 μm. However, that critical CMAS-penetration depth would depend on various factors, including thermal gradients, cooling transients, surface temperature, and thermal and mechanical properties of the TBC constituents [37], many of which are unknown for the present system. Thus, consideration of these issues is beyond the scope of the present paper.

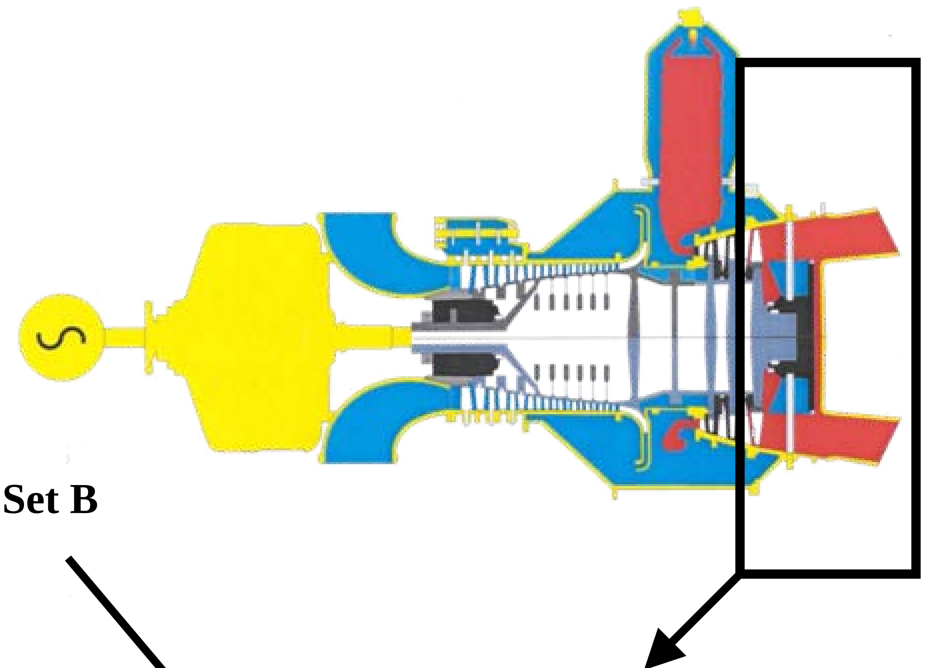
Finally, the SPPS process is very versatile in being able to incorporate metastably a wide range of solutes in a variety of oxide coatings. Thus, the engineered TBCs can serve as reservoirs of tailored solutes that can interact with not only CMAS deposits, but also other types of deposits (salts, ash, and contaminants), and mitigate their attack on TBCs.

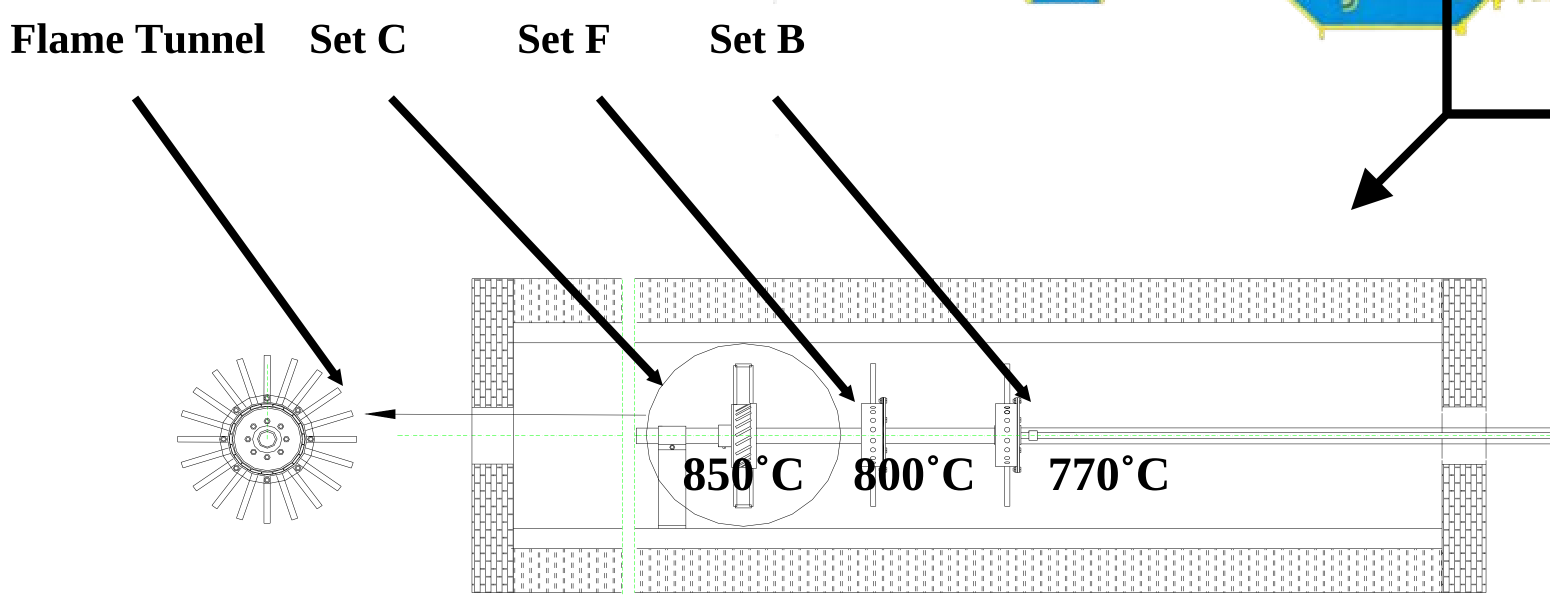
5. Summary

A new approach for mitigating CMAS attack on TBCs is presented, where up to 20 mol.% Al_2O_3 and 5 mol.% TiO_2, in the form of a solid solution and not as discrete second phases, have been incorporated into YSZ TBCs. The SPPS process, which is uniquely suited for producing coatings of metastable ceramics with extended solid-solubilities, has been used to deposit such TBCs with engineered chemistries. Here, the TBC serves as a reservoir of Al and the Ti solutes, which are incorporated into the molten CMAS glass that is in contact with the TBC. An accumulation of Al concentration in the CMAS glass, as it penetrates the TBC, shifts the glass composition from the difficult-to-crystallize psuedo-wollastonite field to the easy-to-crystallize anorthite field. The incorporation of Ti in the glass

Bio-fuel Combustion

Flame Tunnel Test





Wood Waste Derived Pyrolysis Oil

<table>
<tr><th>Parameter</th><th>Units</th><th>Bio-Fuel</th><th>Diesel</th></tr>
<tr><td>Net Calorific Value</td><td>MJ/kg</td><td>15-20</td><td>42.0</td></tr>
<tr><td>Viscosity</td><td>cSt</td><td>3-15@80 ^{o}C</td><td>2-4@20 ^{o}C</td></tr>
<tr><td>Acidity</td><td>pH</td><td>2.3-3.0</td><td>5</td></tr>
<tr><td>Water</td><td>wt %</td><td>19-24</td><td rowspan="2">0.05 v% (combined)</td></tr>
<tr><td>Particulate</td><td>wt %</td><td>0.1-0.6</td></tr>
<tr><td>Ash</td><td>wt %</td><td>0.01-0.5</td><td>0.01</td></tr>
<tr><td>Alkali (Na + K)</td><td>ppm</td><td>5-400</td><td><1</td></tr>
</table>

Materials for Hot Corrosion Test

The List of Coatings for Gas Turbine Components

Specimens	Substrate alloys	Coatings	Coating Process	Test temperature (ºC)
Combustion liner	Alloy I	DC I	Si-modified slurry aluminide coating	850
		OC I	HVOF	
		DC VI	Cr-Al pack coating	
		TBC I	EB-PVD	
		TBC III	Al_2O_3+SiO_2 barrier coating	

List of Coatings for Gas Turbine Components

Specimens	Substrate alloys	Coatings	Coating Process	Test temperature (ºC)
Stage 1 and stage 2 nozzle	Alloy II	DC I	Si-modified slurry aluminide coating	800
		DC II	Si-modified slurry aluminide coating	
		DC IV	Cr-Al pack coating	
		DC V	Cr-Al pack coating	
		DC VI	PVD	
Stage 1 blade	Alloy III	DC I	Si-modified slurry aluminide coating	770
		DC III	Pt-modified CVD	
		DC IV	Cr-Al pack coating	
		TBC II	EB-PVD	
		DC VI	PVD	

Experimental

Flame Tunnel Test

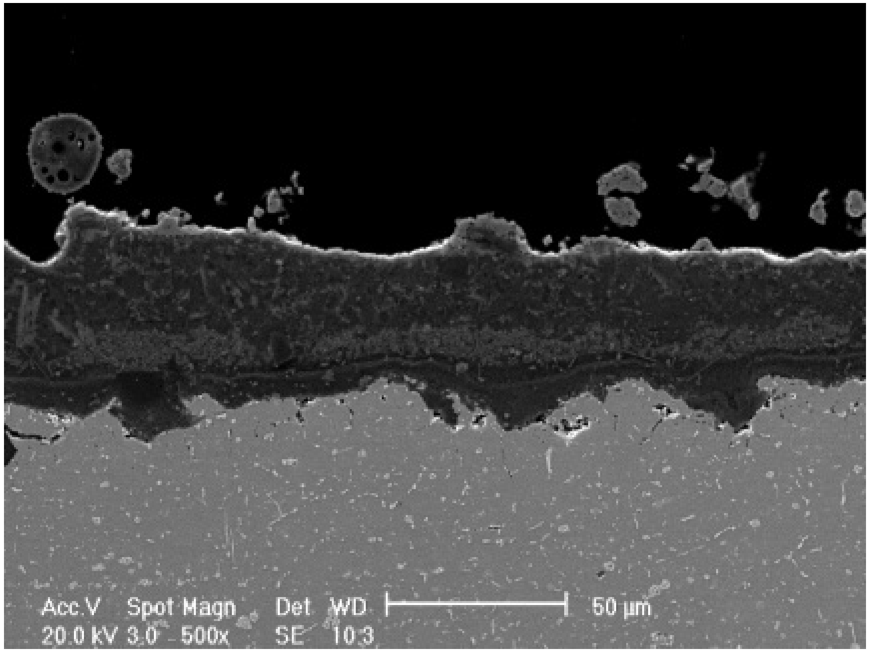
Experimental

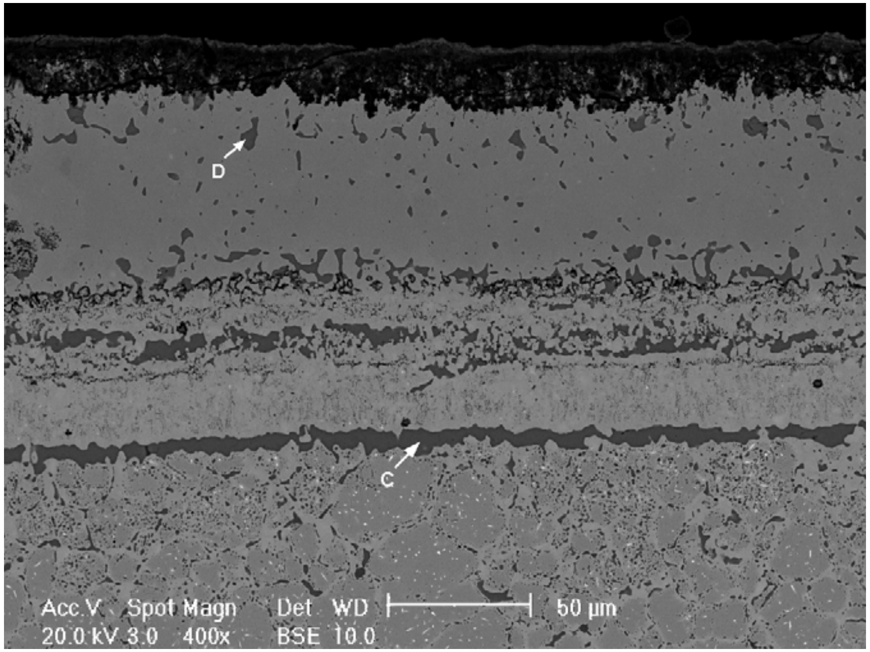
Flame Tunnel Test (continued)

Results

Specimen Set C

Specimens C42 (TBC III)   Specimens C22 (DC IV)





Results

Comparison of coatings at different service temperatures

Coatings	Service Temperatures		
	850ºC	800ºC	770ºC
DCI	– –	+ +	+ +
OC I	+ +	O	O
TBC III	+ +	O	O
DC III	O	O	+ +
DC IV	– –	– –	+ +
TBC I	+	O	O
TBC II	O	O	+
DC V	O	– –	O
DC II	O	– –	O
DC VI	O	– –	– –

+ +: the coating performs very well; +: the bond coating performs well, but TBC spalled off; – –: the coating was severely corroded; o: the coating was not tested at the temperature.

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Hot Corrosion of Sintered α -SiC at 1000^{o}C

Hot Corrosion of Sintered α -SiC at 1000ºC

- The high operating pressures of present and future engines can raise the dew point for sodium sulfate deposition to 1000ºC and higher
- It is important to understand the effects of molten salt deposits on ceramic parts at high temperatures
- Past work has shown that SiC is etched by molten salts

Hot Corrosion of Sintered α -SiC at 1000^{o}C

- The hot corrosion of sintered α -SiC by thin films of Na_2SO_4 and Na_2CO_3 was studied at 1000^{o}C in controlled gas atmospheres
- In all cases the protective SiO_2 layer dissolved to form silicate, leading to corrosion
- In all cases the presence of liquid films is responsible for rapid transport rates and the subsequent enhanced gas permeabilities.
- The reaction of sintered α -SiC with Na_2SO_4 and Na_2CO_3 produces large amounts of SiO_2 and causes dramatic etching of the SiC substrate.

Hot Corrosion of Sintered α -SiC at 1000^{o}C

- Na_2SO_4/0.01% SO_3 melts lead to rough friable scales which cause uniform pitting of the substrate
- Na_2CO_3/0.1% CO_2 and Na_2SO_4/air melts lead to smooth, glassy scales which cause uneven pitting and grain-boundary attack.
- In all cases, it appears that attack occurs by dissolution of the protective oxide film
- It appears that carbon promotes SiO_2 dissolution by formation of CO and CO_2.

Concluding Remarks

- NRC has a number of R&D programs related to Gas Turbine Operation, Durability and life extension in collaboration with their clients and partners. Some programs related to life extension have been presented here.

- NRC has been very active in the surface engineering sector across the council. The aerospace sector has been addressed by the IAR on PVD, IMI on Thermal Spray and Laser Technologies, respectively.

- The current challenges facing the aerospace coating industry in terms of of developing coatings for alternate fuel usage in the Gas Turbines have been identified and NRC collectively is ready to respond to the industry needs .

- The collaboration with NTI in terms of EB-PVD coating technologies brings in an ideal and timely opportunity for technology collaboration, joint development,Technology Demonstration and commercialization.

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Questions ?