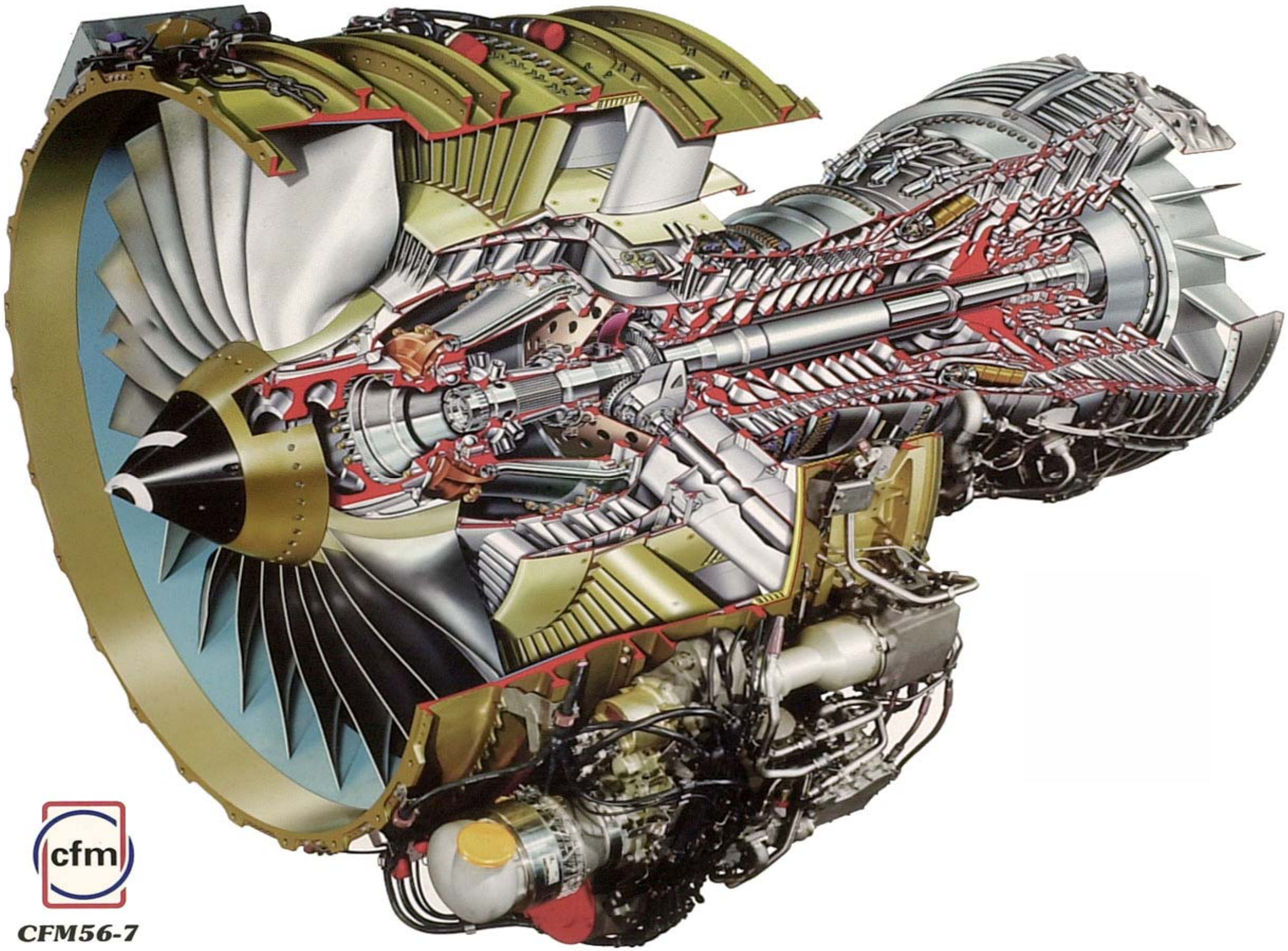
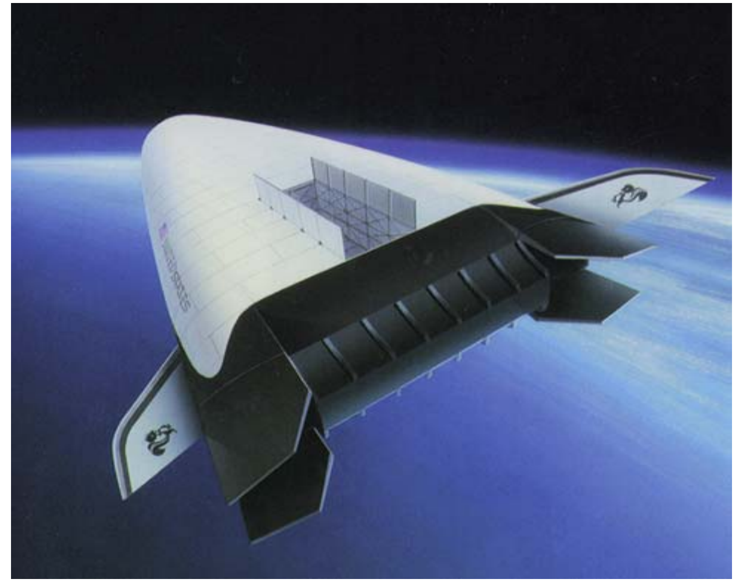
Materials and Structures for Aerospace Propulsion Systems

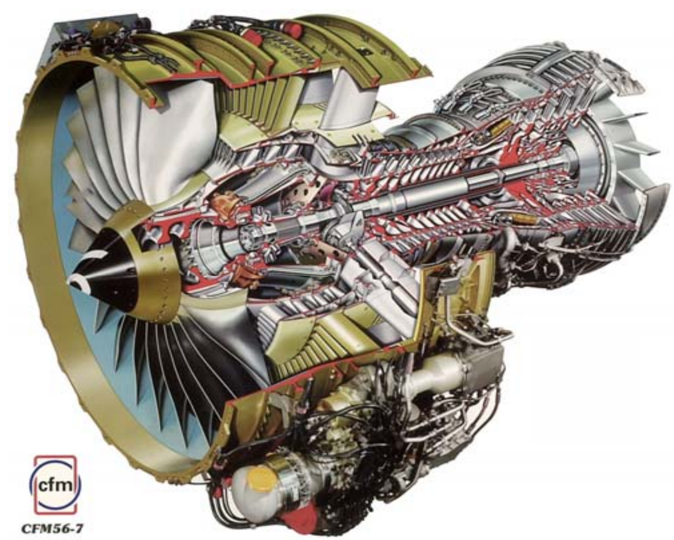


Scramjets

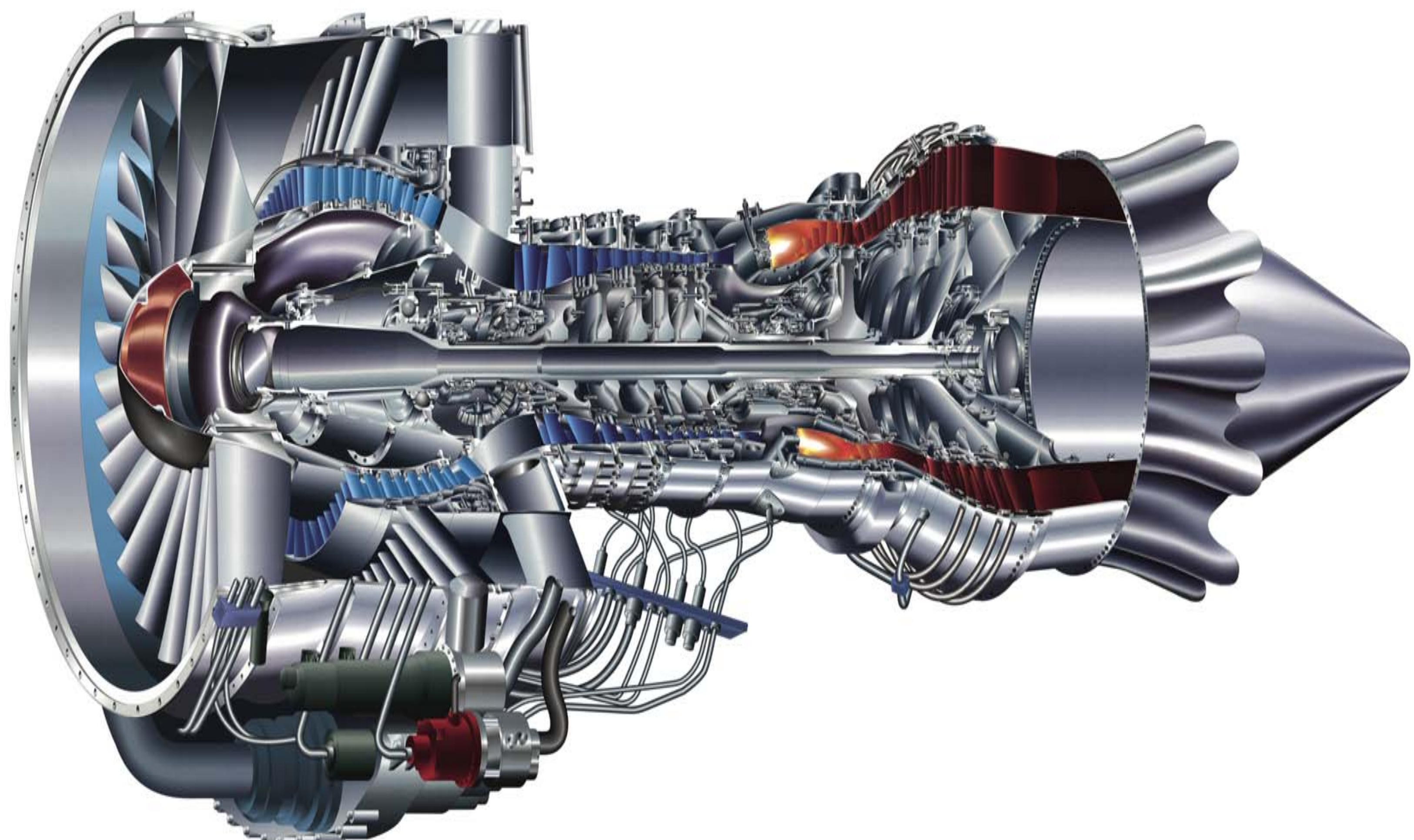
Rocket

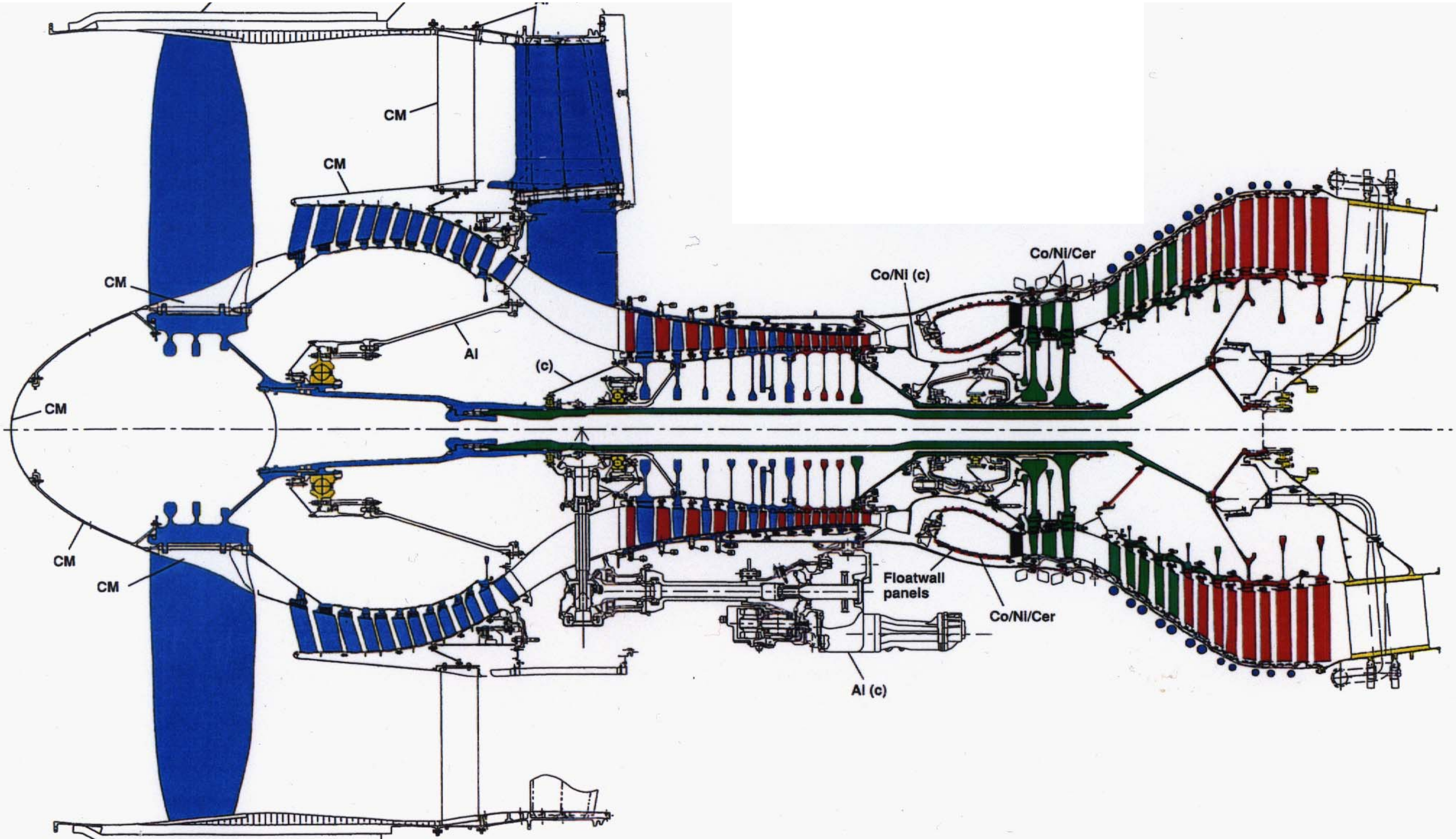


Aeroturbine

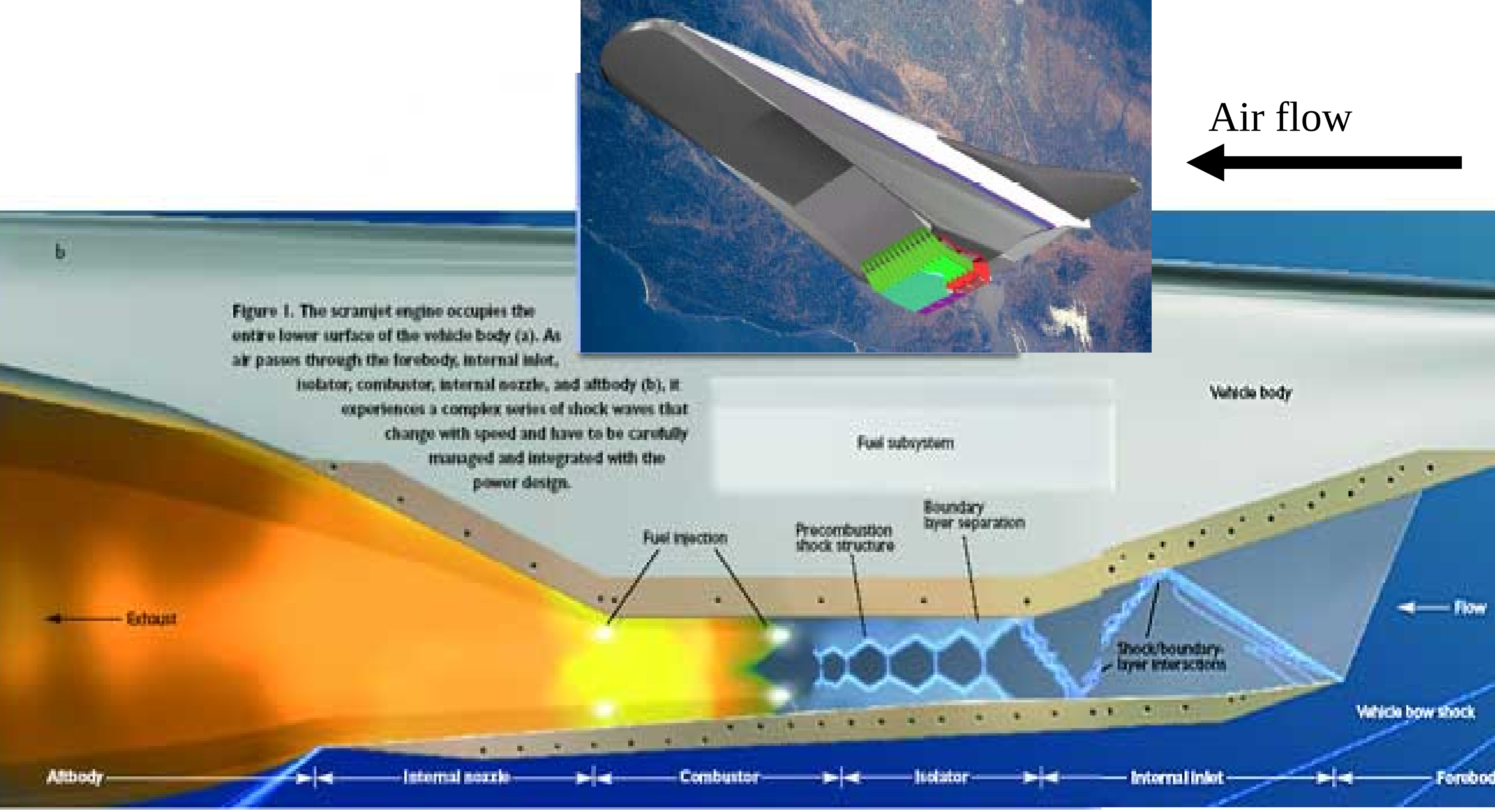


High By-pass Aeroturbine





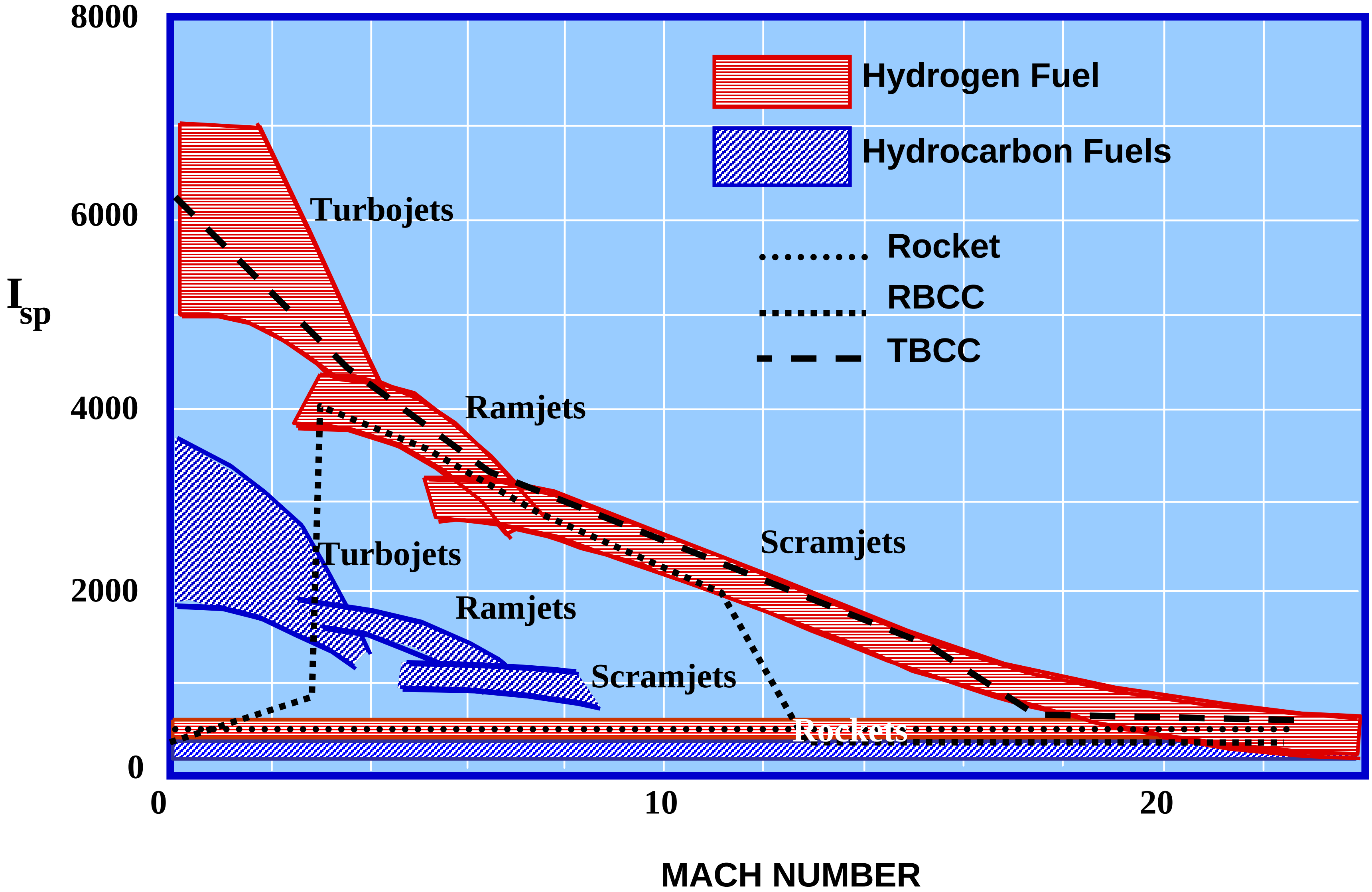
CEB3050-1
R961402



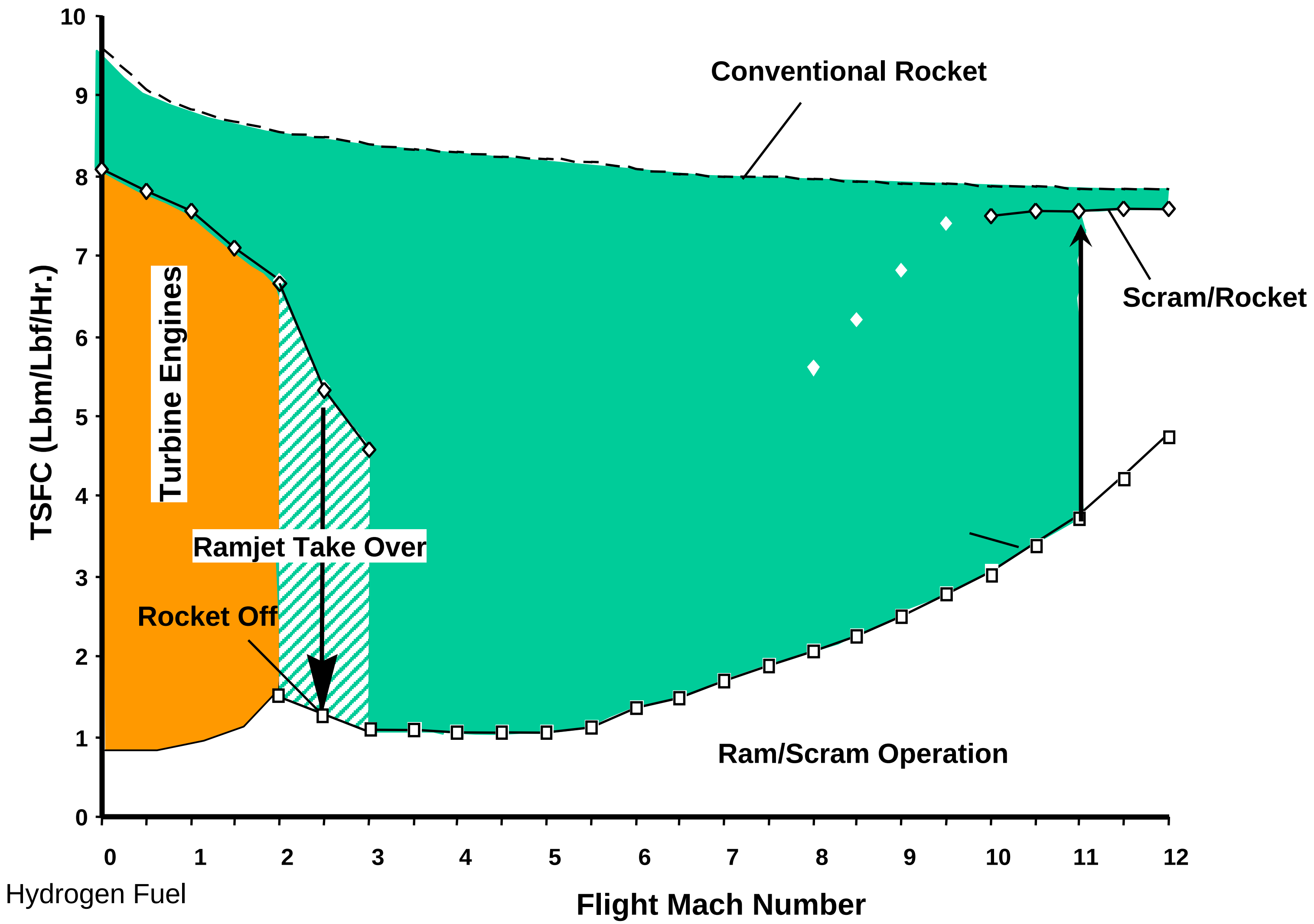
http://www.aip.org/tip/INPHFA/vol-10/iss-4/p24.html

Scramjets integrate air and space by Dean Andreadis

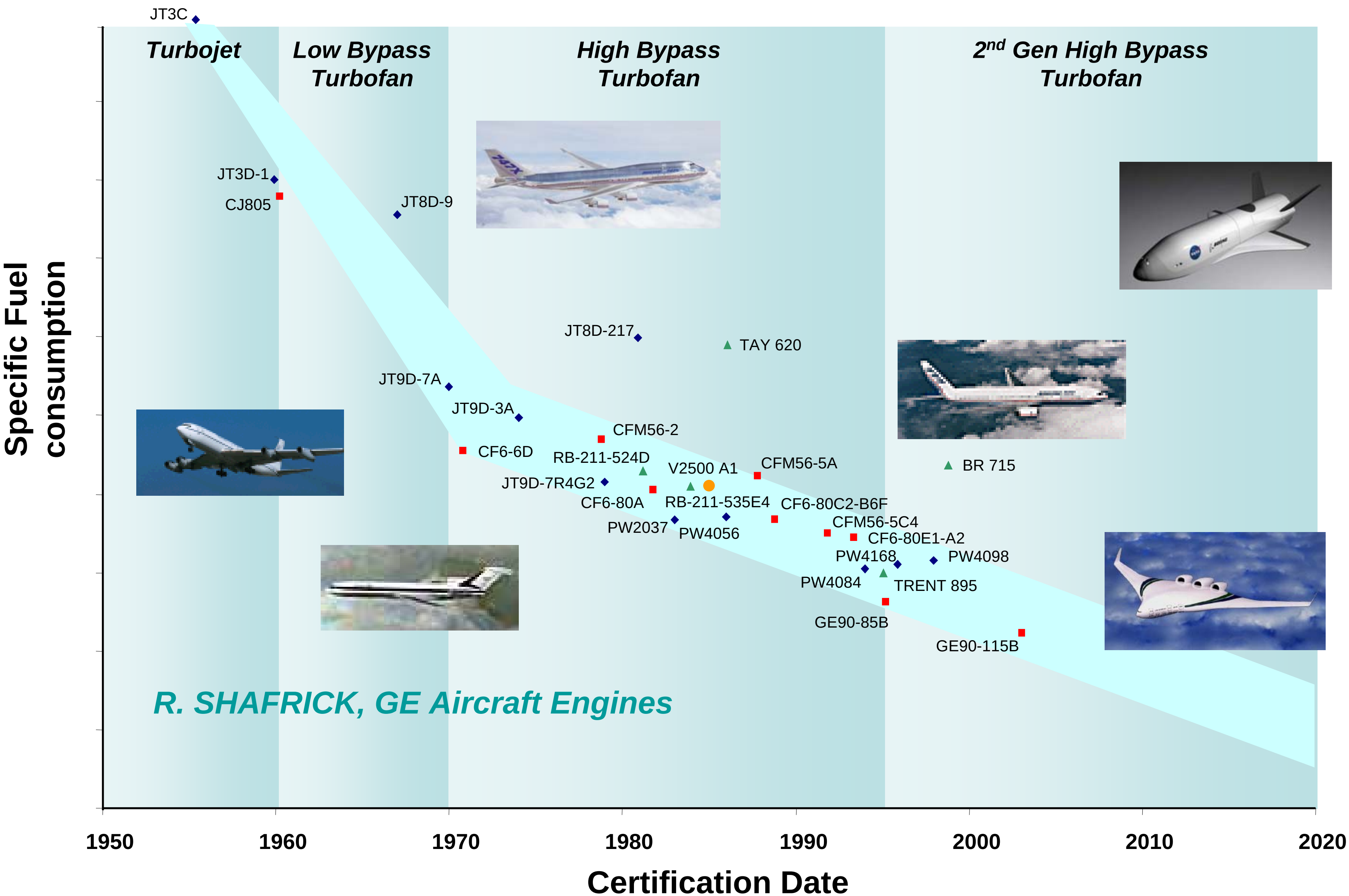
Efficiency of Various Propulsion Cycles: Specific Impulse (Thrust/weight)



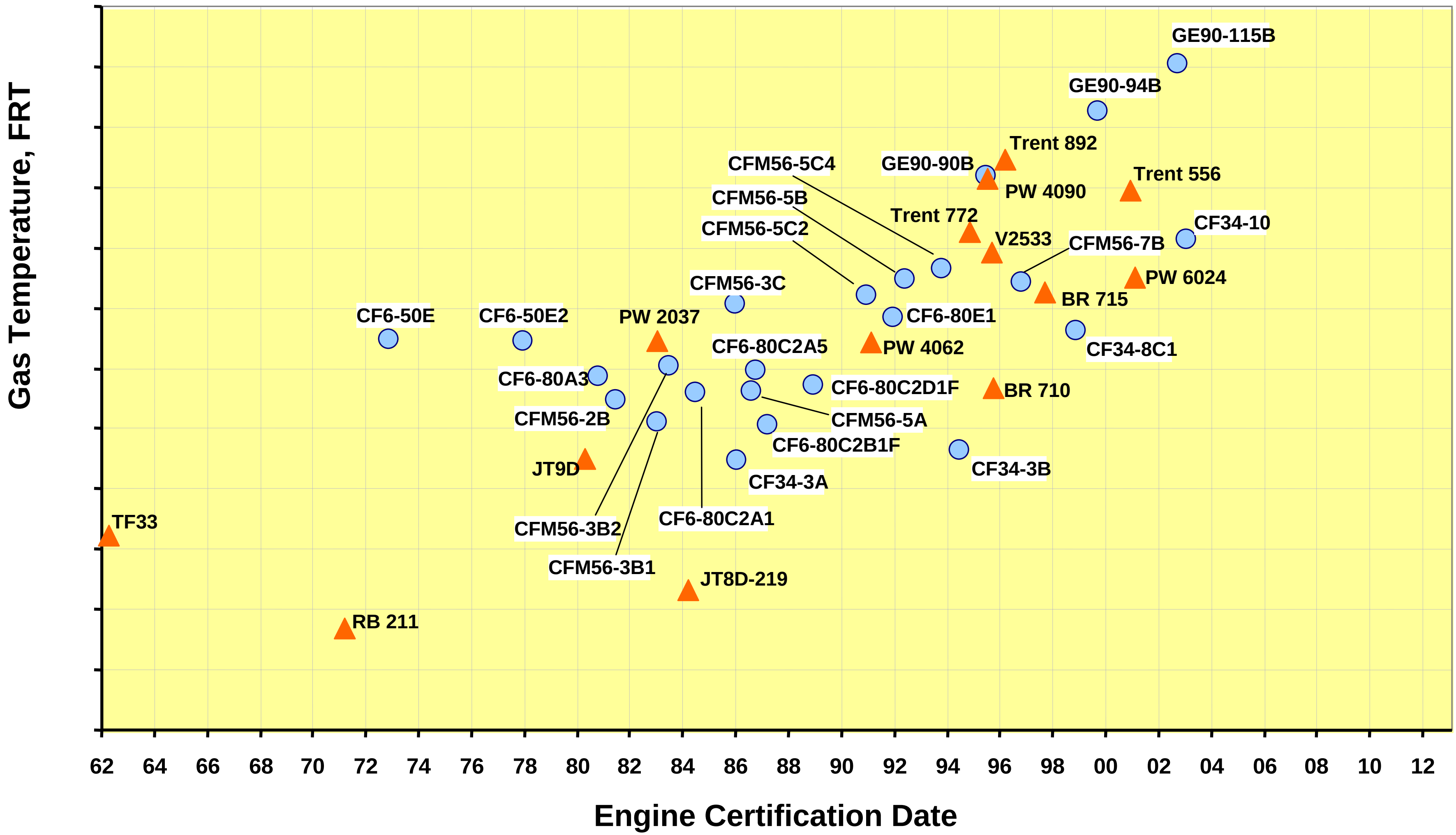
Specific Fuel Consumption for Various Concepts



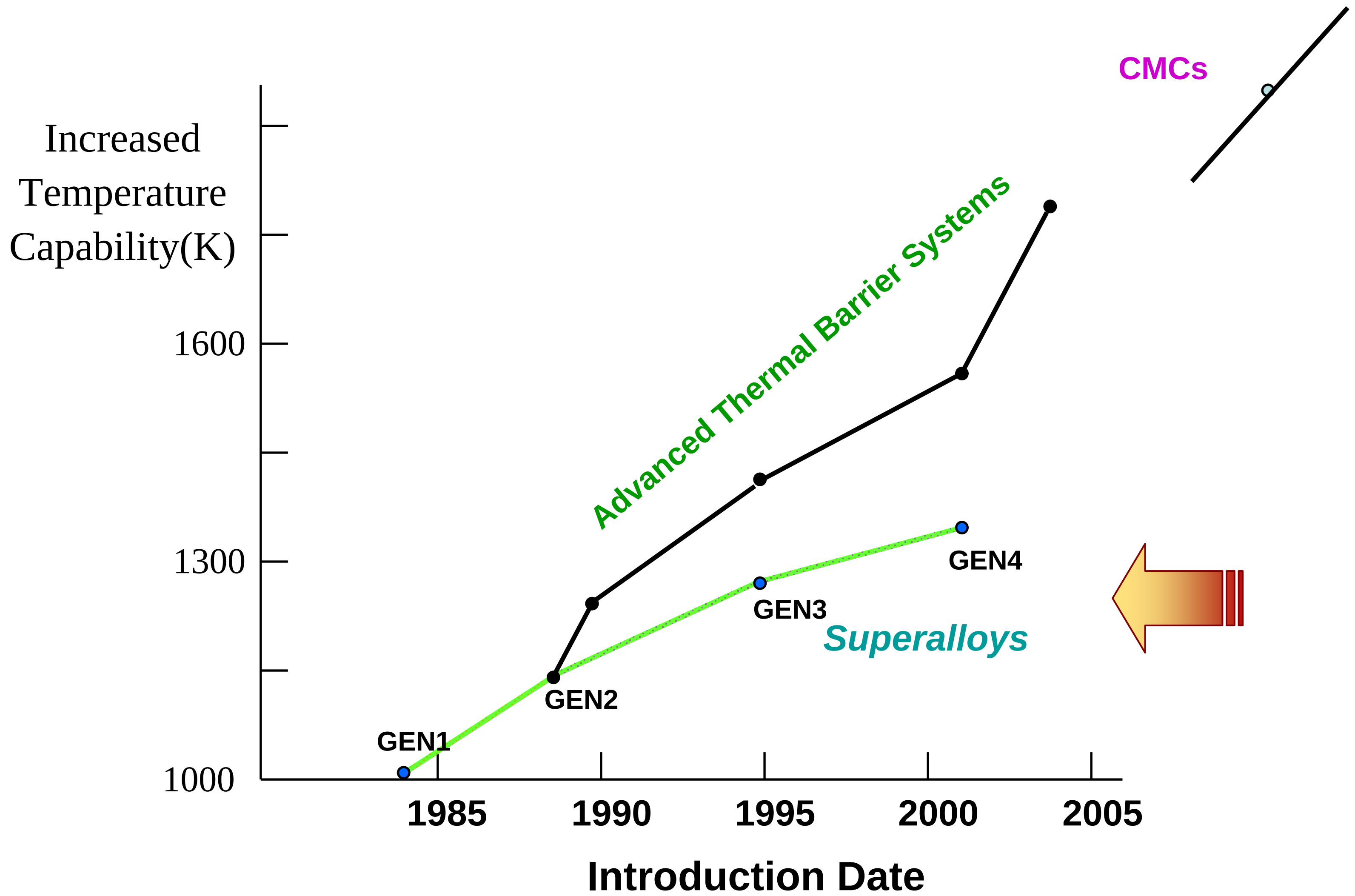
Fuel Efficiency In the Aero-turbine Industry:



Engine Temperature Trend

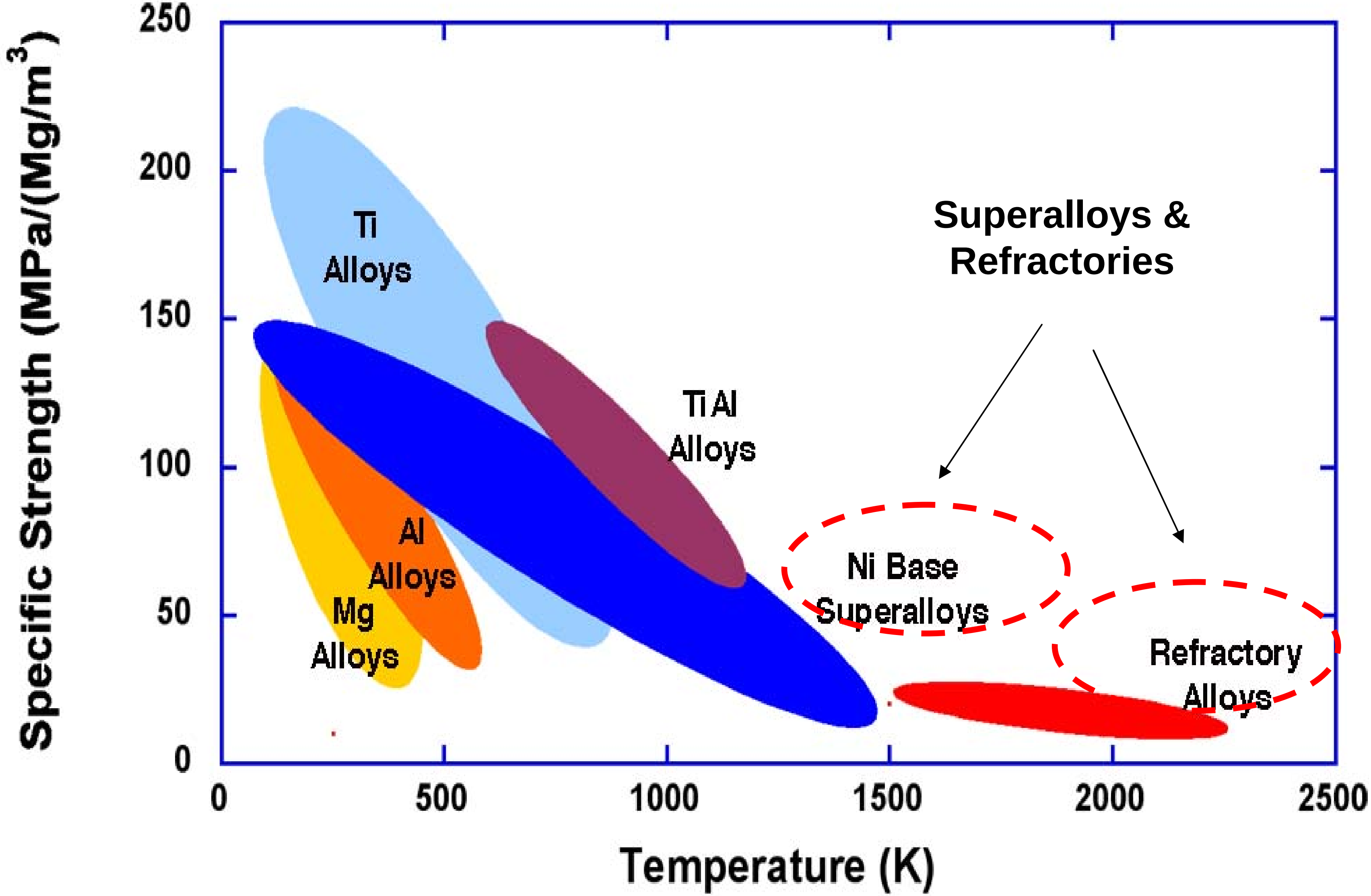


Role of Airfoil Materials

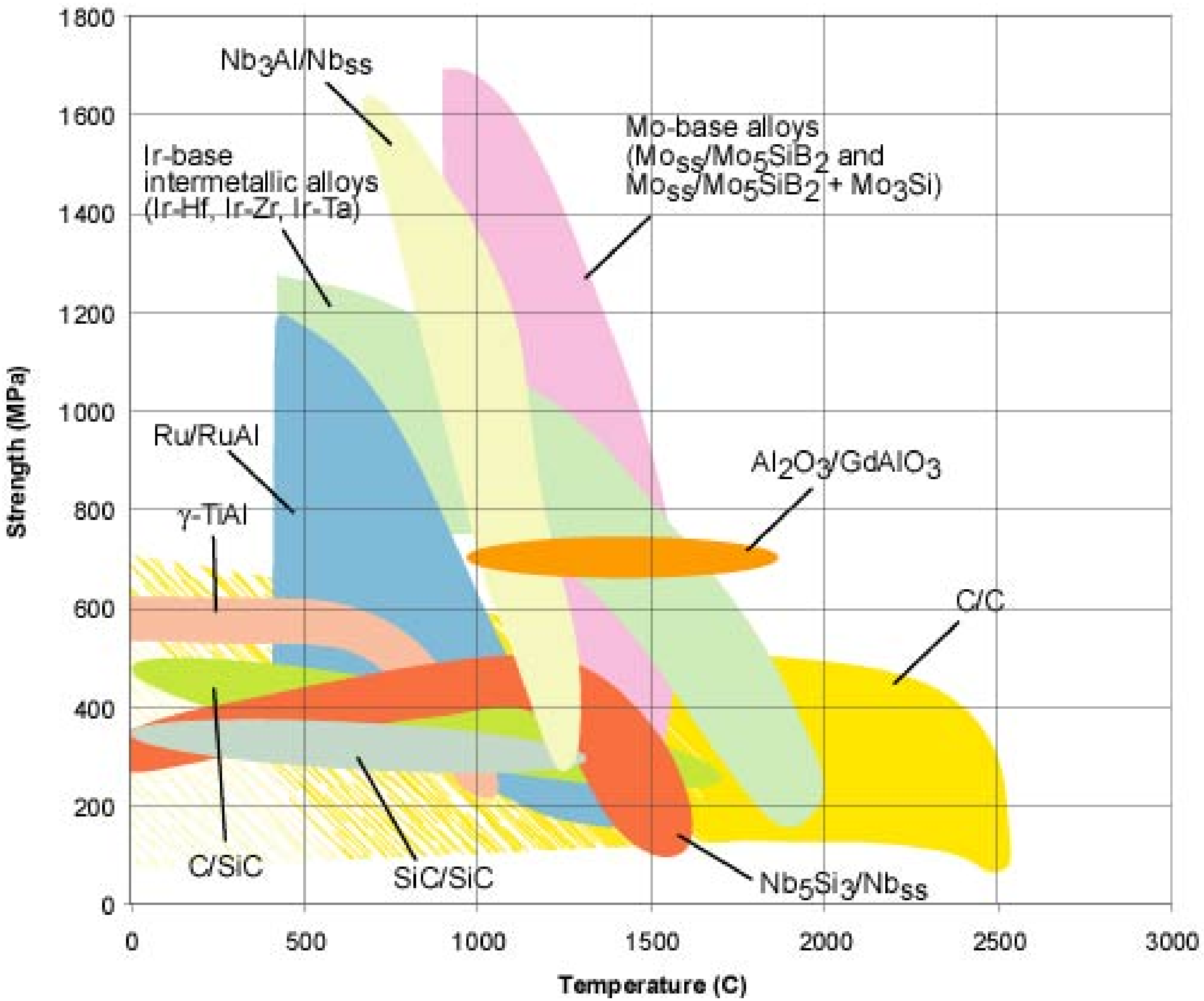


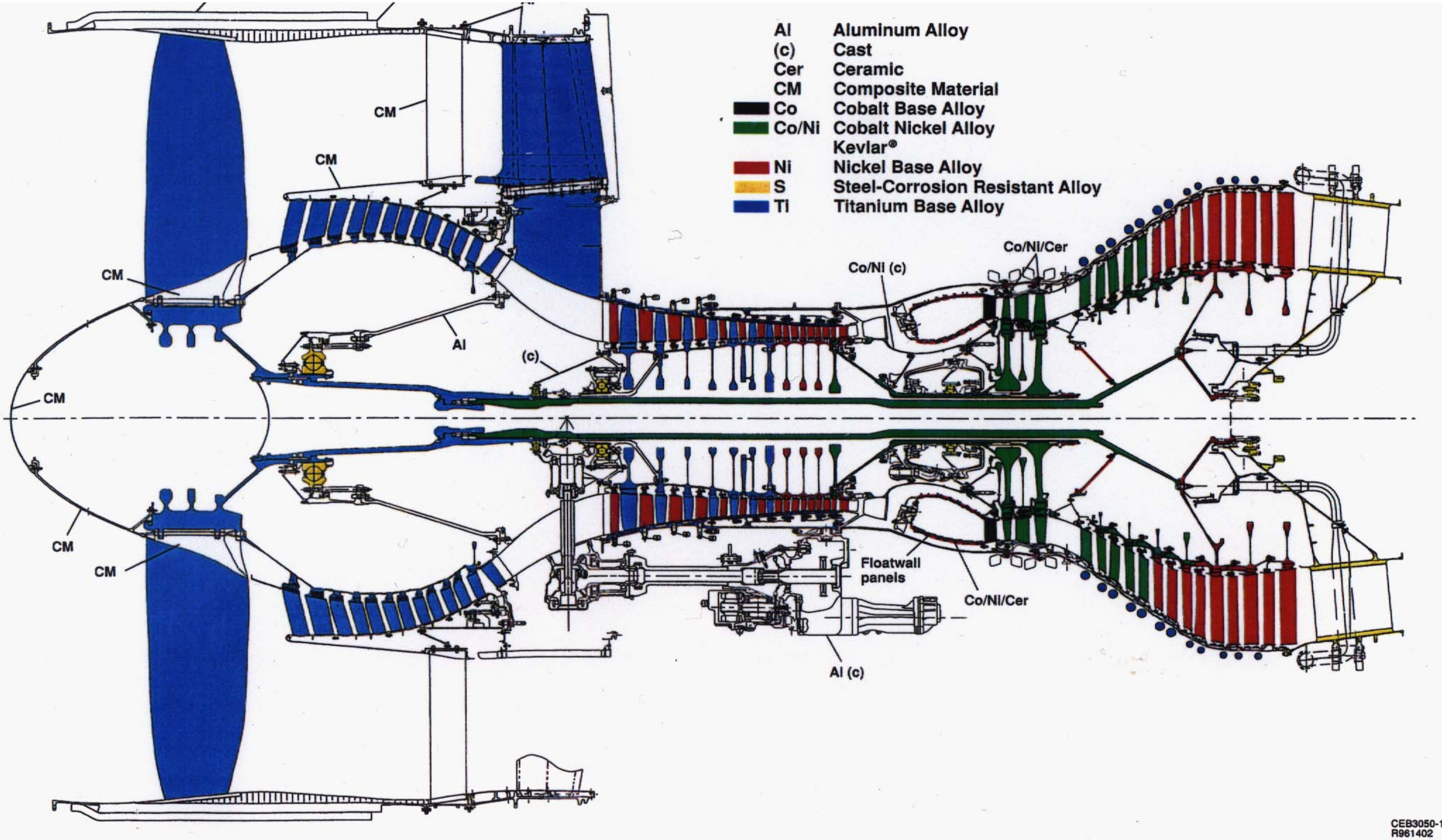
Turbine Airfoil Material Advancements

Specific Strengths of Metallic Systems



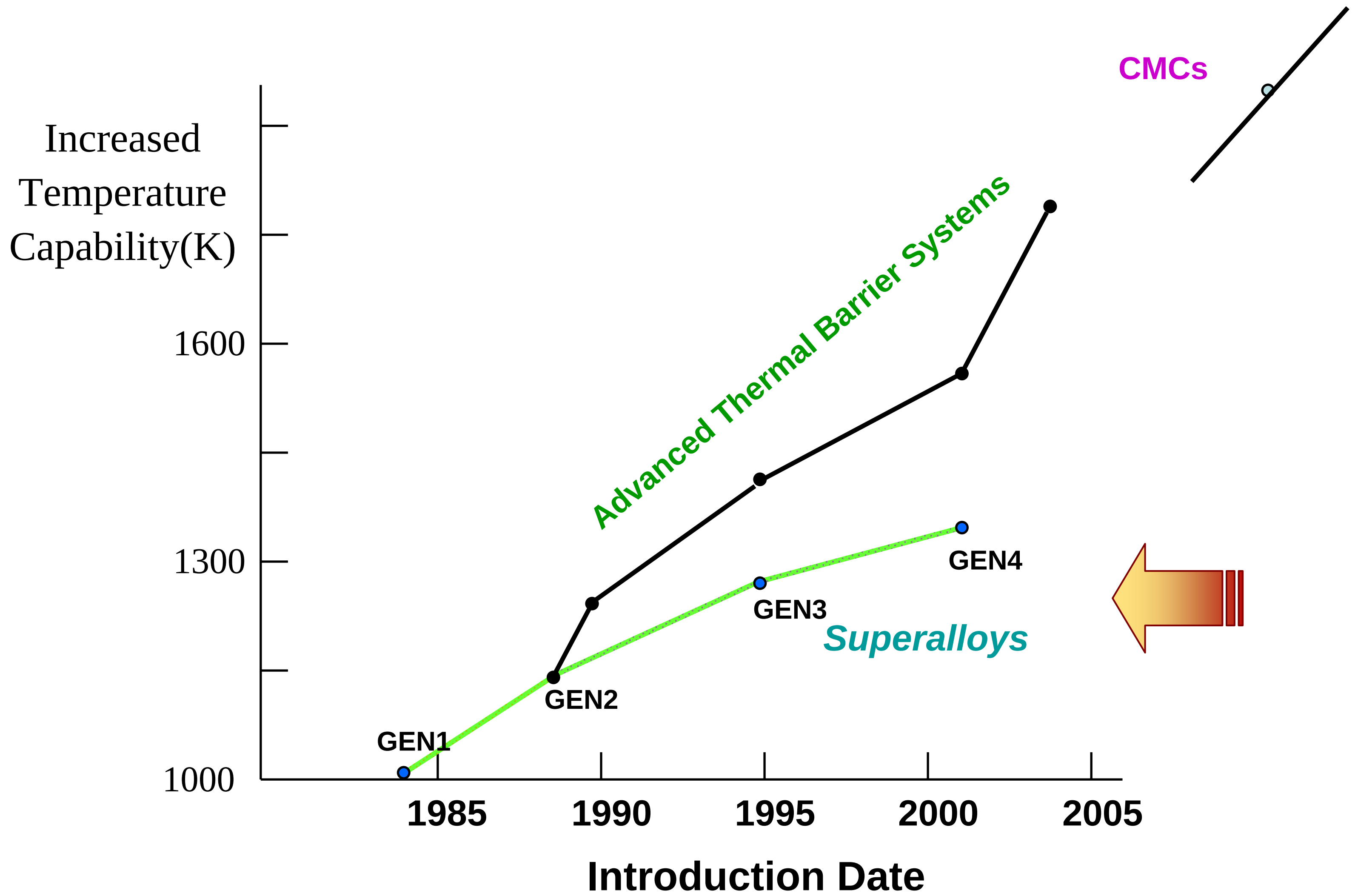
More High Temperature Materials





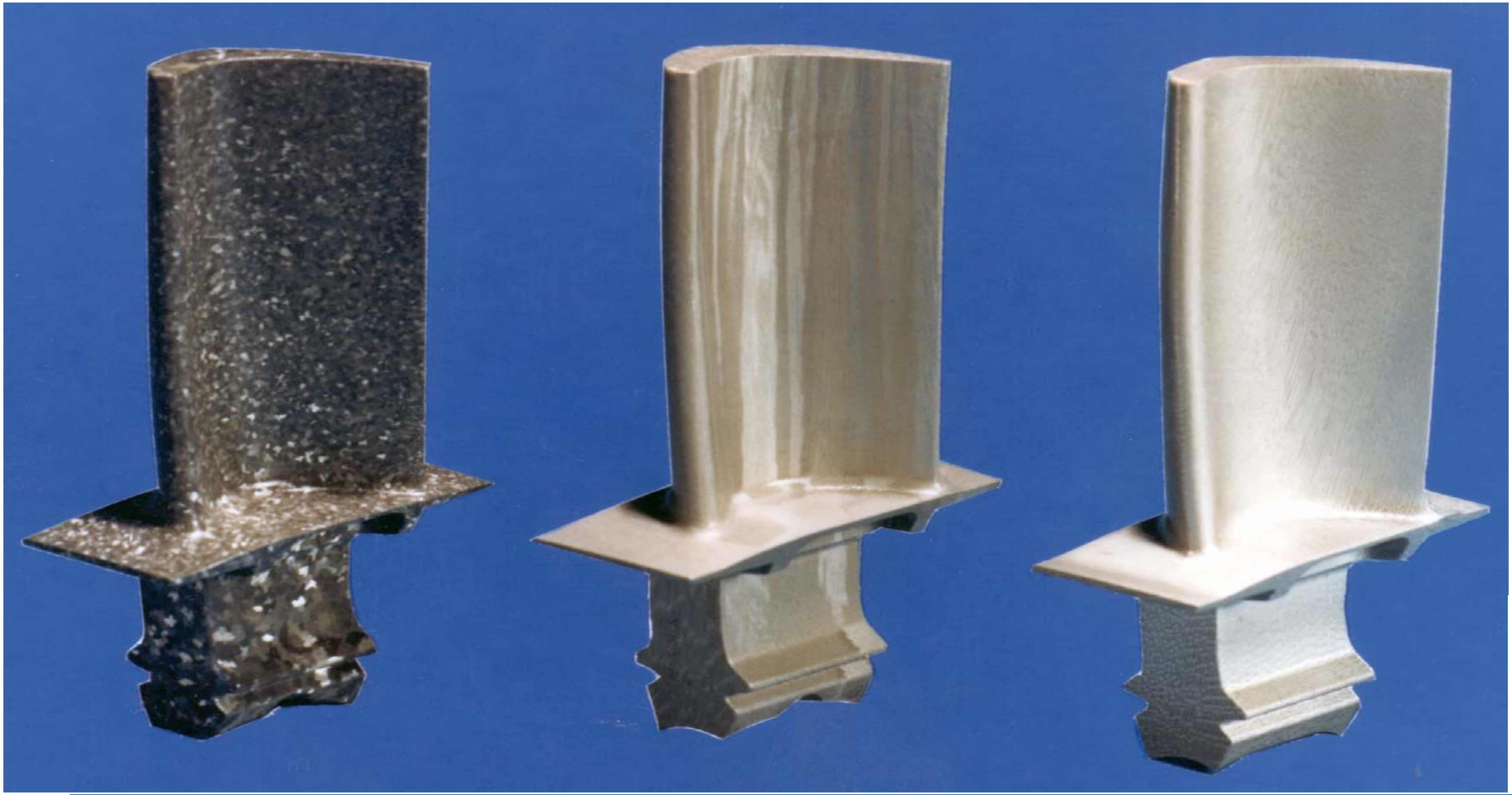
Al Aluminum Alloy
(c) Cast
Cer Ceramic
CM Composite Material
Co Cobalt Base Alloy
Co/Ni Cobalt Nickel Alloy
Kevlar®
Ni Nickel Base Alloy
S Steel-Corrosion Resistant Alloy
Ti Titanium Base Alloy
CM
CM
CM
CM
CM
CM
CM
Al
(c)
Co/Ni (c)
Co/Ni/Cer
Floatwall panels
Co/Ni/Cer
Al (c)
CEB3050-1
R961402

Role of Airfoil Materials



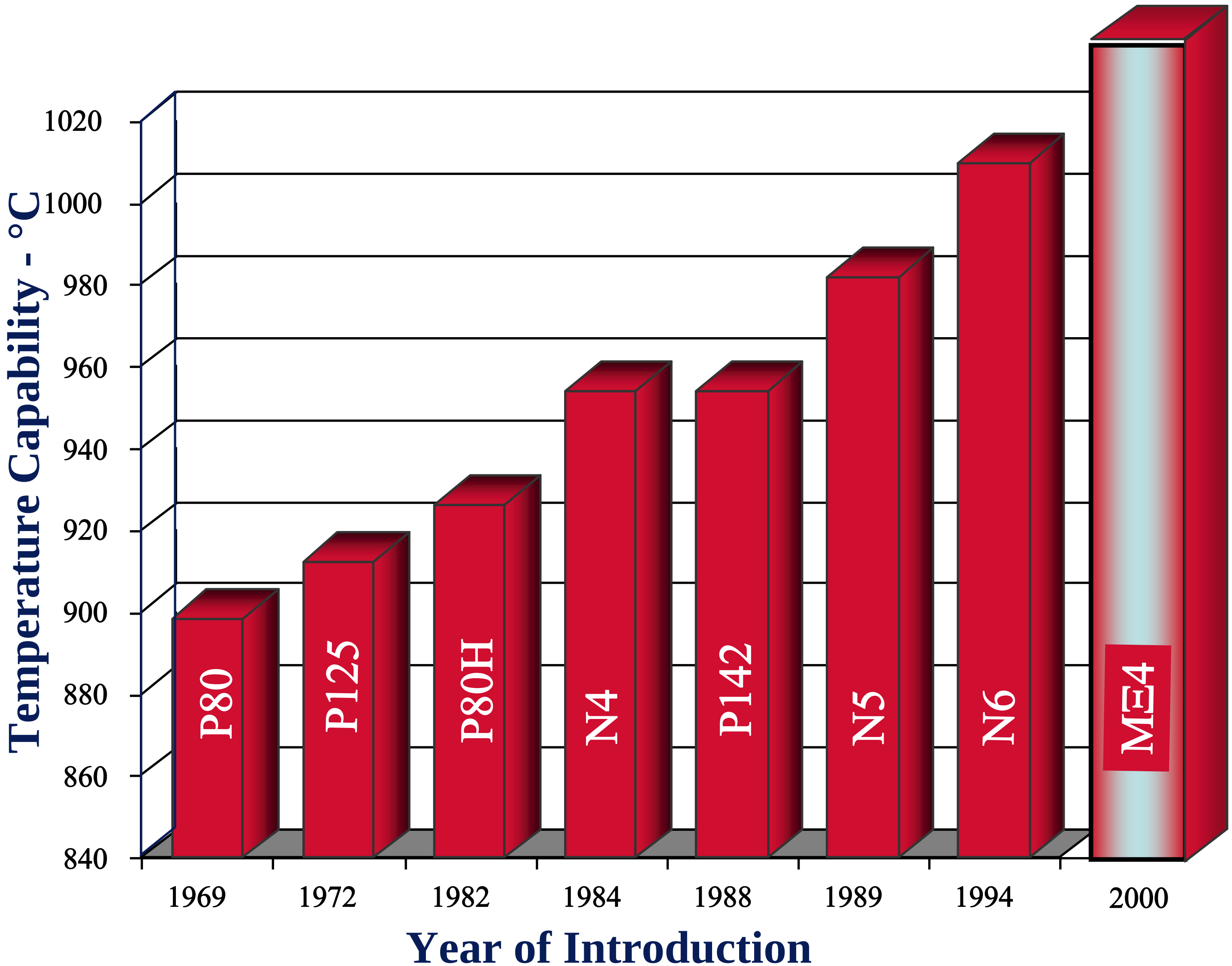
Turbine Airfoil Material Advancements

Superalloy Turbine Air Foils

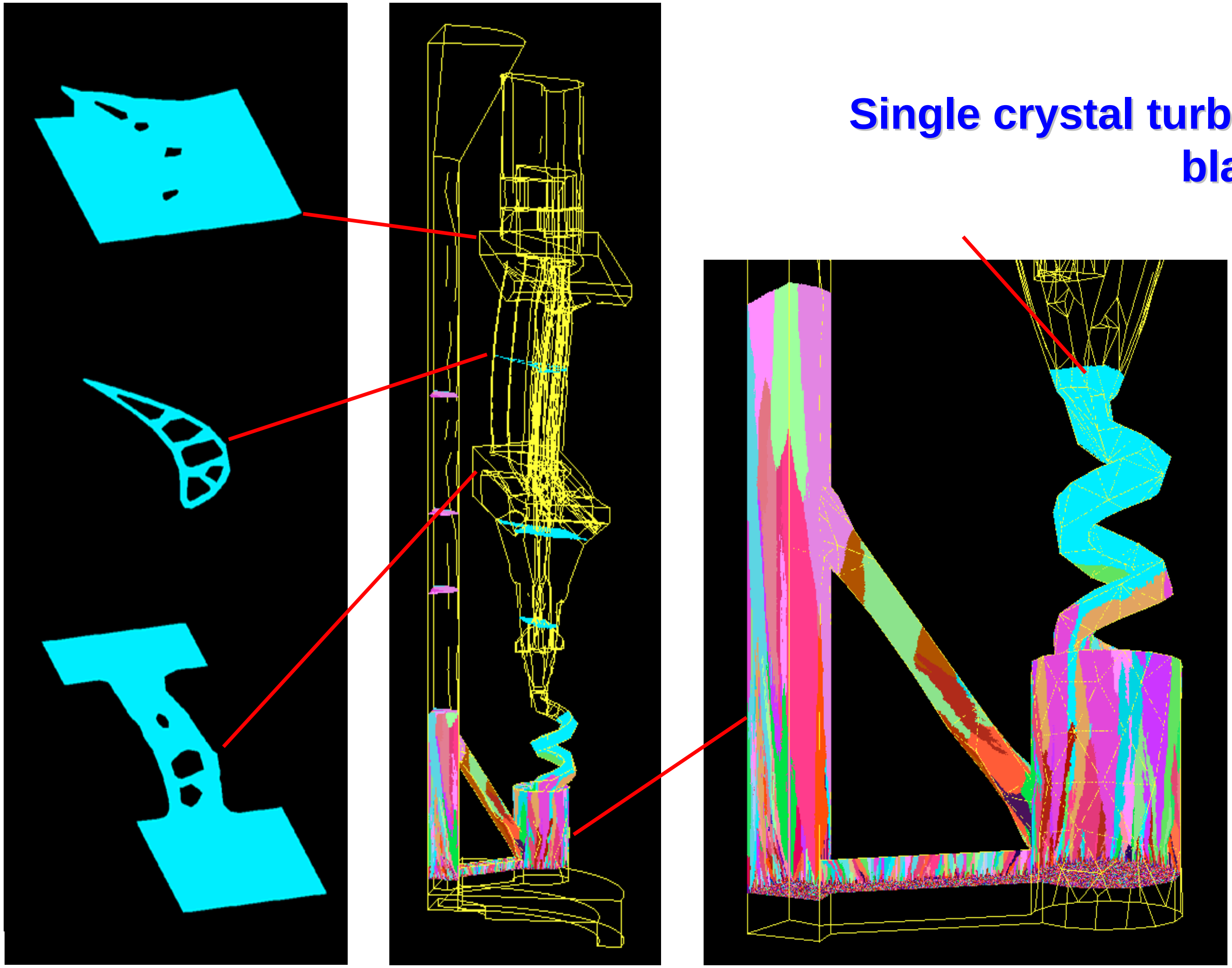


Equiaxed (EQ)	**Dir. Sol. (DS)**	**Single Xtal (SX)**

Ni Superalloy Improvements

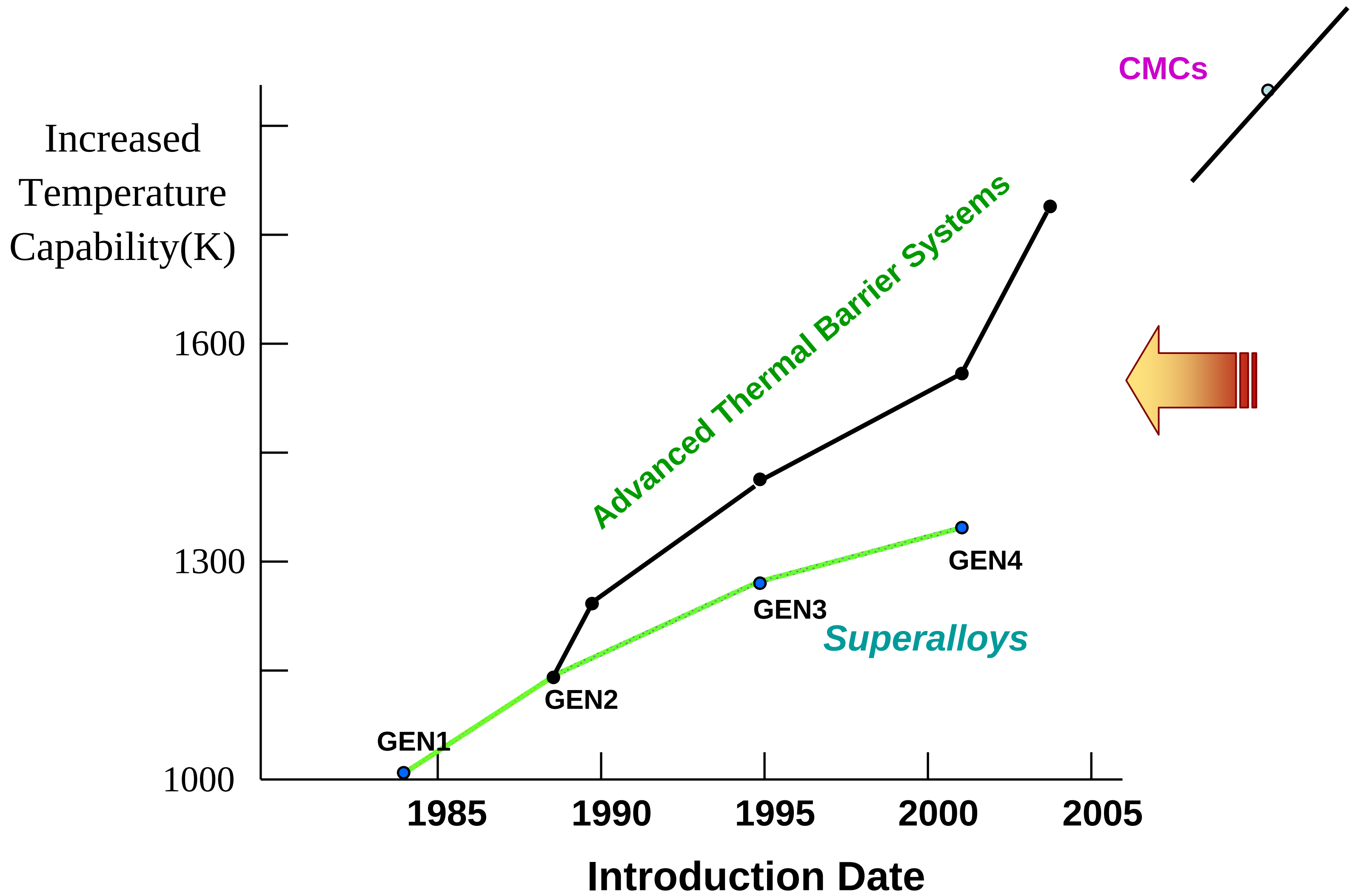


Modeling at the scale of the grains



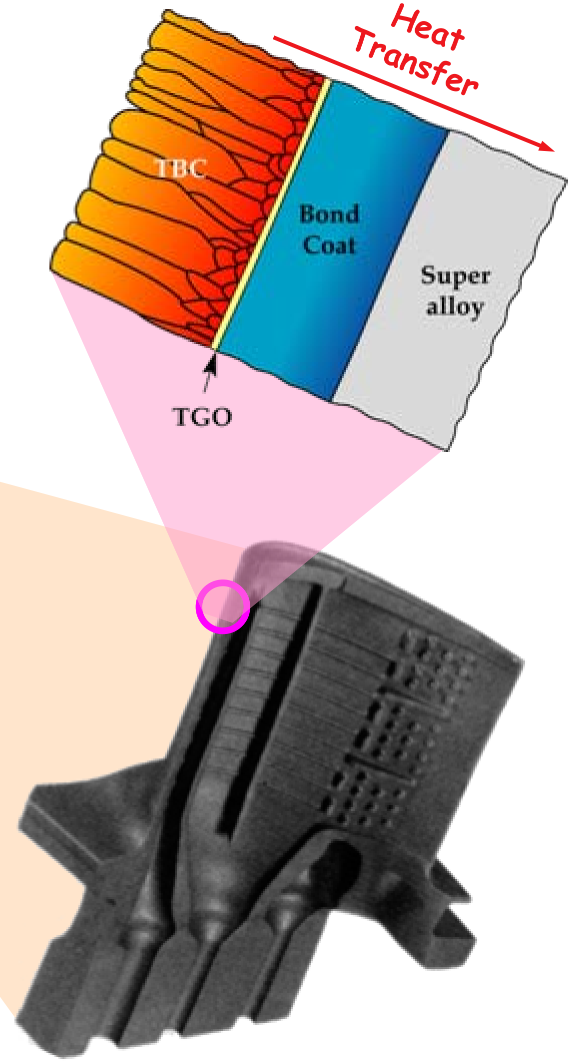
Single crystal turbine blade

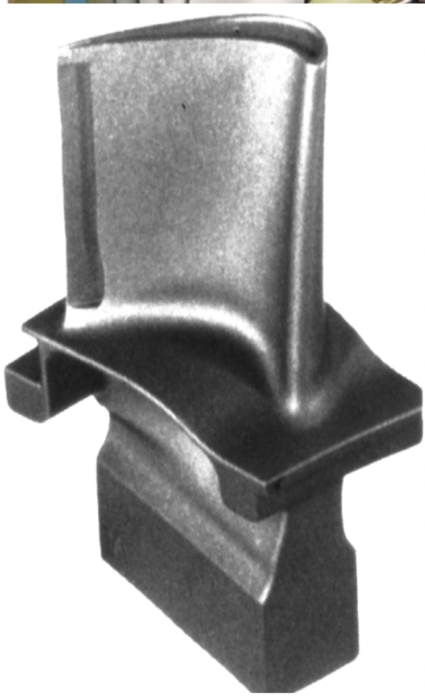
Role of Airfoil Materials



Turbine Airfoil Material Advancements

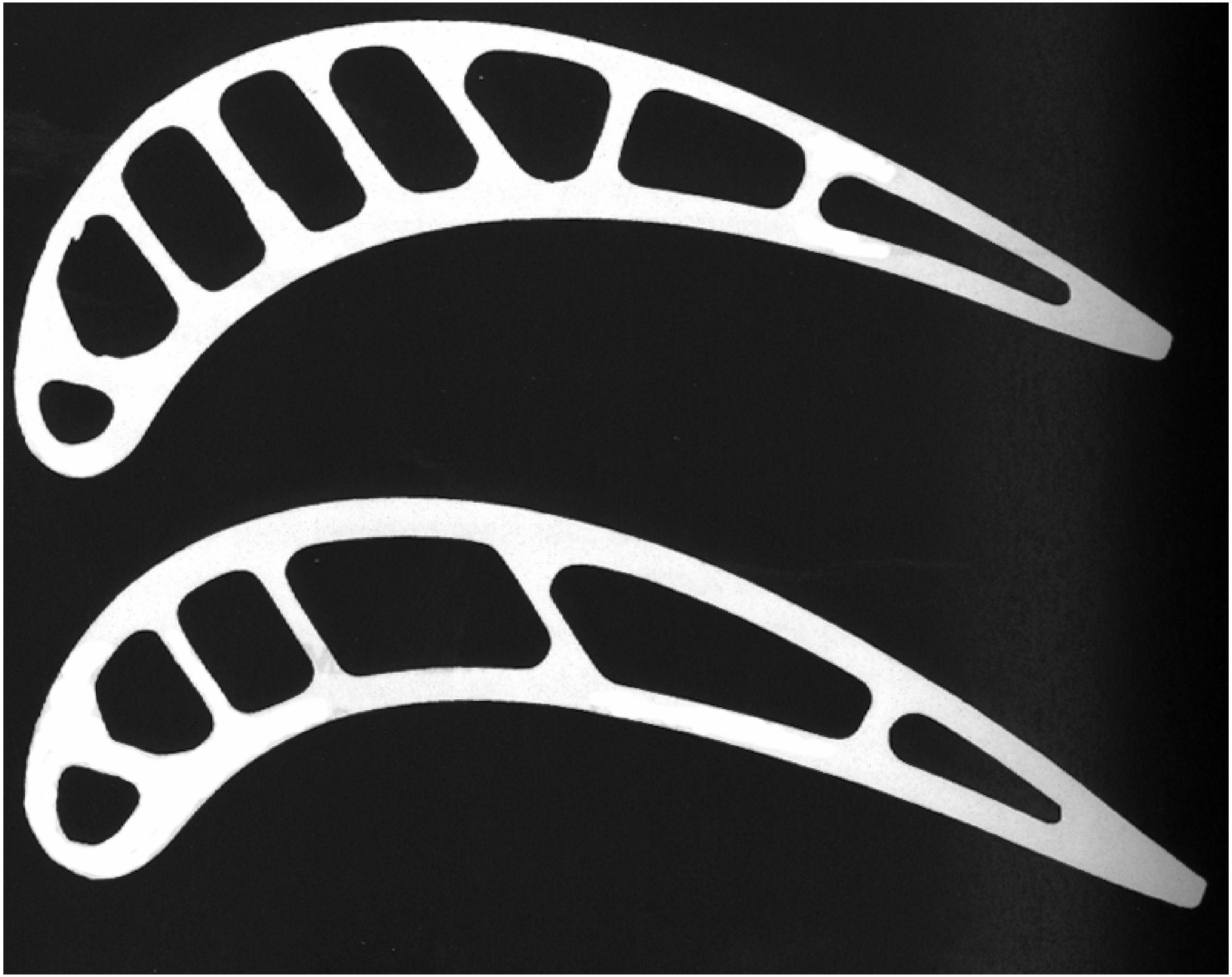
Airfoil Technology



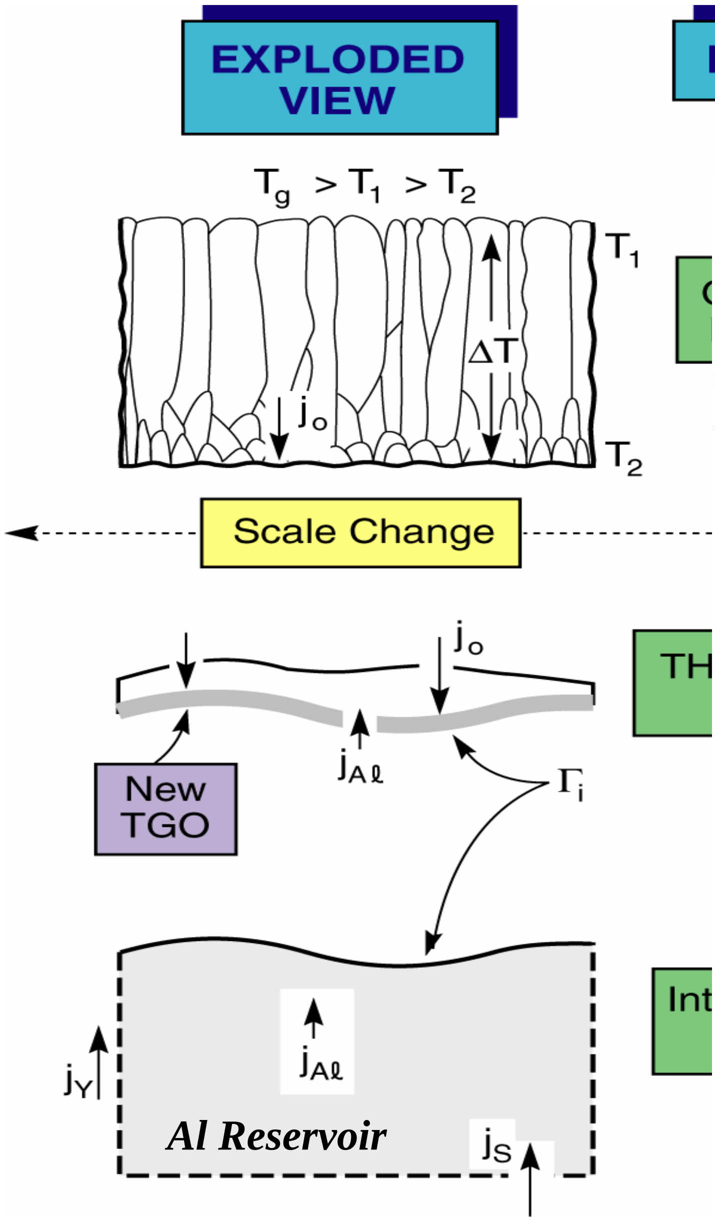


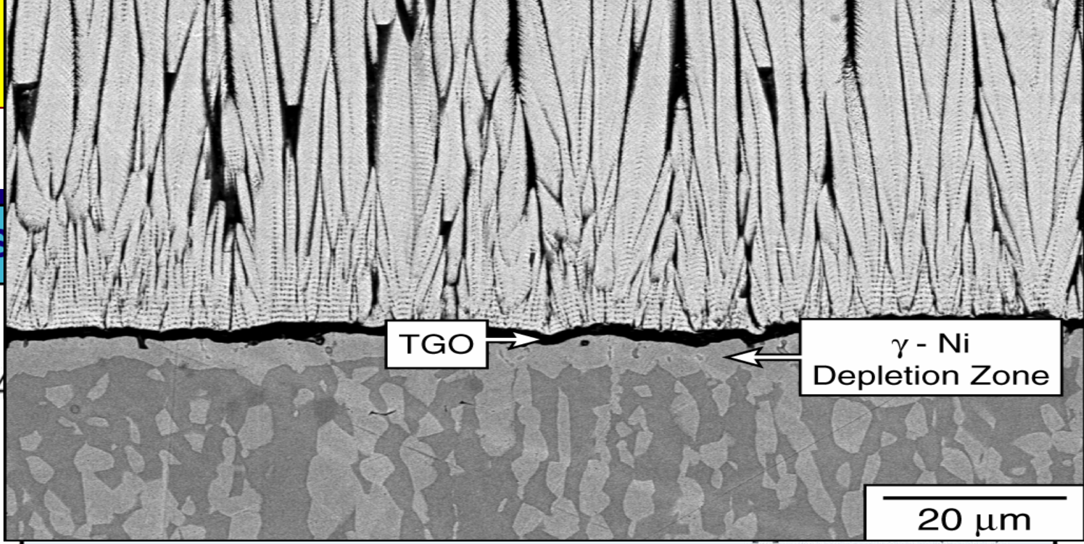
nce Coating Systems:
for advanced gas turbines

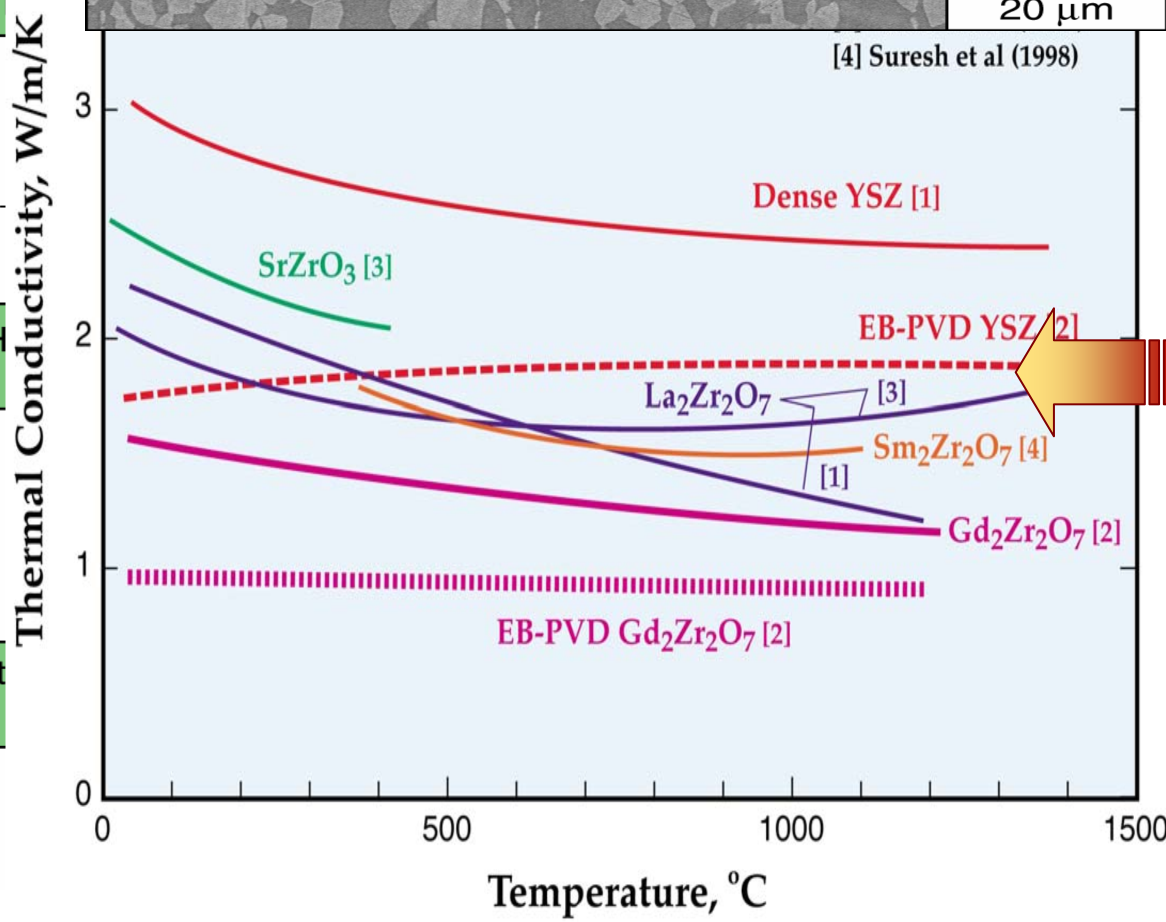
Transverse Section

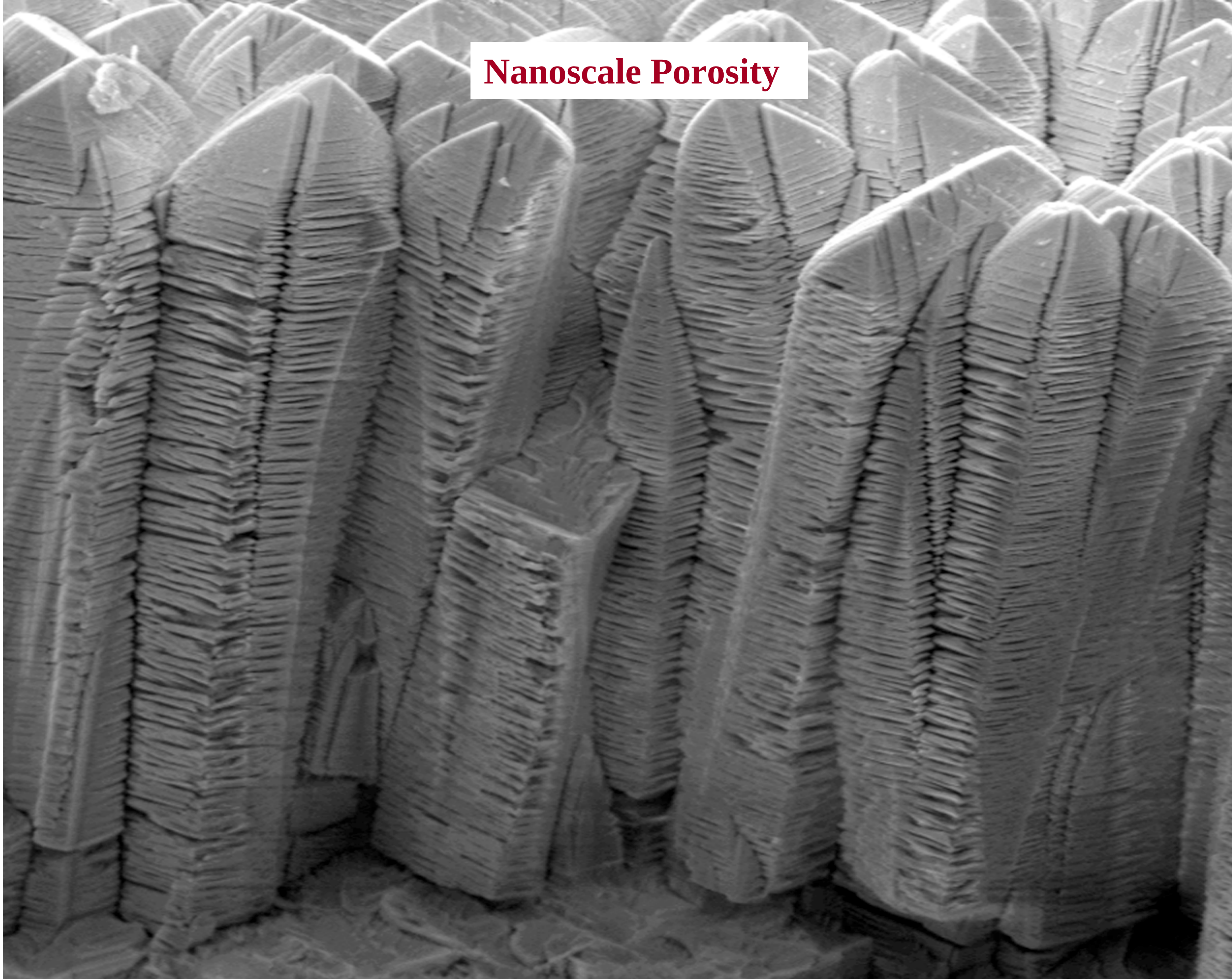


Thermal

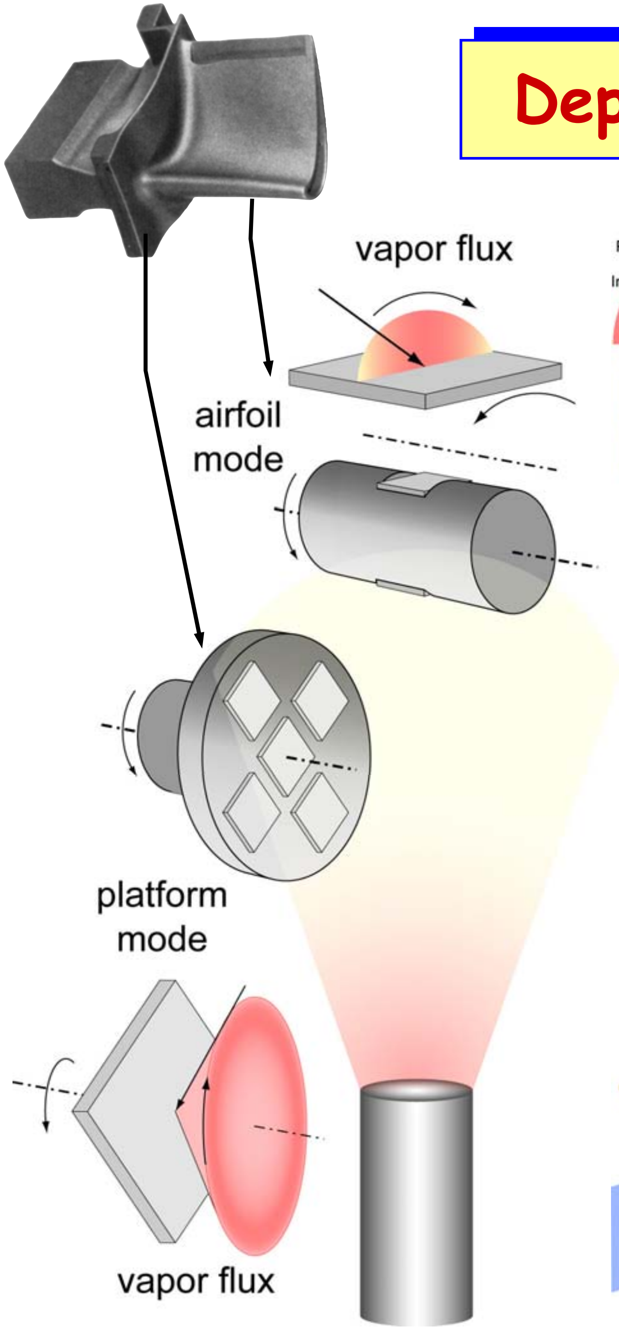

EXPLODED VIEW
DES
$T_g > T_1 > T_2$
T_1
ΔT
j_o
T_2
Scale Change
TH
j_o
New TGO
$j_{A\ell}$
Γ_i
Int
j_Y
$j_{A\ell}$
Al Reservoir
j_S

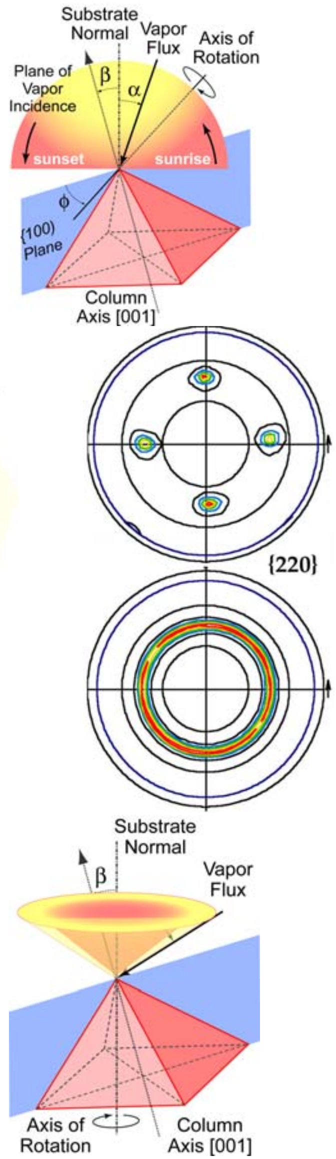

TGO
γ - Ni Depletion Zone
20 μm

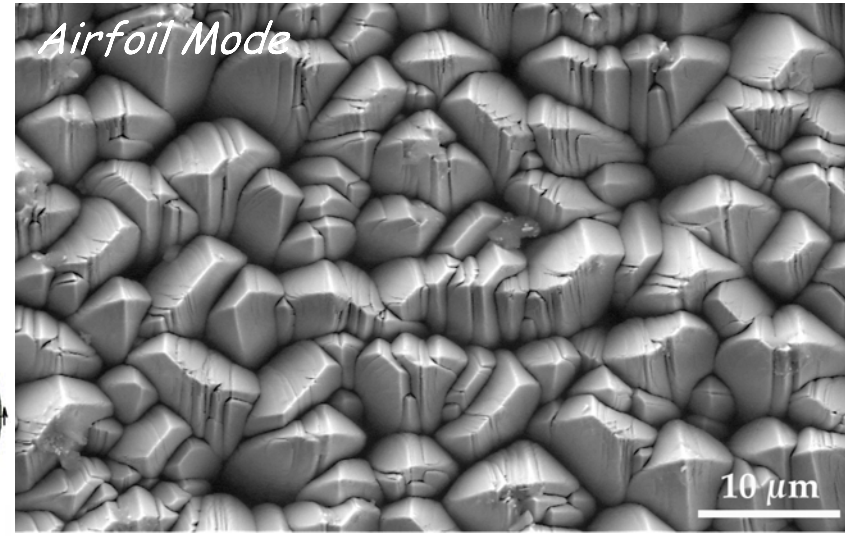

[4] Suresh et al (1998)
Thermal Conductivity, W/m/K
Temperature, °C
Dense YSZ [1]
$SrZrO_3$ [3]
EB-PVD YSZ [2]
$La_2Zr_2O_7$
[3]
[1]
$Sm_2Zr_2O_7$ [4]
$Gd_2Zr_2O_7$ [2]
EB-PVD $Gd_2Zr_2O_7$ [2]
0
1
2
3
500
1000
1500


Nanoscale Porosity

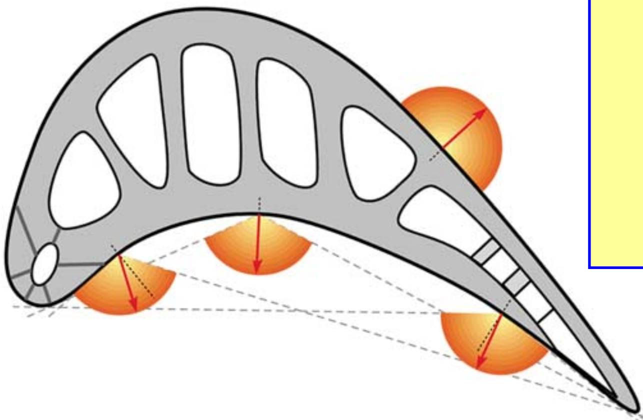
Deposition Effects on Microstructure

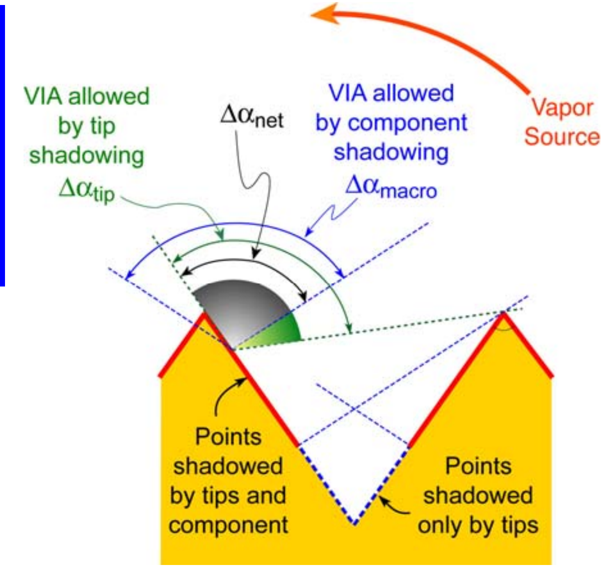


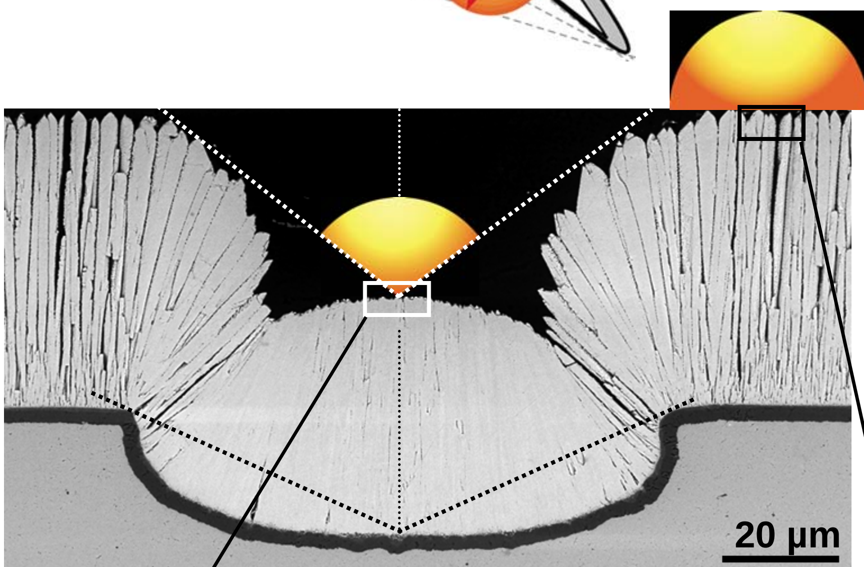




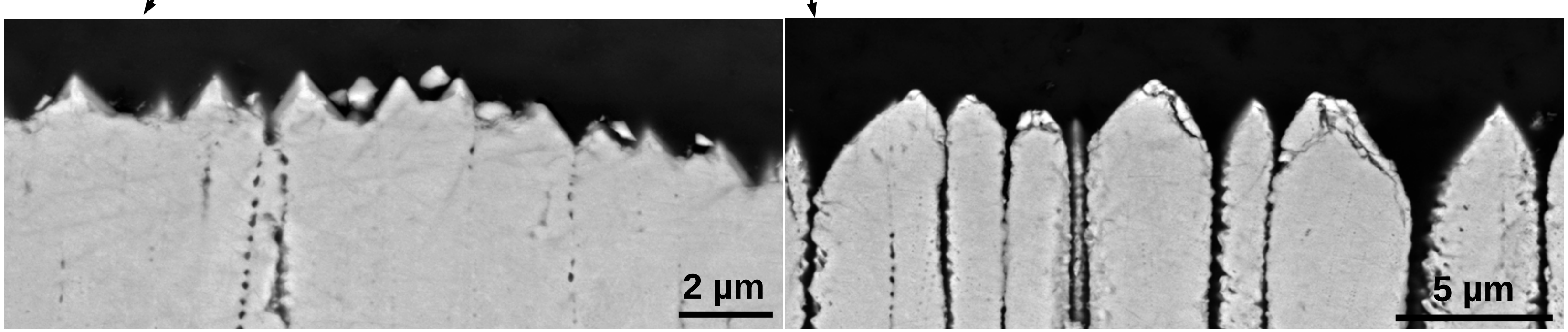
Interplay with Component Geometry



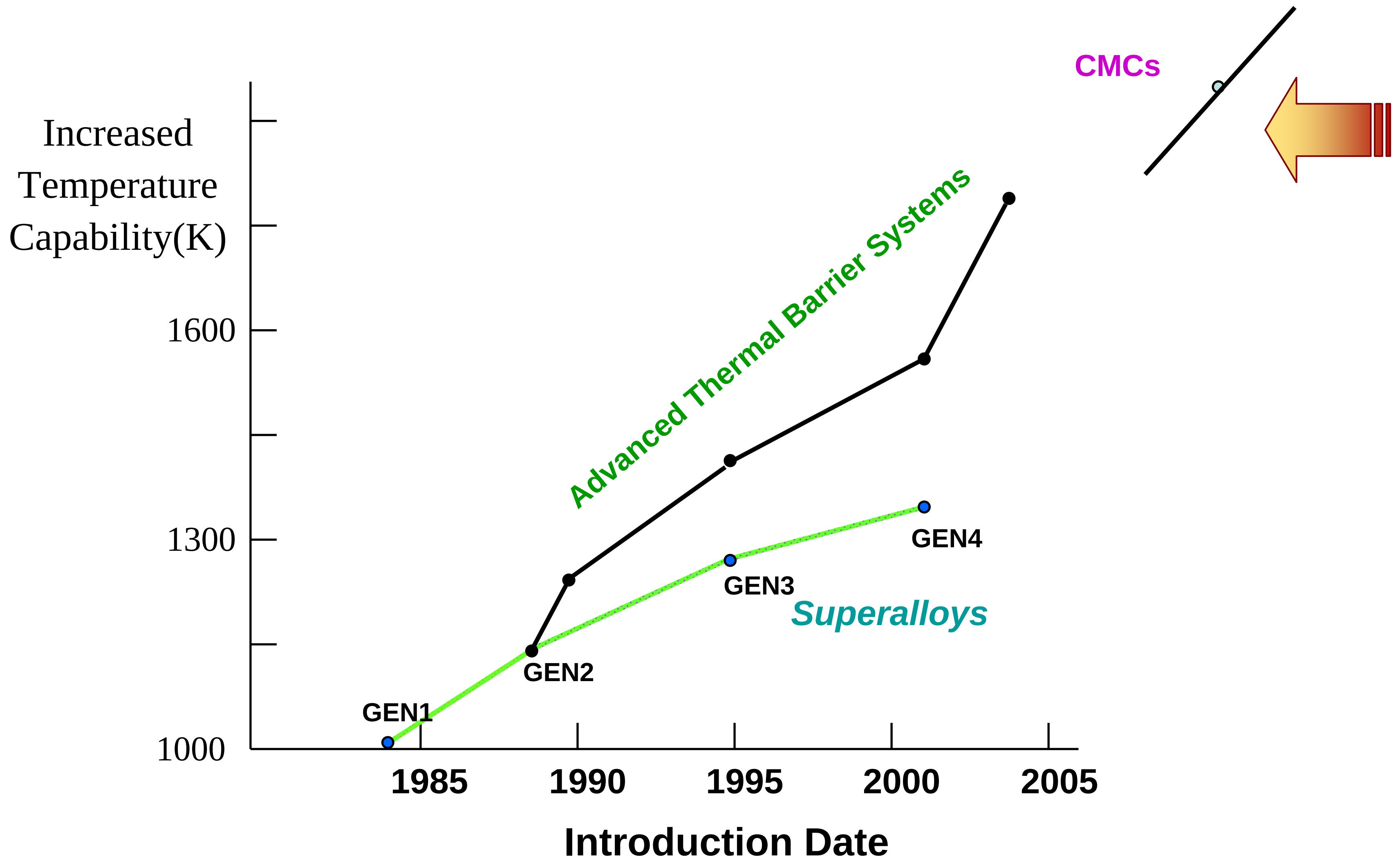




- *Reduced coating thickness within recess, quantitatively consistent with reduction in integrated flux due to shadowing by corners.*
- *Reduced inter-columnar gap width—and increased propensity to sintering—due to elimination of most oblique vapor flux.*

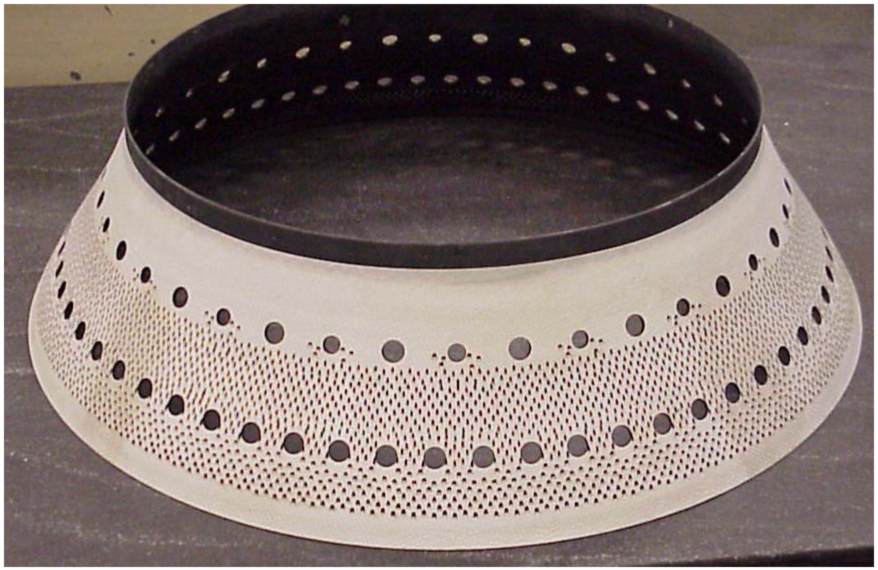


Role of Airfoil Materials



Turbine Airfoil Material Advancements

Ceramic Matrix Composites (CMC)



CMC Combustor Liner

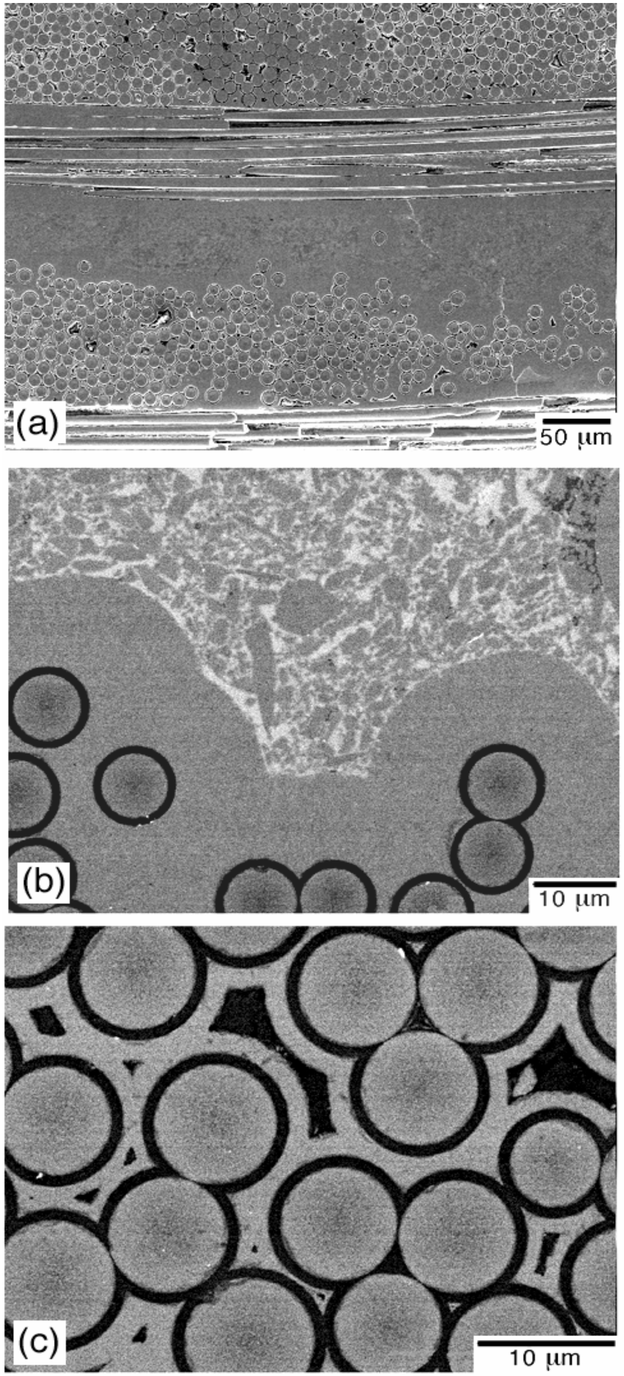
Cooling Air Reduction
Weight Reduction
20% NOx Reduction

CMC Vane

CMC Blade

Weight Reduction
Reduced Cooling Air
Increased Efficiency

CMC's Reduce Weight and Improve Performance



(MI) SiC/SiC (DENSE MATRIX)

T = 1400C (Metals < 1100C)

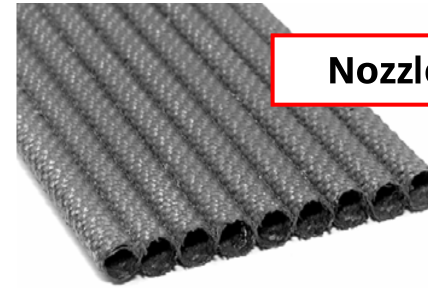
- High Thermal Conductivity
- Inter-laminar Shear Strength
- Reduced Sensitivity to Pesting

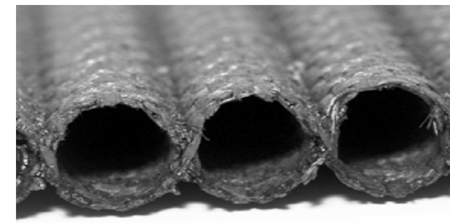
Integrally woven CMC Structures

Transition duct

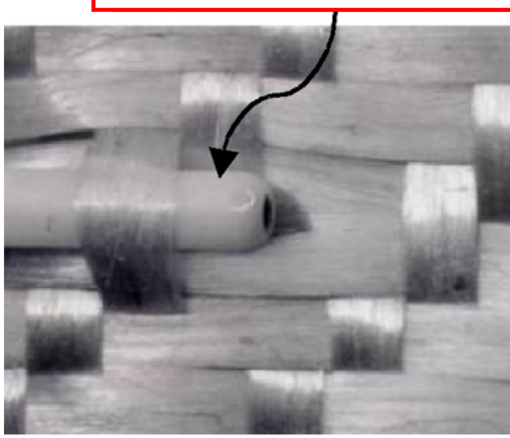
Braided SiC/SiC
Hyper-Therm Inc.

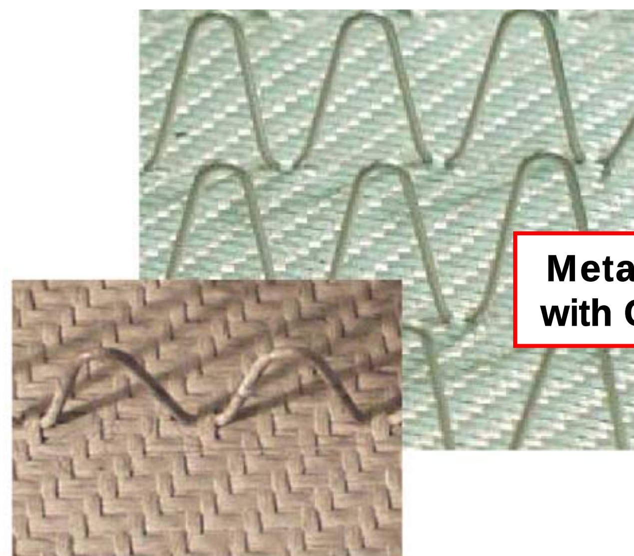
Nozzles





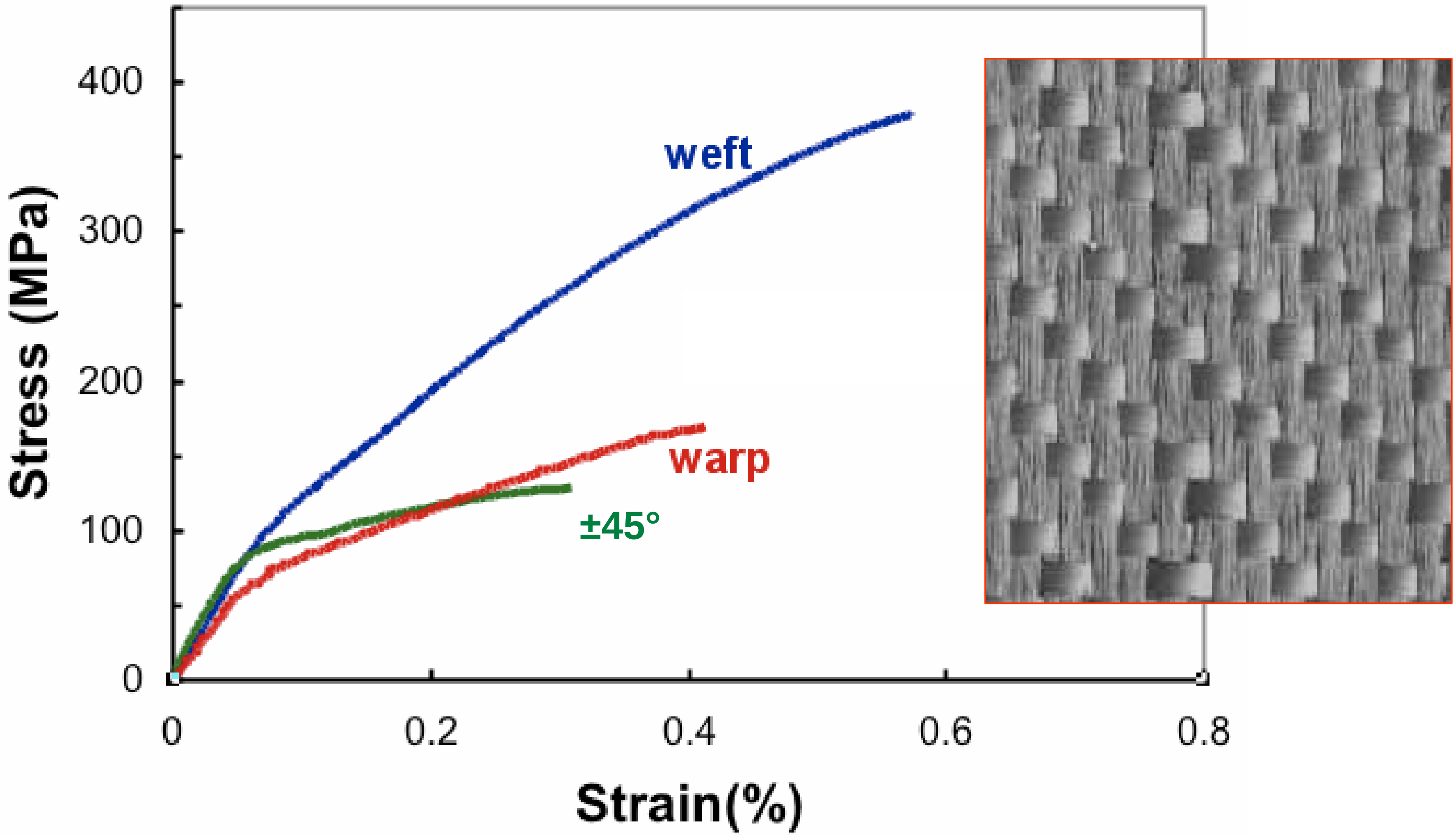
Alumina anchor tube in CMC skin for pin joint





Metallic struts with CMC skin

Angle Interlock
Sylramic/SiC



CMC Combustor Liners

CMC Inner Combustor Liner After Engine Testing

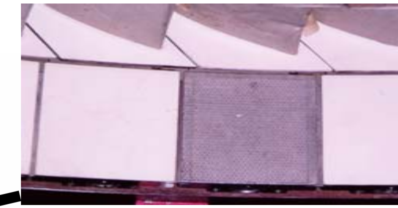
- Hi-Nicalon, Slurry Cast
- Successful Engine Testing
- Pre and Post Engine Test NDE Revealed Degradation
- Additional Engine Testing

CMC Combustor Liner Rig & Engine Testing Successful

CMC Applications in Utility Gas Turbines

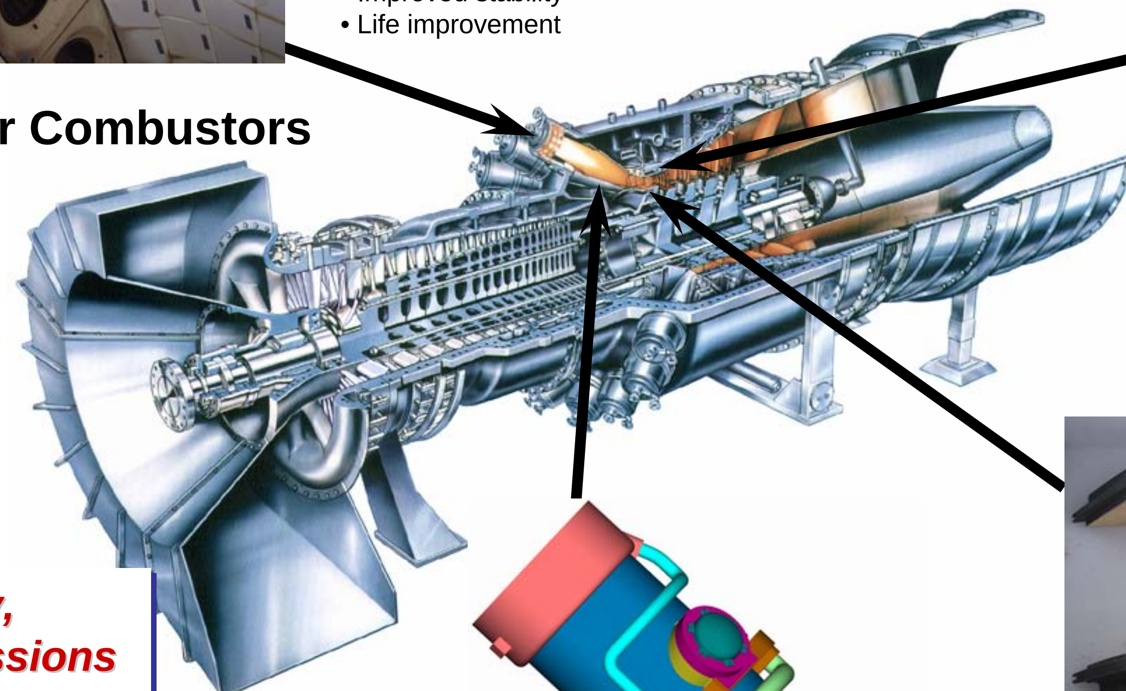
Benefits:
- NOx reductions (50%)
- CO reductions (50%)
- Improved stability
- Life improvement

Annular Combustors

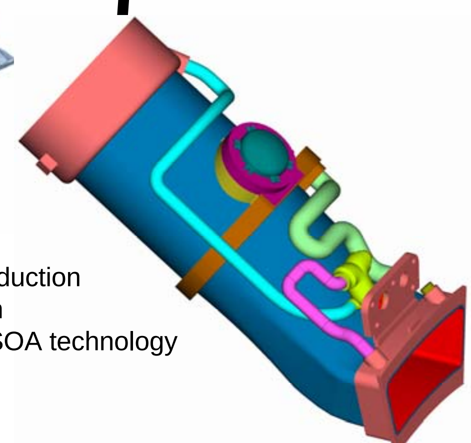


Shroud Segments

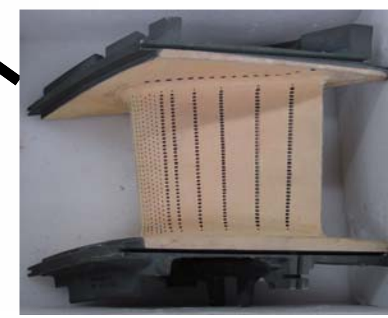
Benefits:
- 90% cooling air reduction
- 0.2% efficiency gain
- Reduced tip clearance



These efficiency, power, and emissions benefits translate to $M in annual savings for each installation.



Benefits:
- >90% cooling air reduction
- 0.4% efficiency gain
- Cost savings over SOA technology

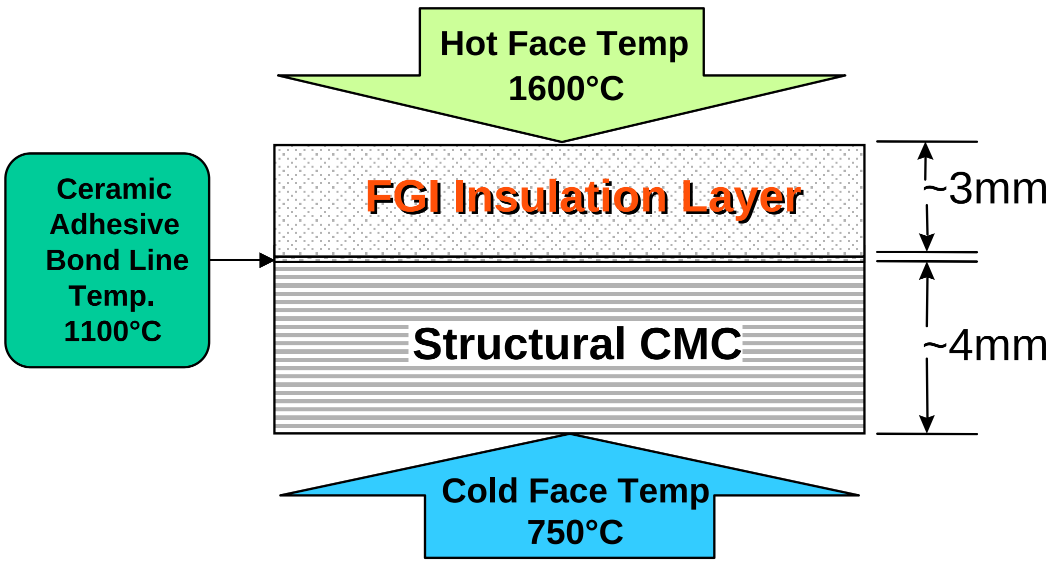


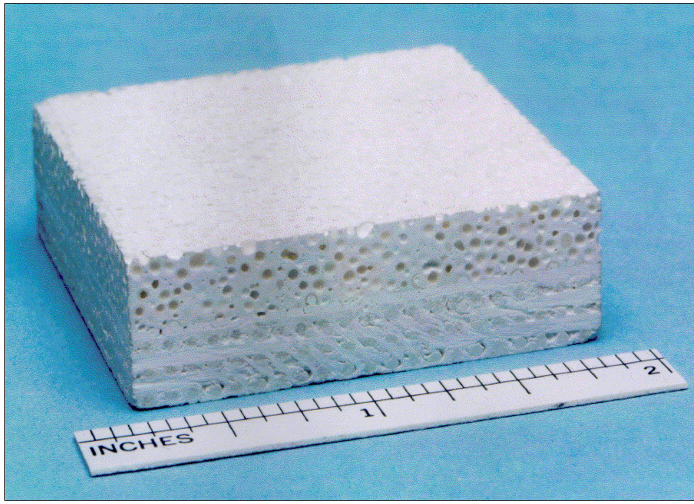
Vanes

Benefits:
- 90% cooling air reduction
- Efficiency gains of >1%
- NOx reductions (50%)

Hybrid CMC Concept

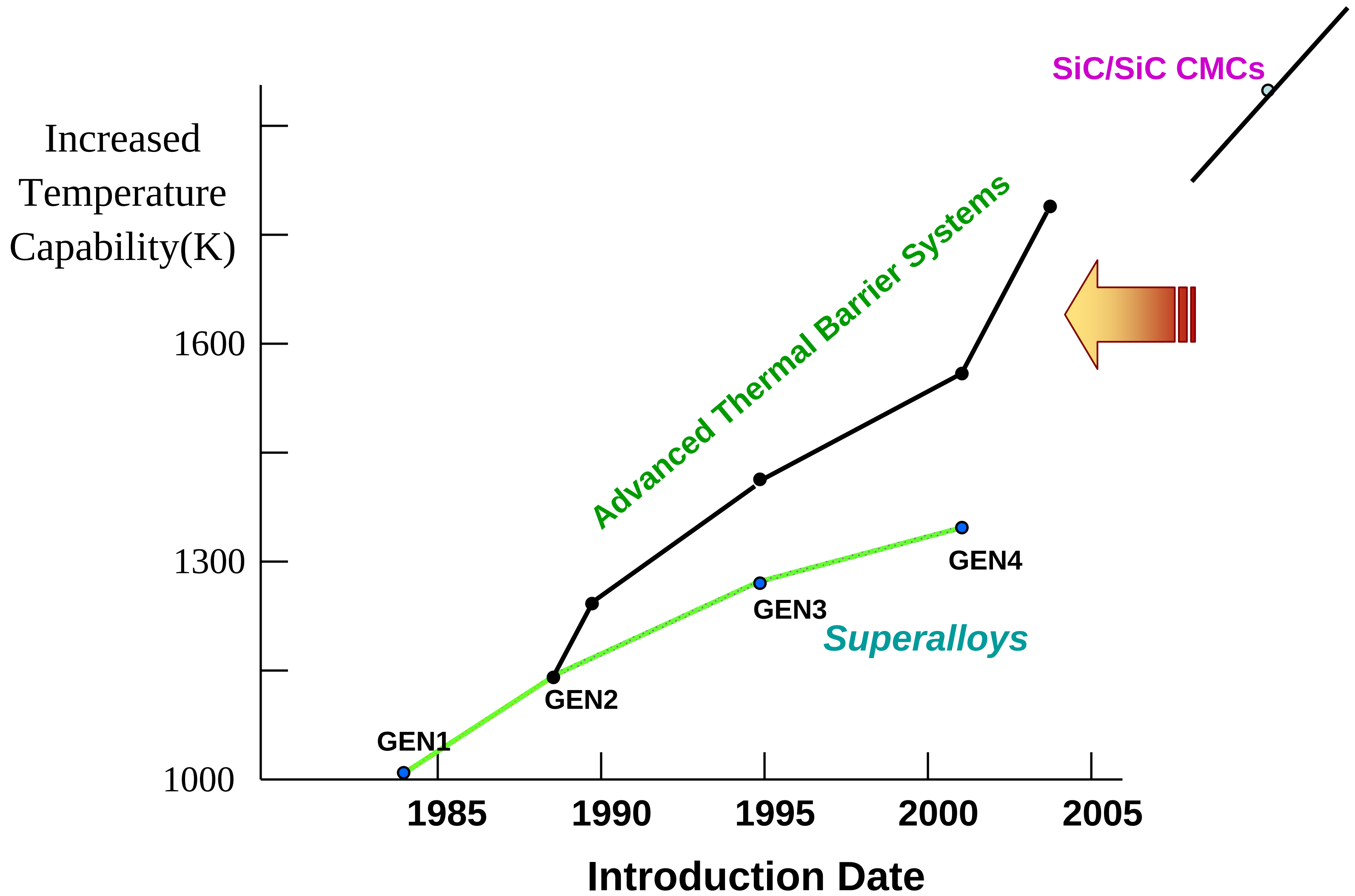
The **"hybrid" concept** involves use of a moderate temperature (~1100° - 1200°C) CMC structural member bonded to a ceramic insulating material having good stability at 1600°C and good erosion resistance.





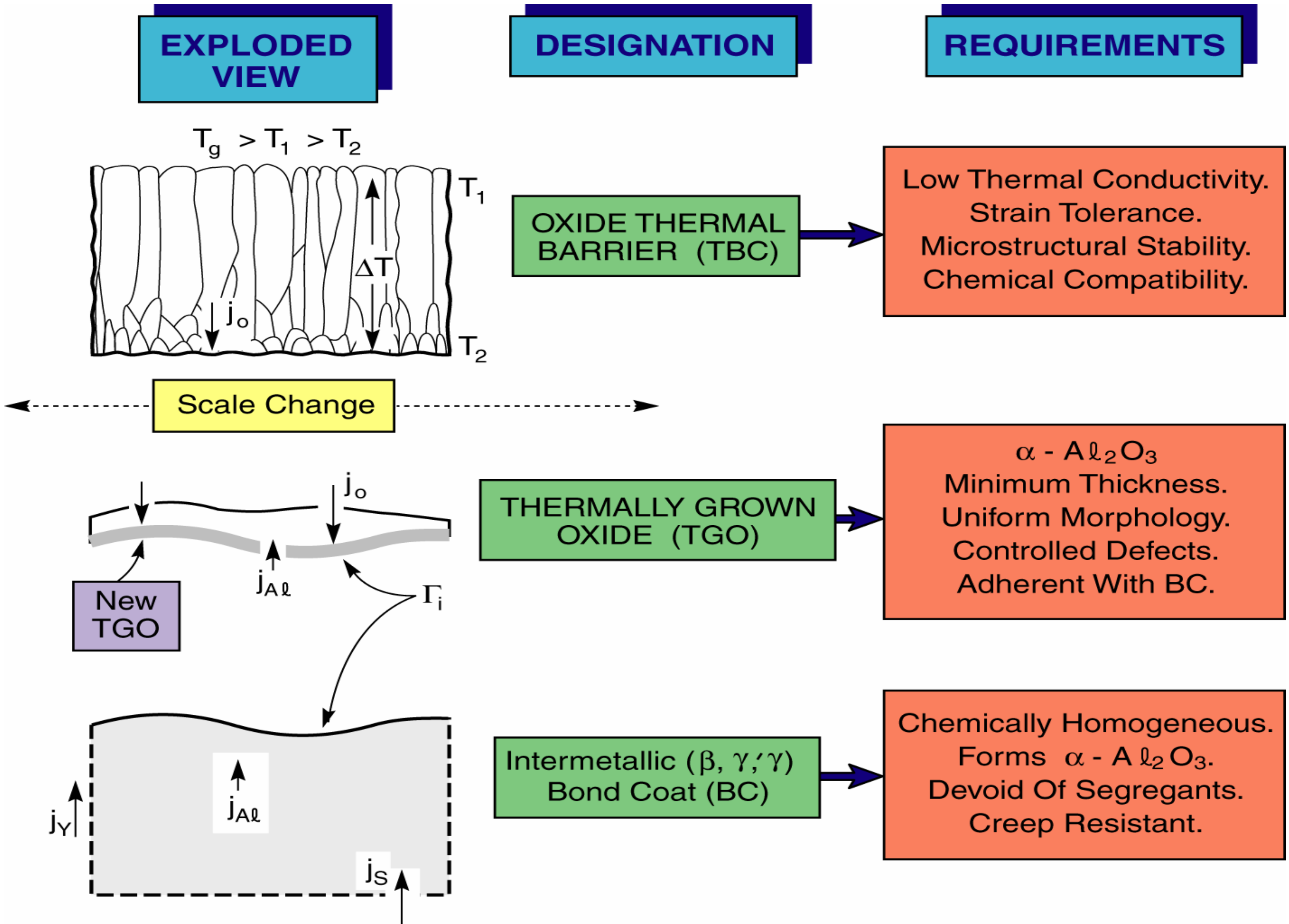
- Oxide fiber available
- Insulating material technology available
- Reduces cooling needs drastically

Role of Airfoil Materials

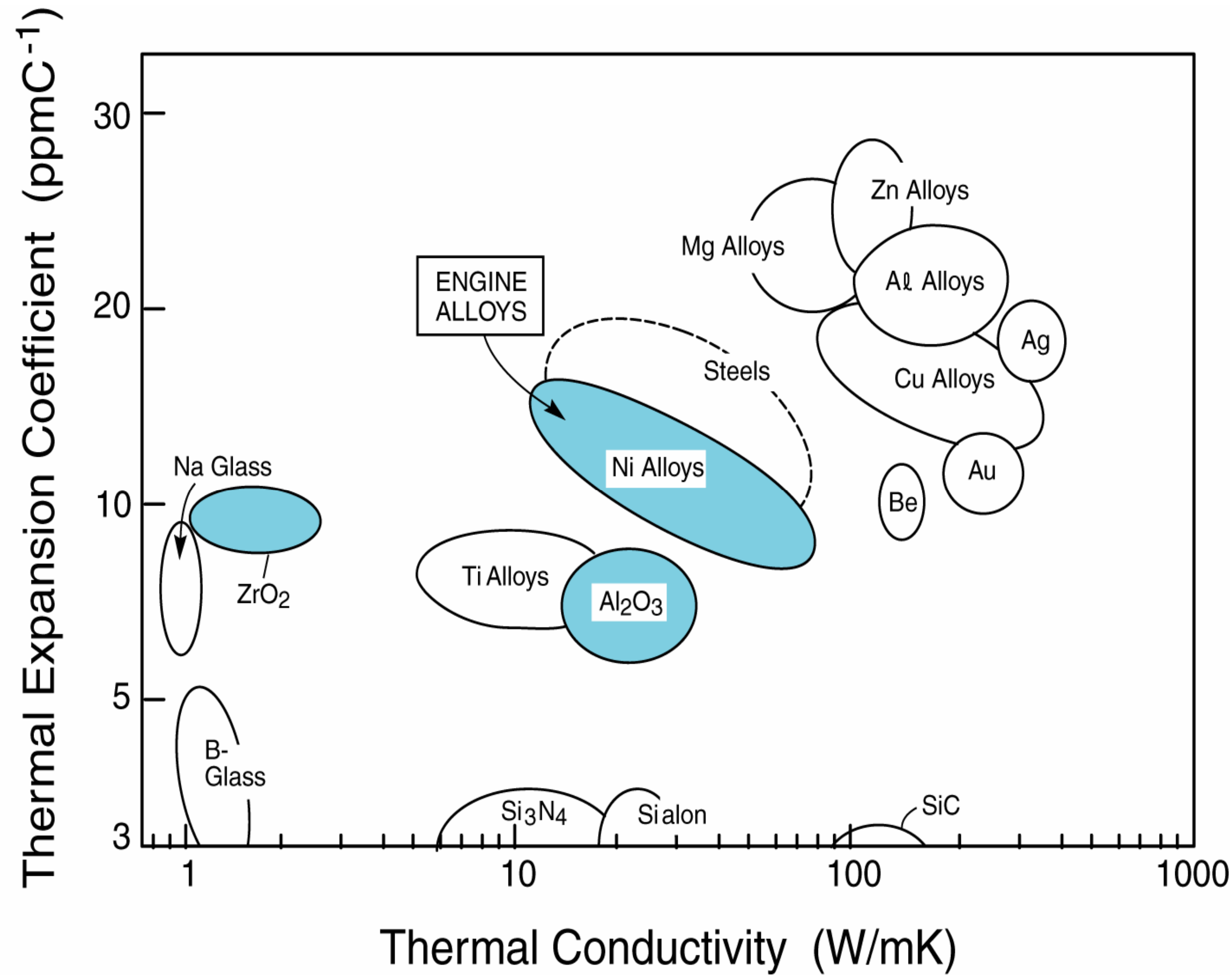


Turbine Airfoil Material Advancements

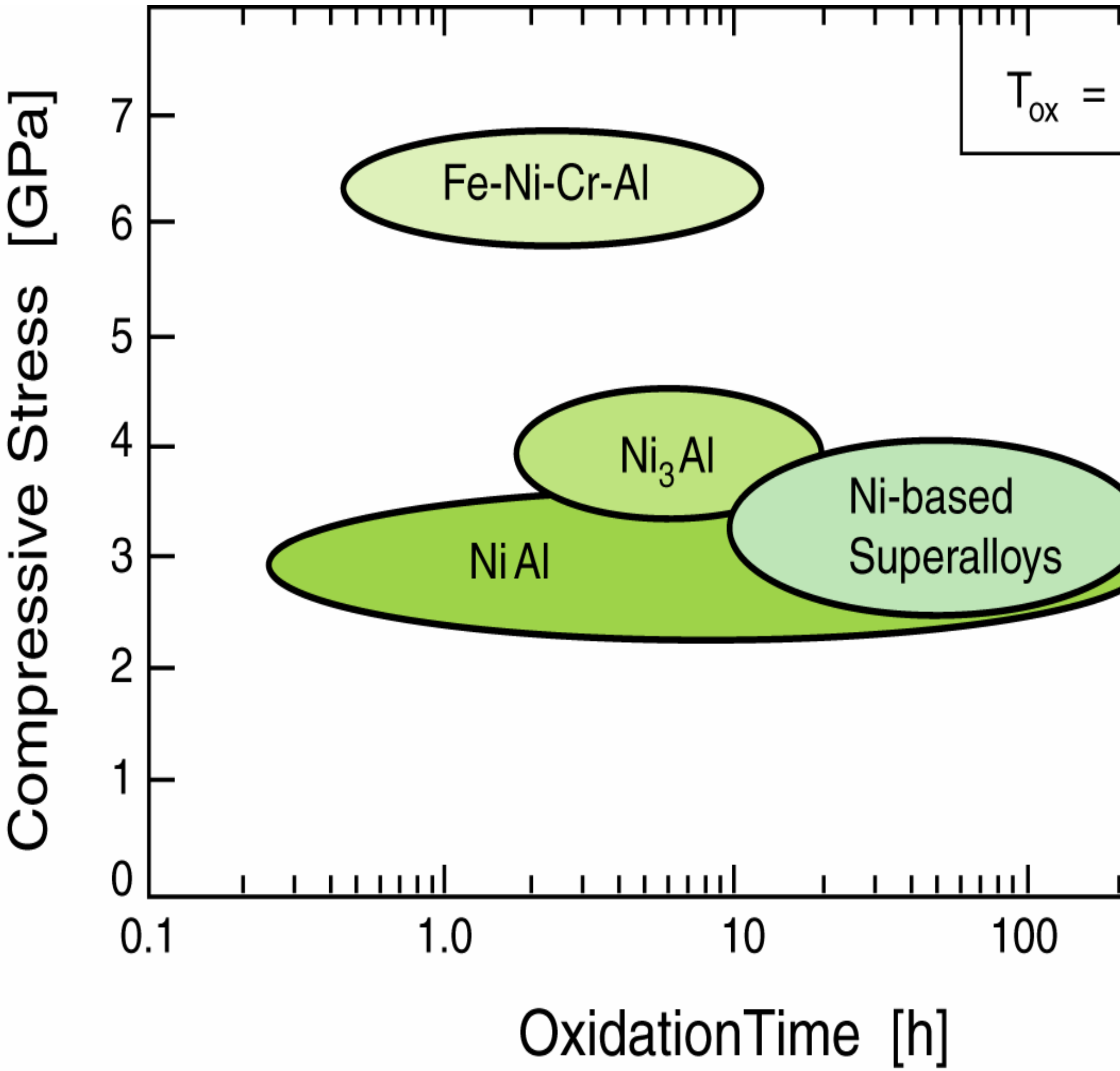
Thermal Barrier Multilayer: Challenging Thermo-Chemo-Mechanical System

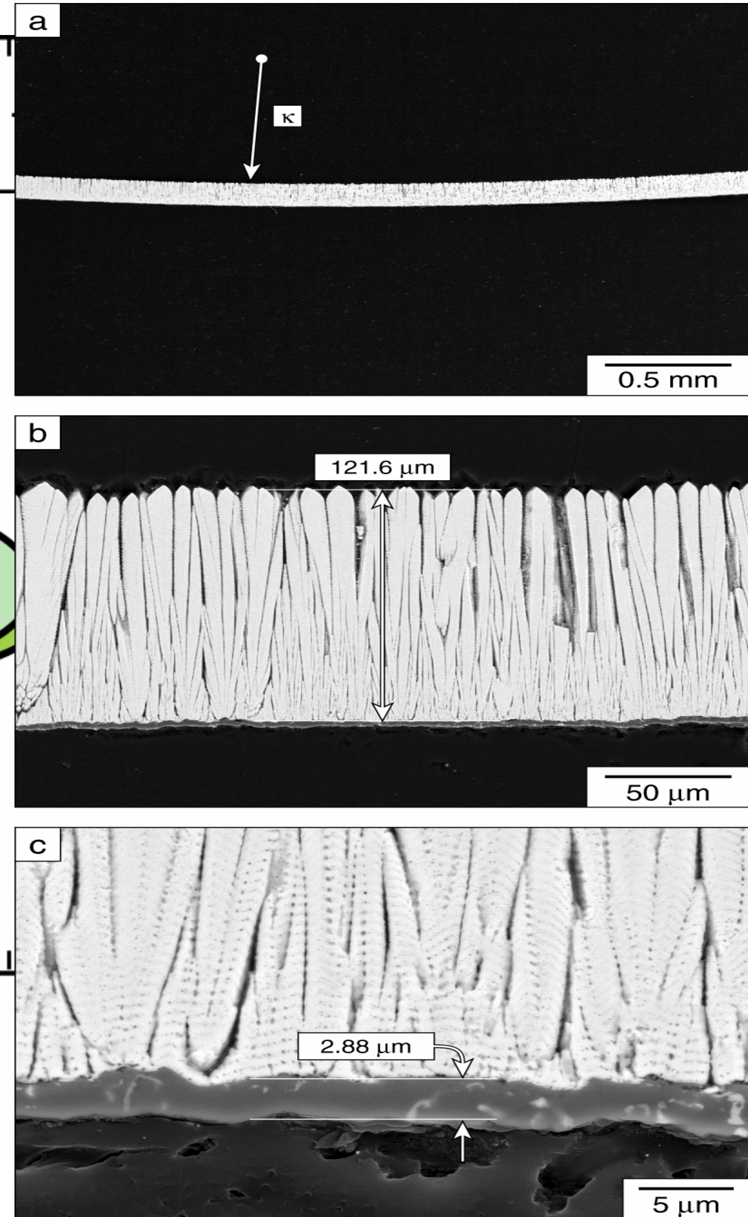


Thermal Property Interplay

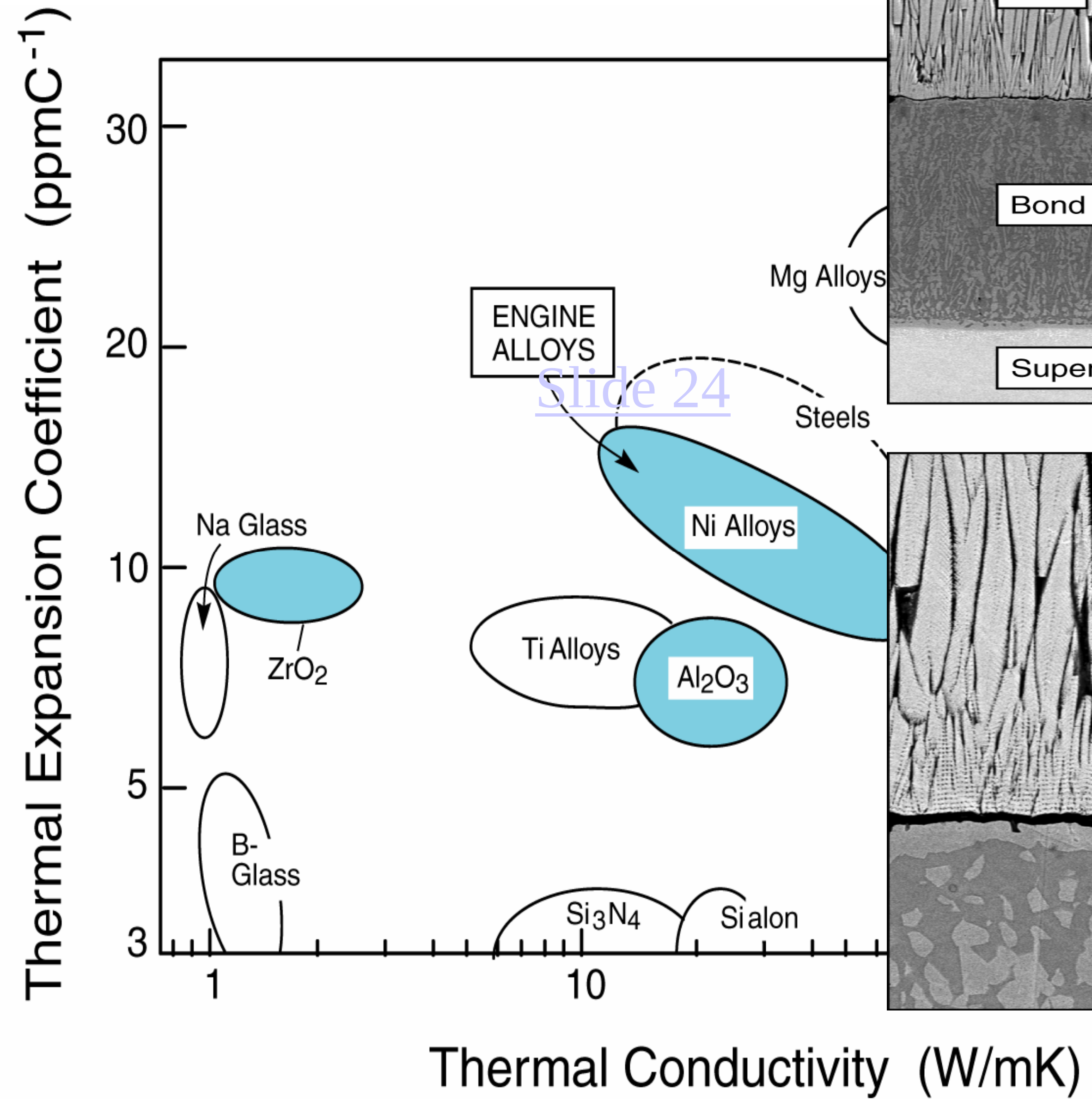


RESIDUAL STRESS IN TGO

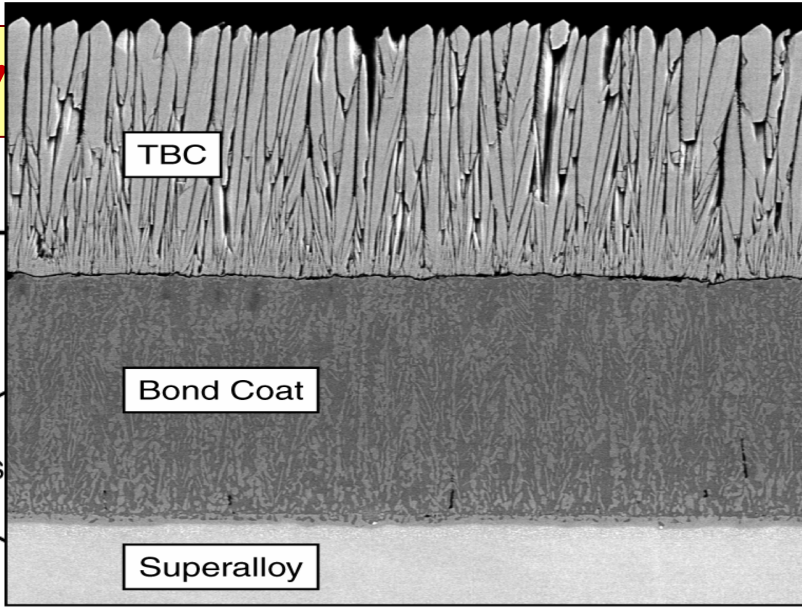


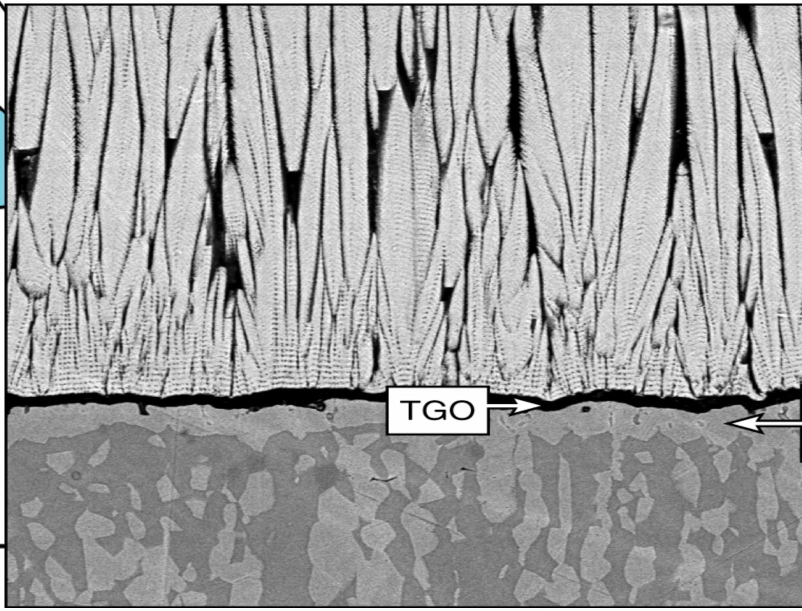


Thermal Property

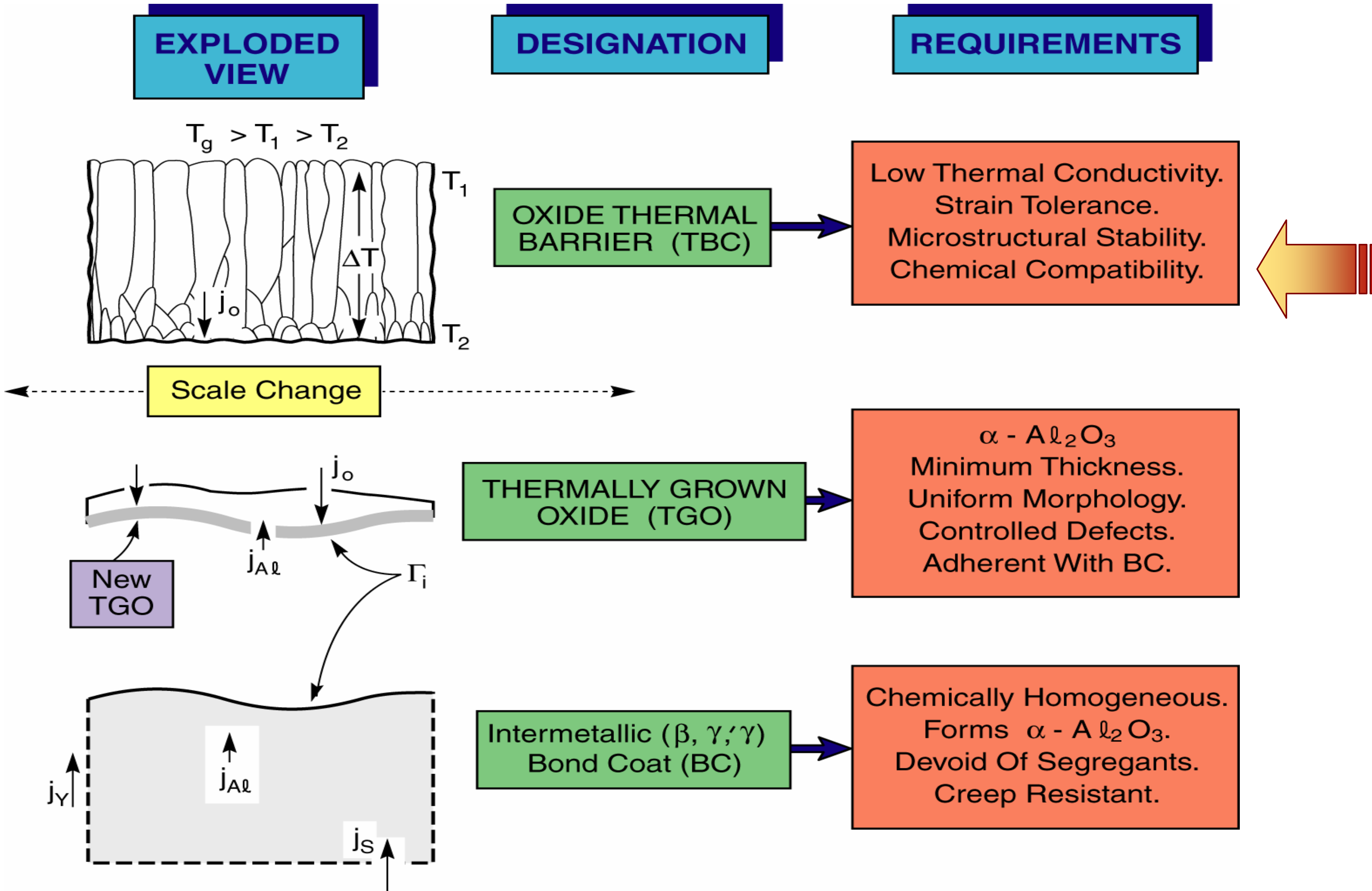


Slide 24



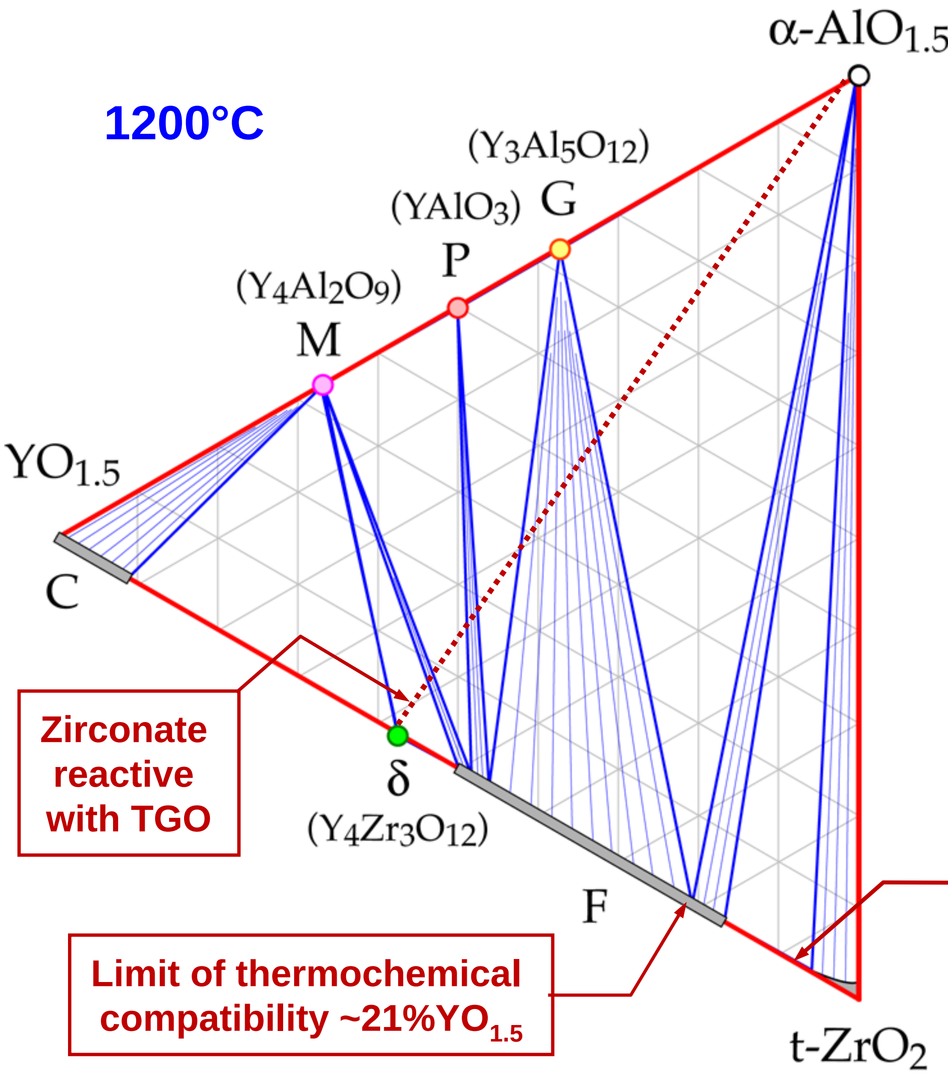


Thermal Barrier Multilayer: Challenging Thermo-Chemo-Mechanical System



YSZ Compatibility with TGO

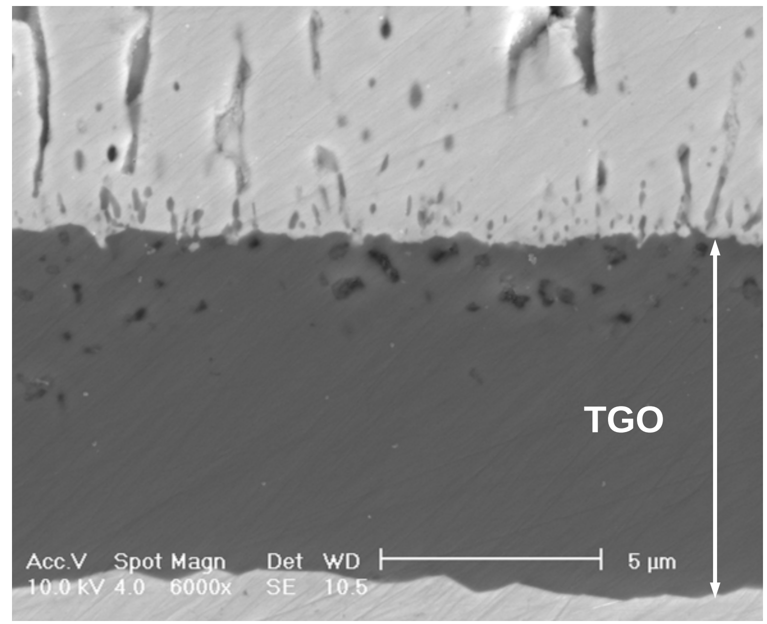
1200°C



Zirconate reactive with TGO

Limit of thermochemical compatibility ~21%$YO_{1.5}$

EB-PVD on FeCrAlY substrate

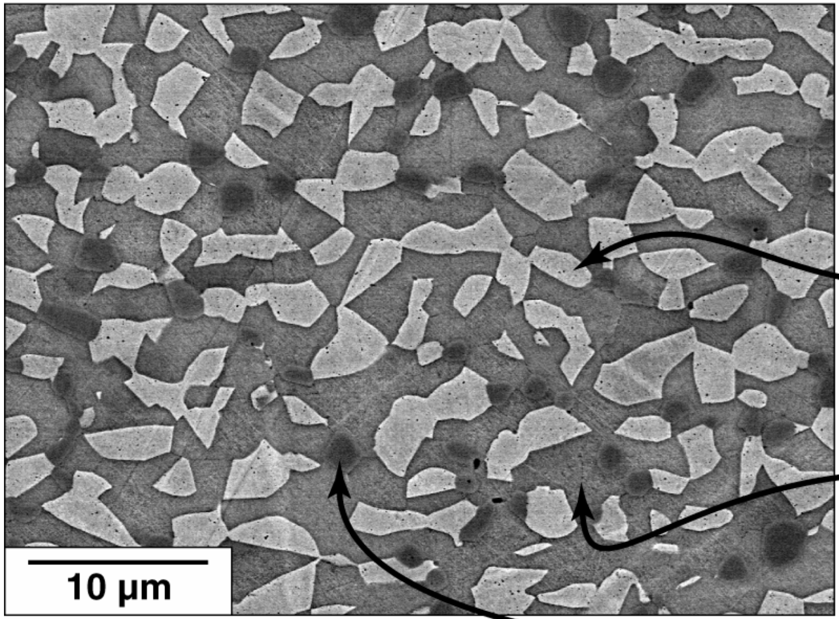


After 100h at 1200°C

1 µm

7YSZ compatible with TGO (no inter-phases formed)

Bond Coat Chemistry and Structure

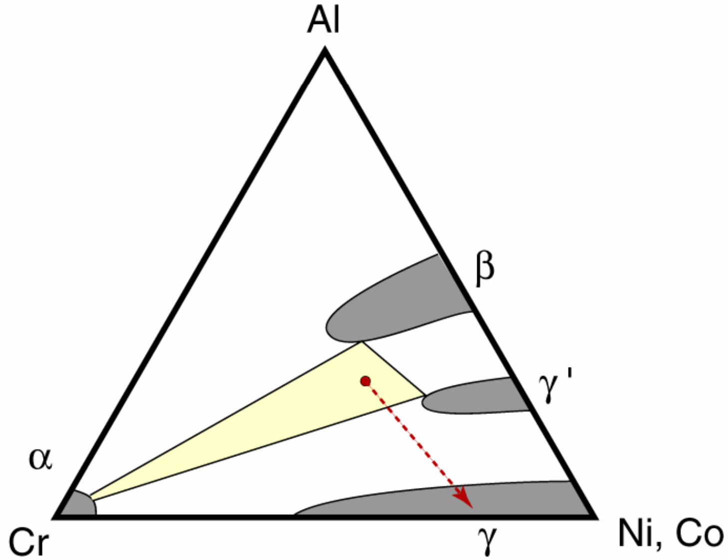


X-Ray Diffraction
Microprobe
Orientation Imaging Microscopy (EBSP)

[1] γ' - Ni_3Al Phase — 9 at% Al
$(Ni_{34}Co_{28}Cr_{13})(Al_9Cr_{16})$
Ordered FCC

[2] β - NiAl Phase — 34 at% Al
$(Ni_{45}Co_{13})(Al_{34}Cr_8)$
Primitive Cubic

[3] α - Cr Phase — 0 at % Al
$(Cr_{90}Ni_5Co_5)$
BCC

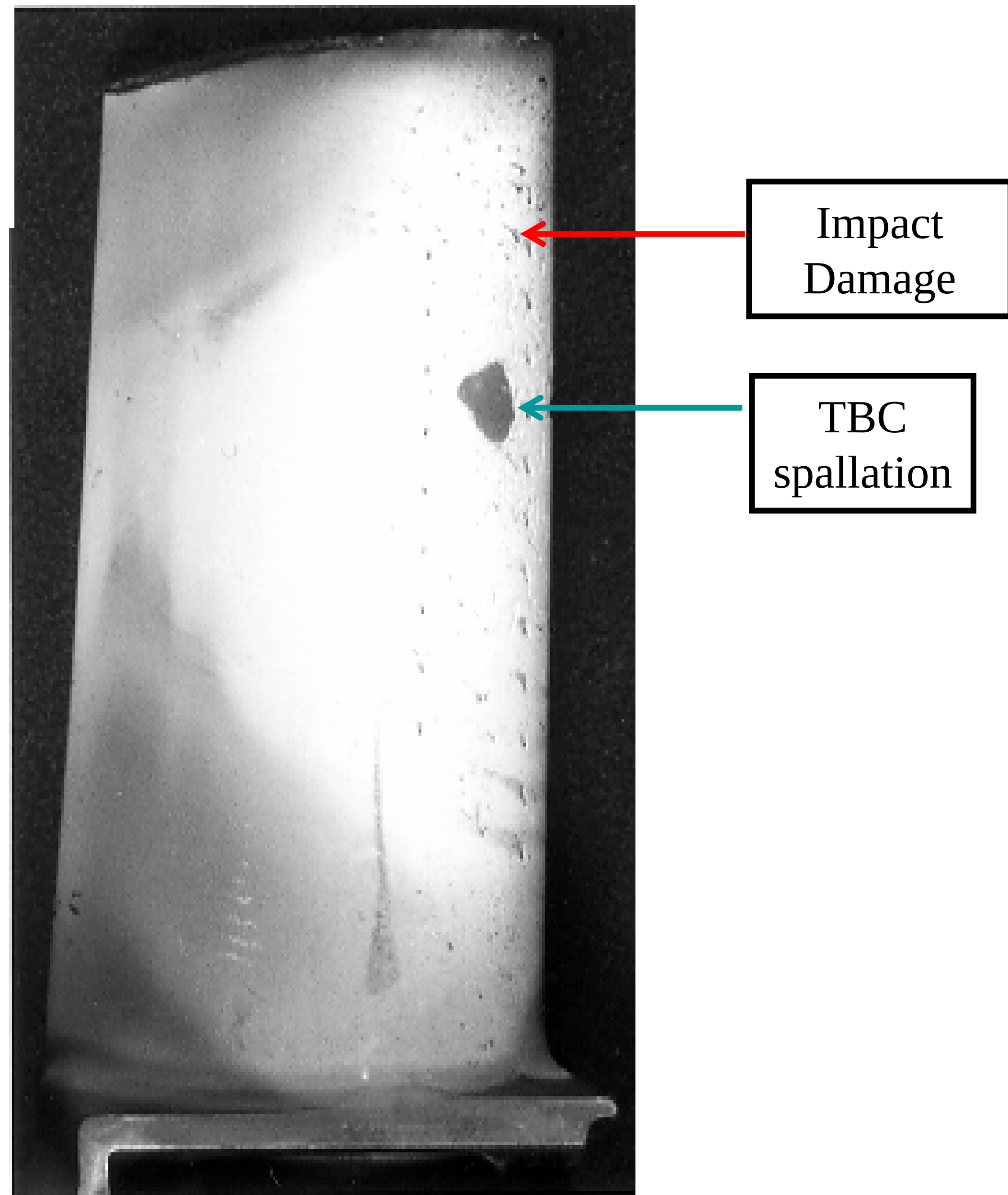


Non-Uniform Distribution of Aluminum
Non-Uniform Distribution of Yttrium ?

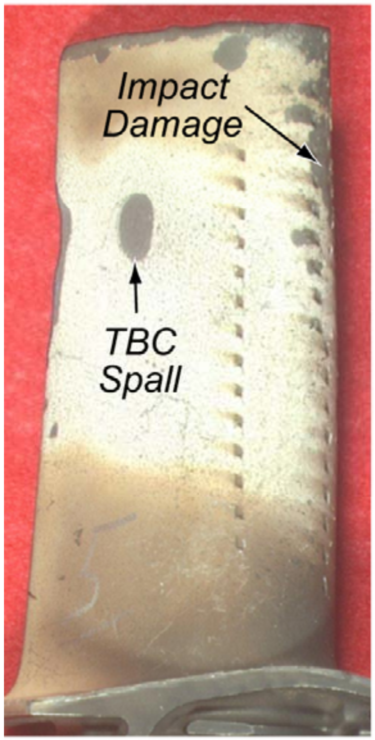
Degradation Modes In Engines

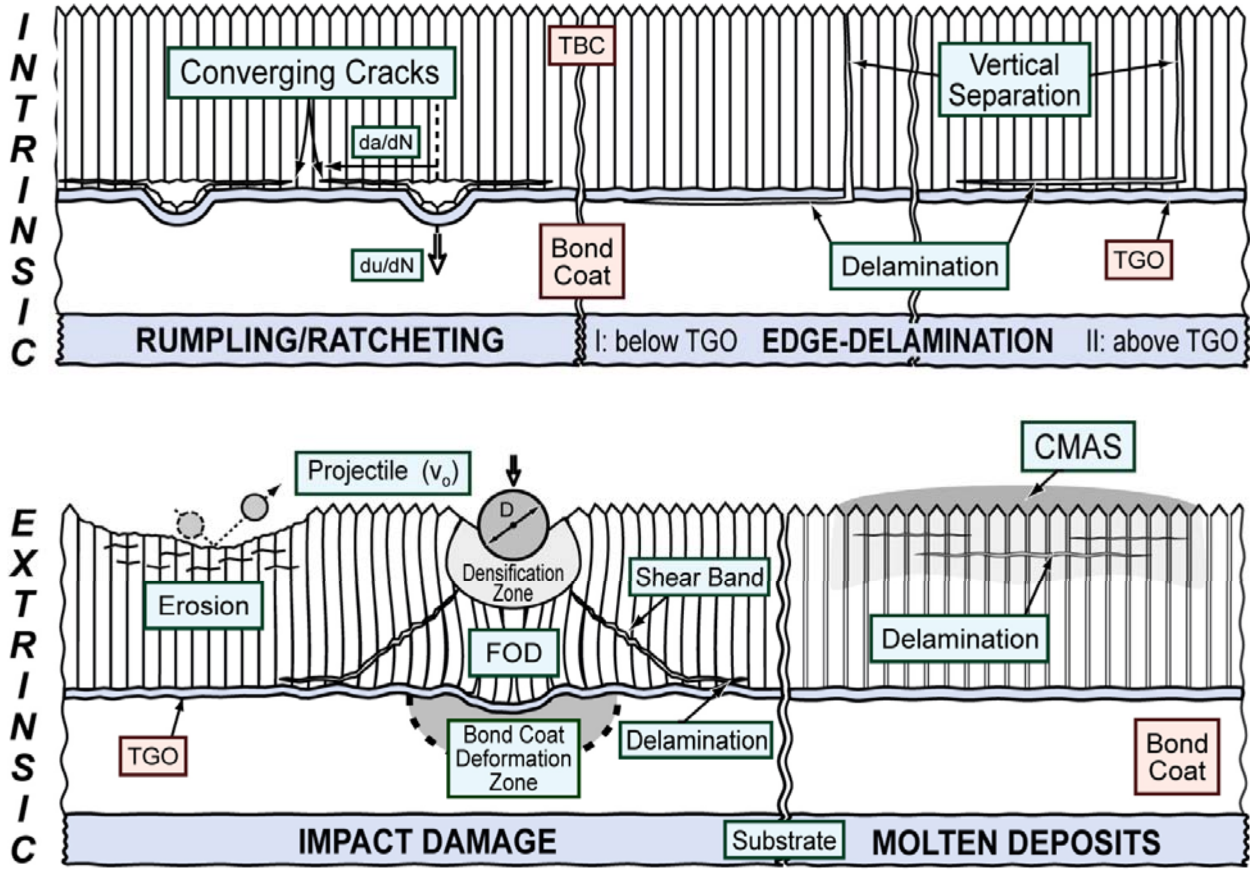
Delay Spalling By Understanding Mechanisms
And Adjusting Constituent Properties

1820 engine cycles



Step I:Identify All Mechanisms Limiting Durability



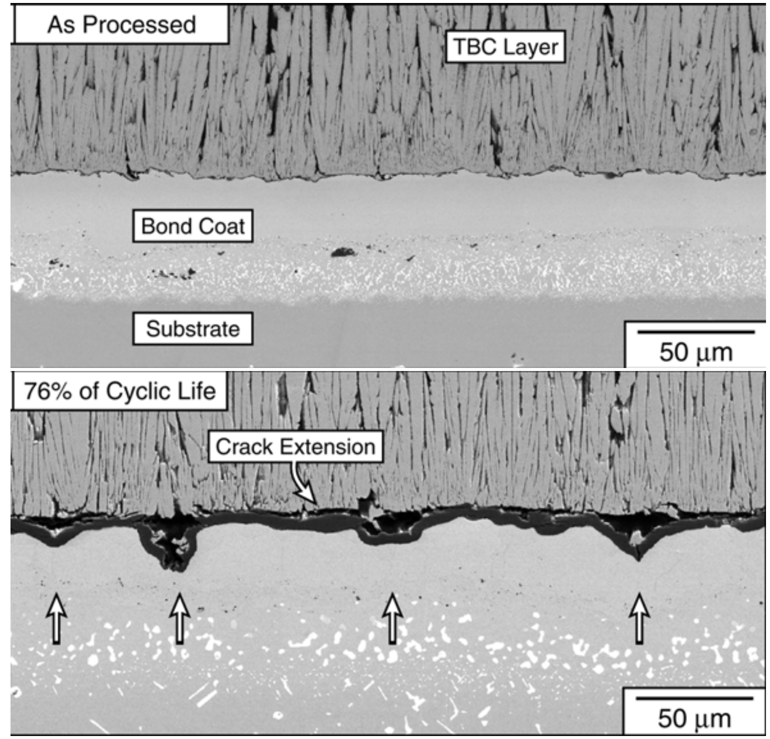


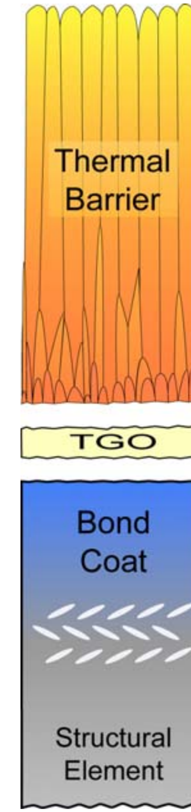
Step II: Develop Models that Relate Durability to Material Properties

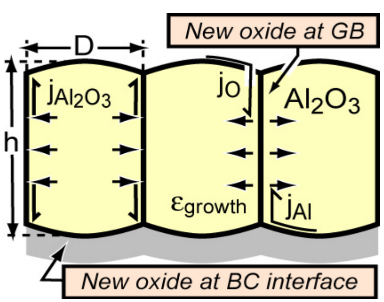
Example I (Intrinisc): Failure by TGO Rumpling

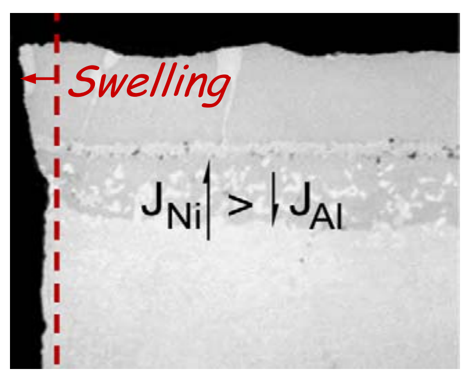
- *Strain misfits cause cyclic stresses that motivate cycle-by-cycle crack growth in TBC*
- *Highly non-linear: Requires numerical code*

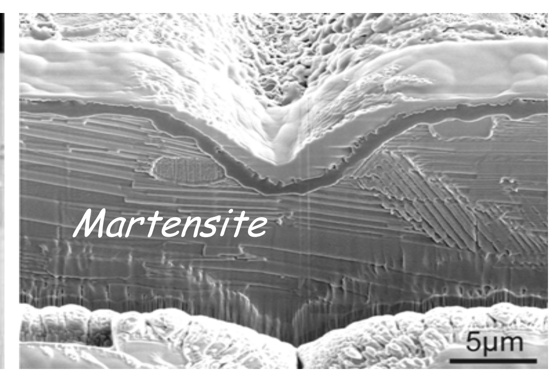
- *Phenomena include TGO lateral growth, thermal expansion misfit (martensite), cyclic plasticity.*

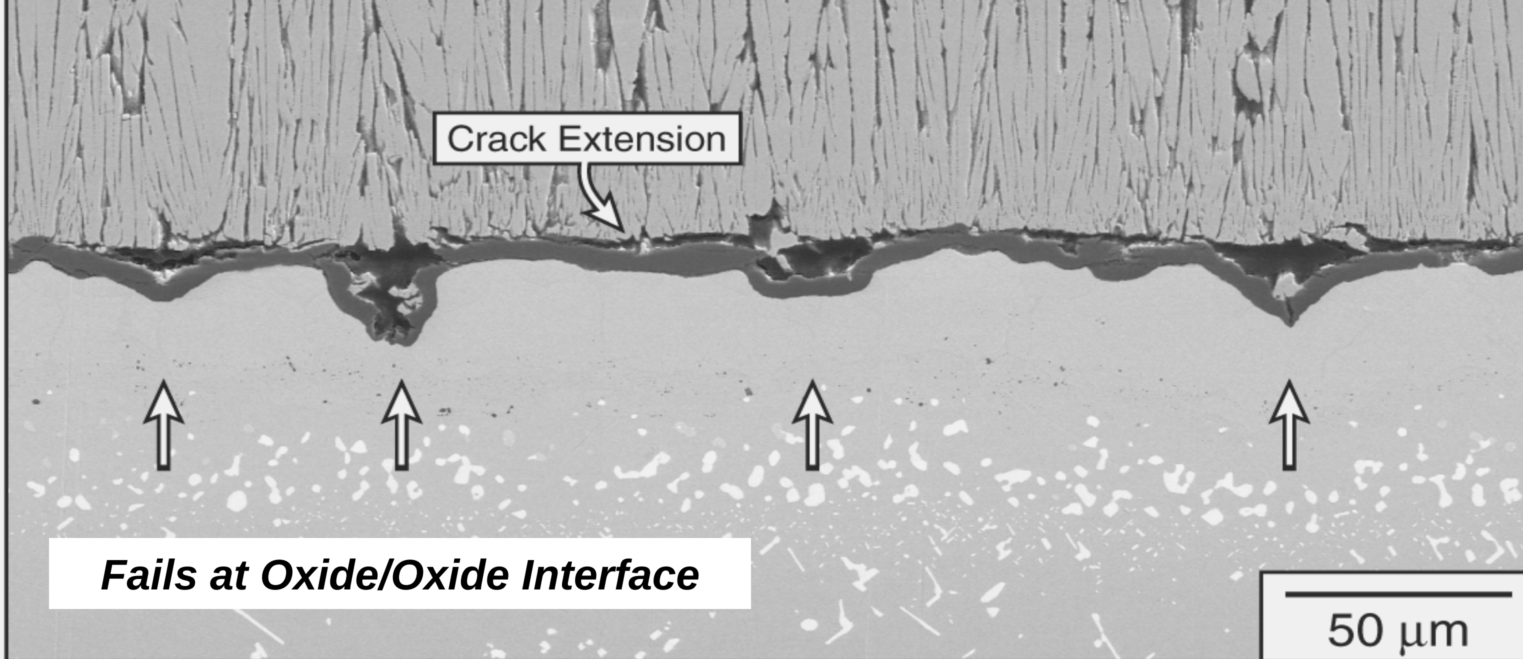








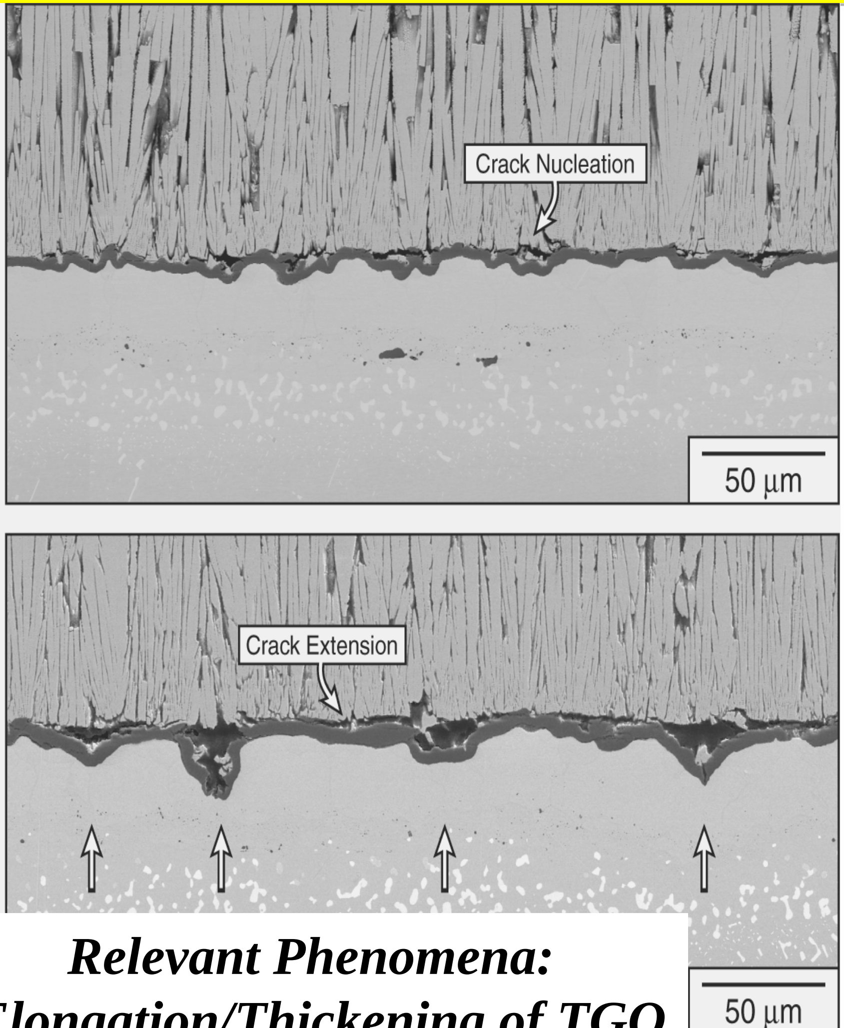


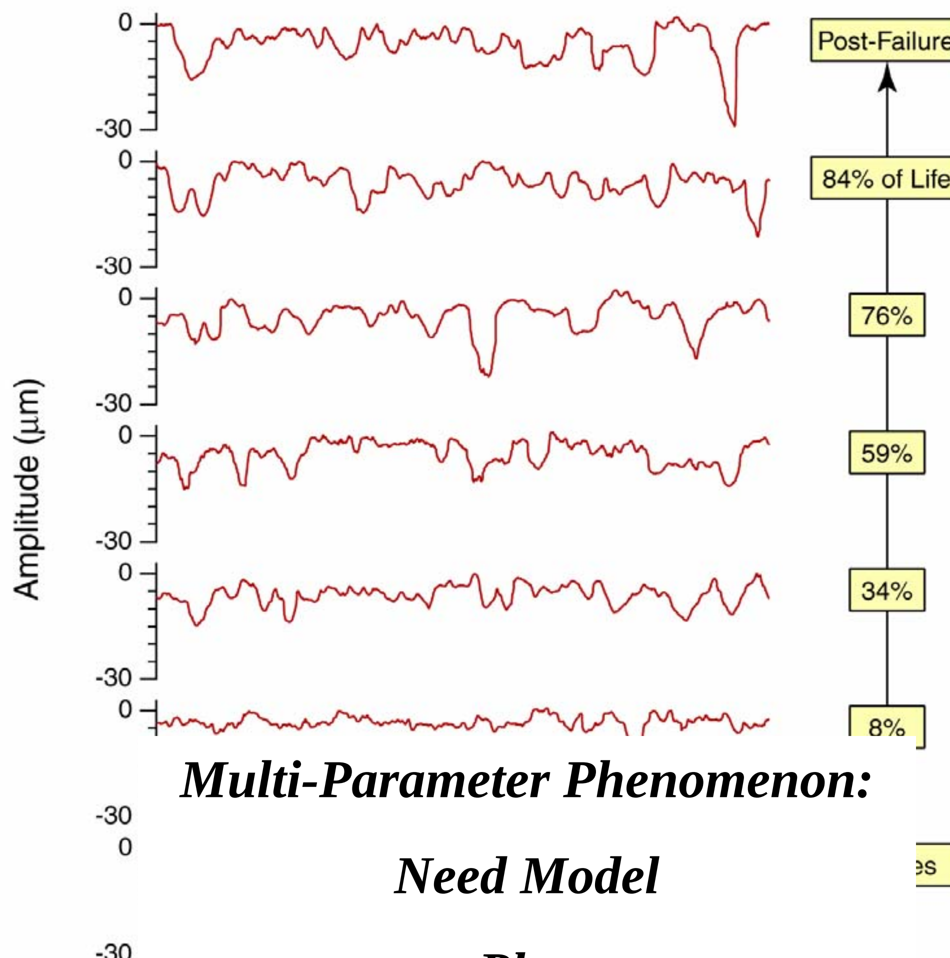


LARGE SCALE BUCKLE: THE END OF LIFE

• *WHAT HAPPENED EARLIER*?

DISPLACEMENT INSTABILITY





Relevant Phenomena:
•Elongation/Thickening of TGO
•Plastic Flow of Bond Coat
•Strain Misfit of Bond Coat

Multi-Parameter Phenomenon:

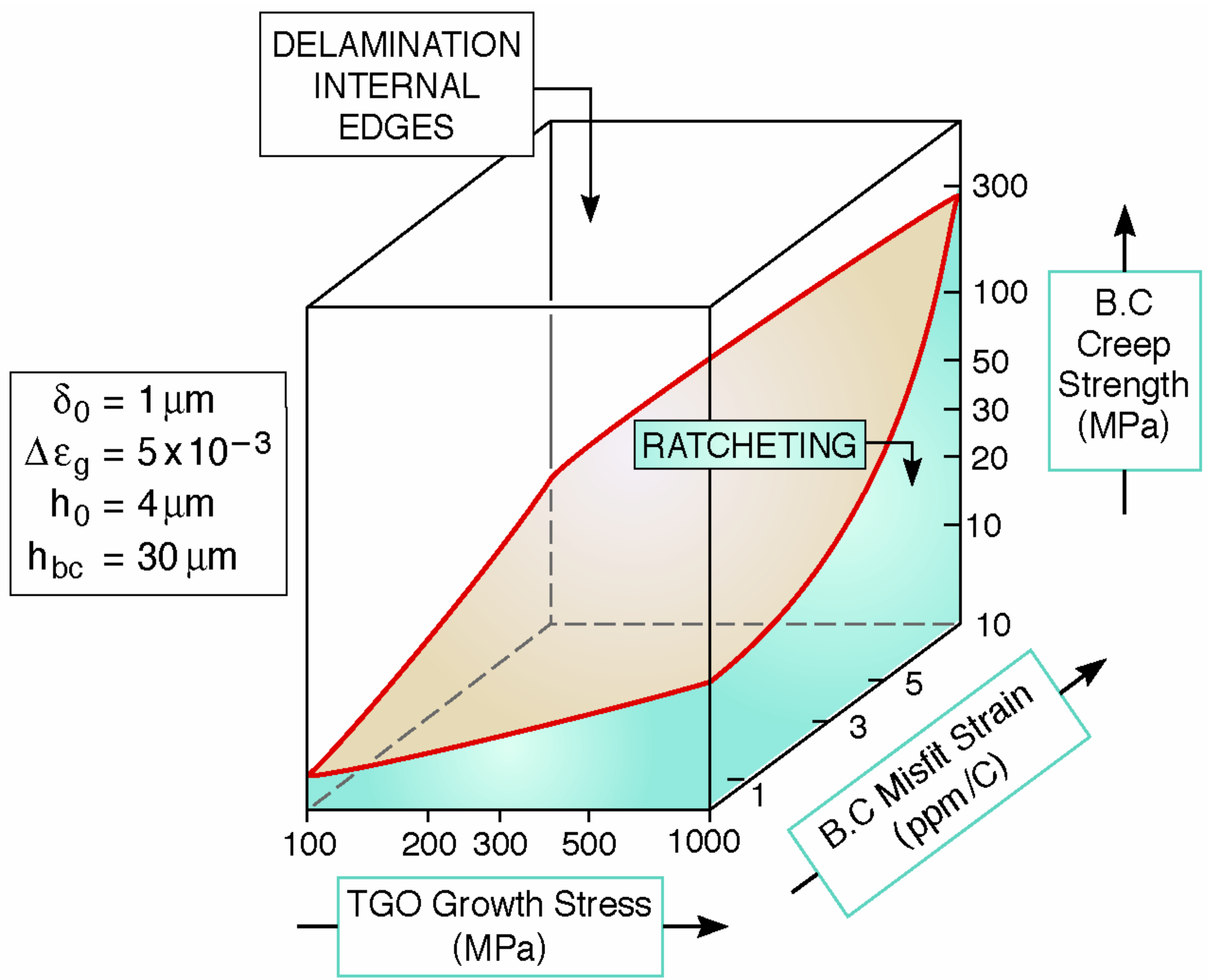
Need Model

Plus

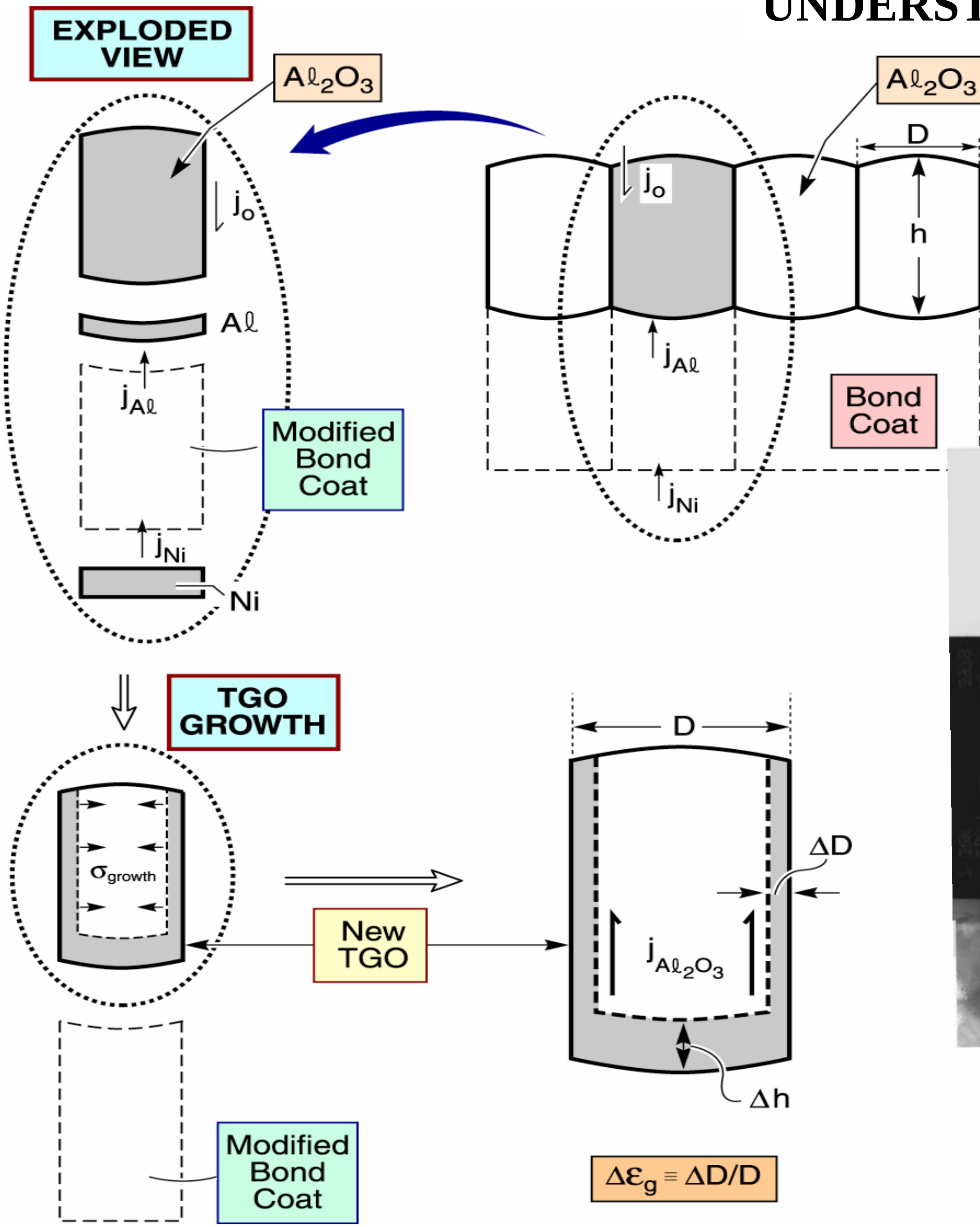
Critical Experiments

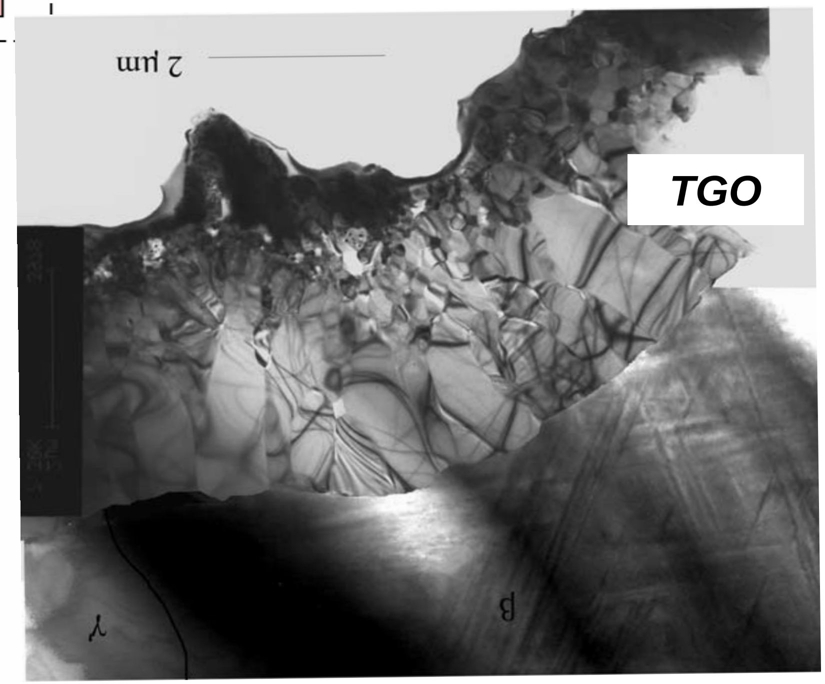
DESCRIBE CONJOINTLY

OBJECTIVE: DEVISE MECHANISM MAPS THAT SPECIFY SALIENT NON-DIMENSIONAL PARAMETERS

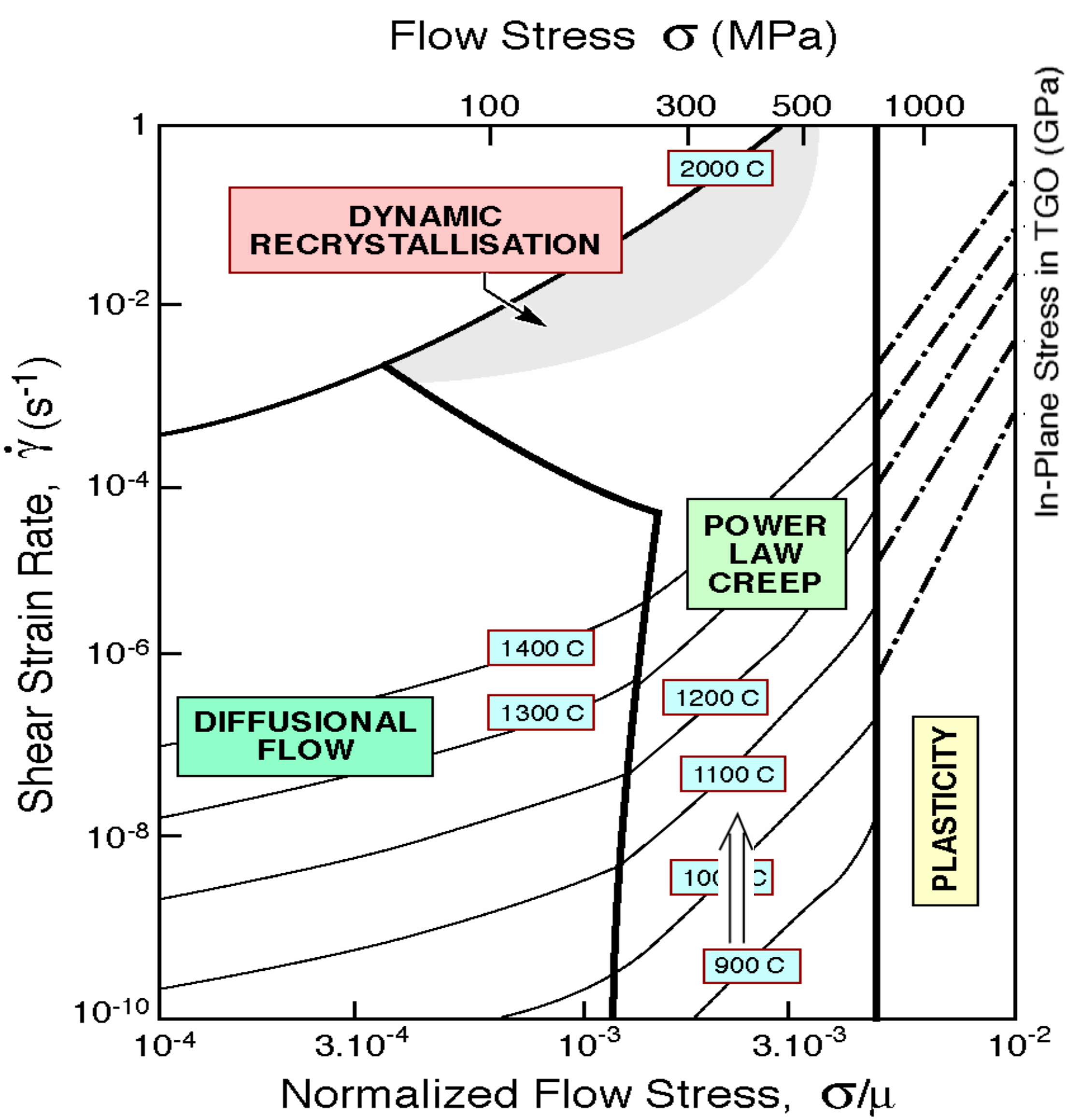


UNDERSTAND THE FUNDAMENTALS

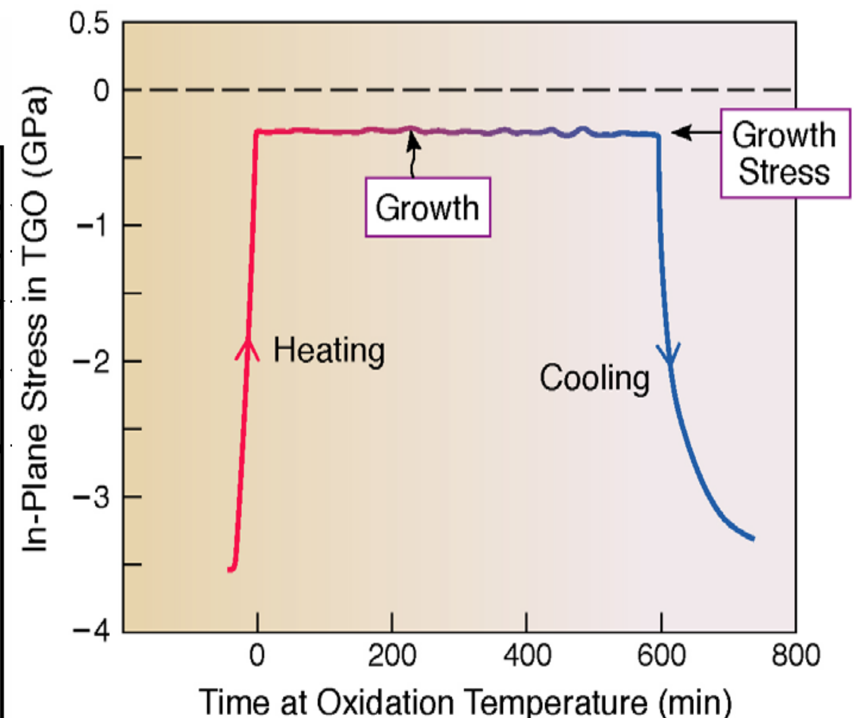


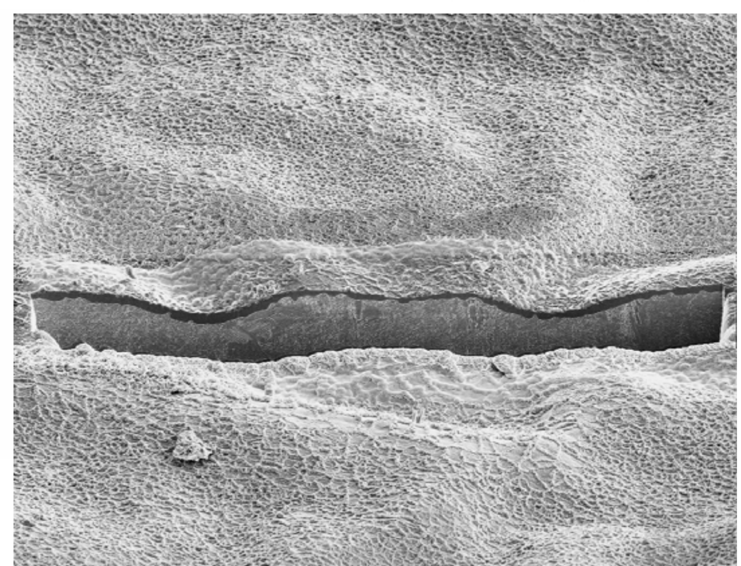


Deformation Mechanism Map

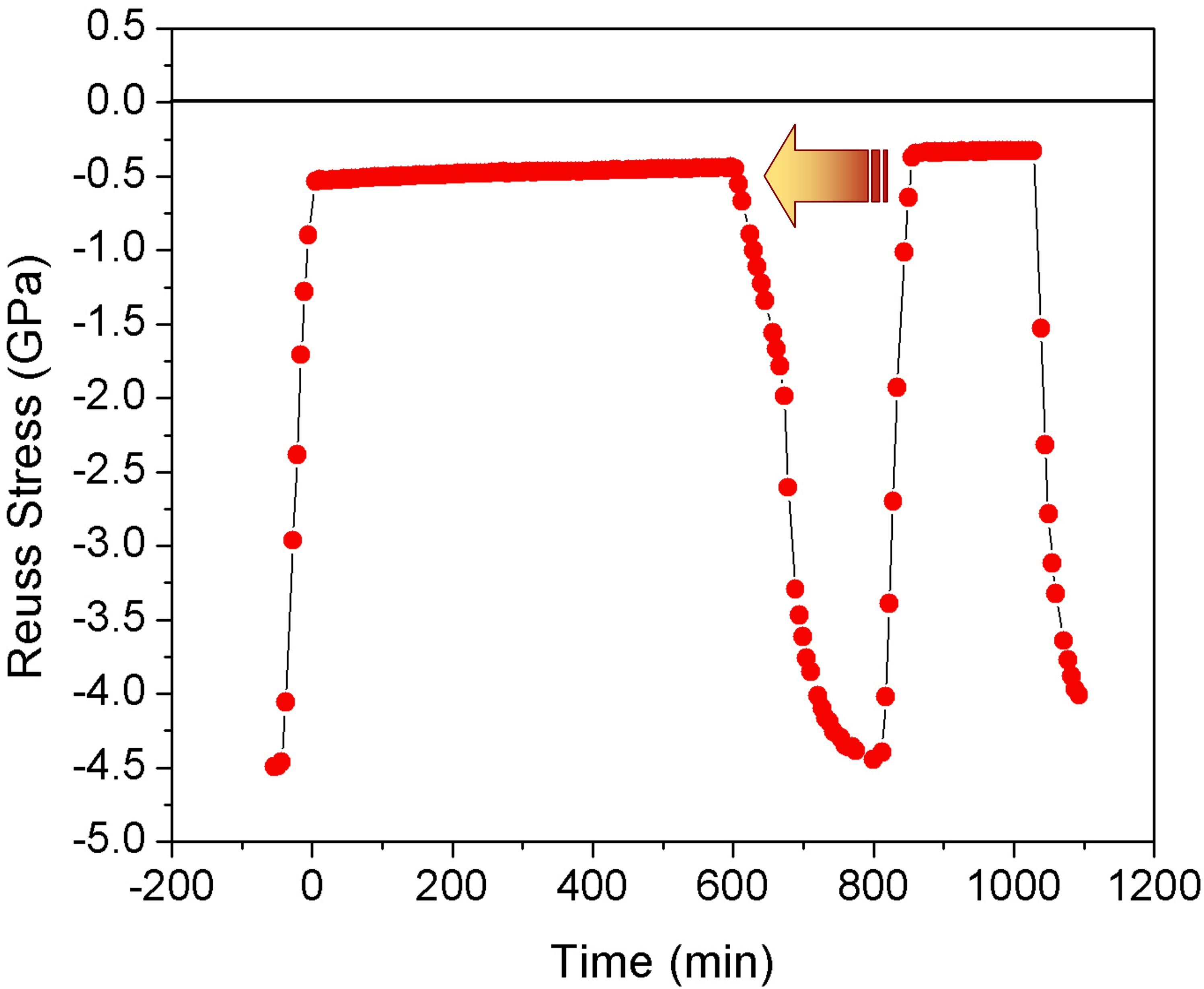


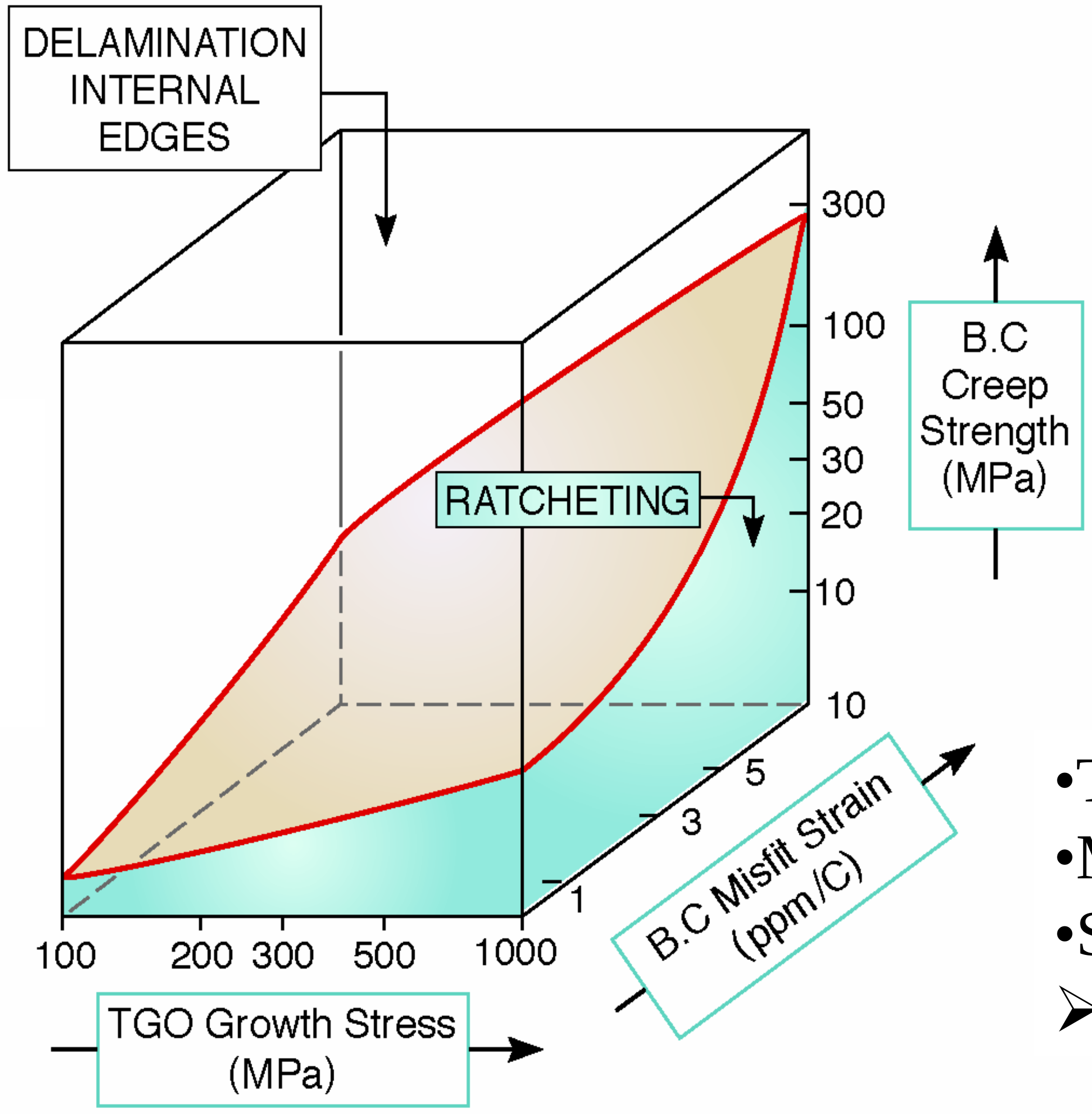
Synchotron Measurements





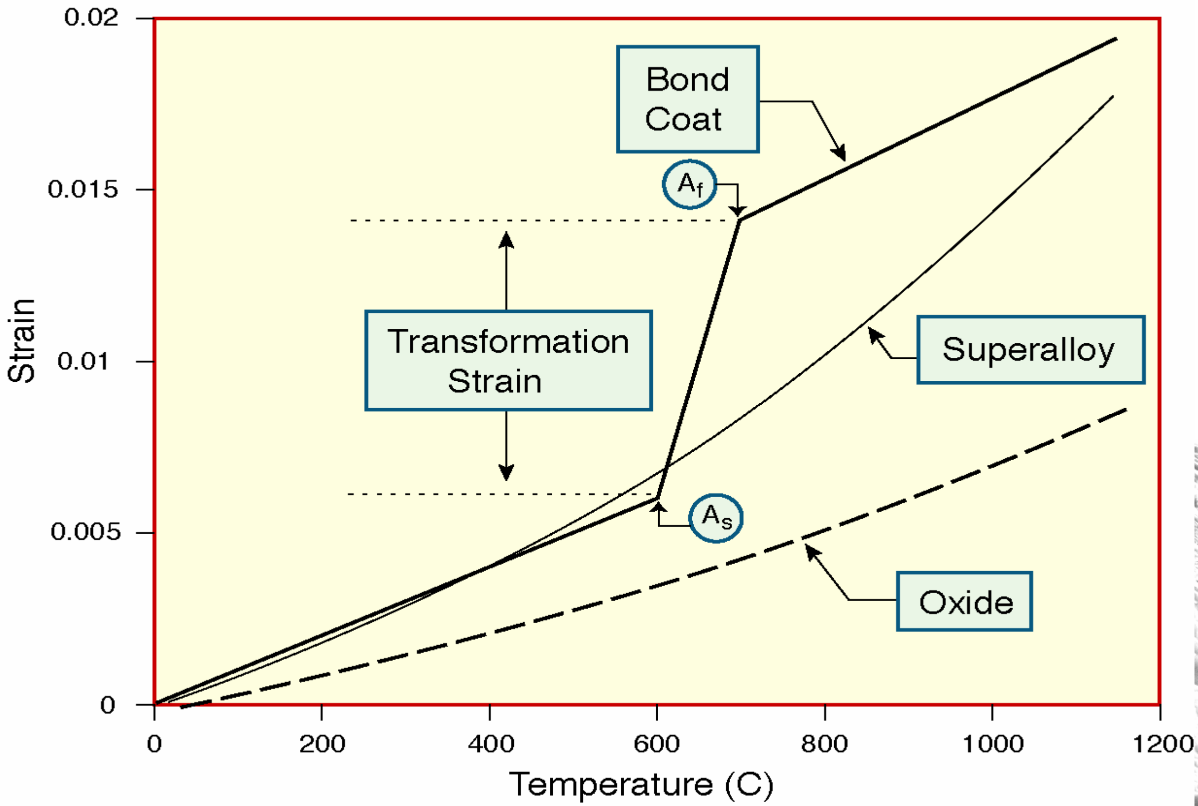
Synchotron Measurements

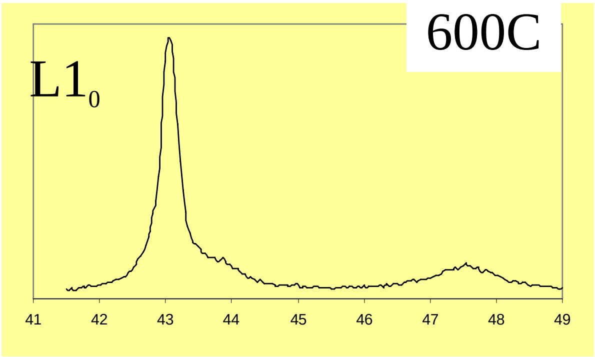


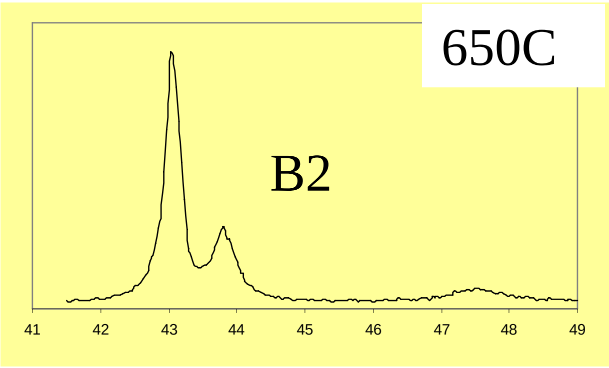


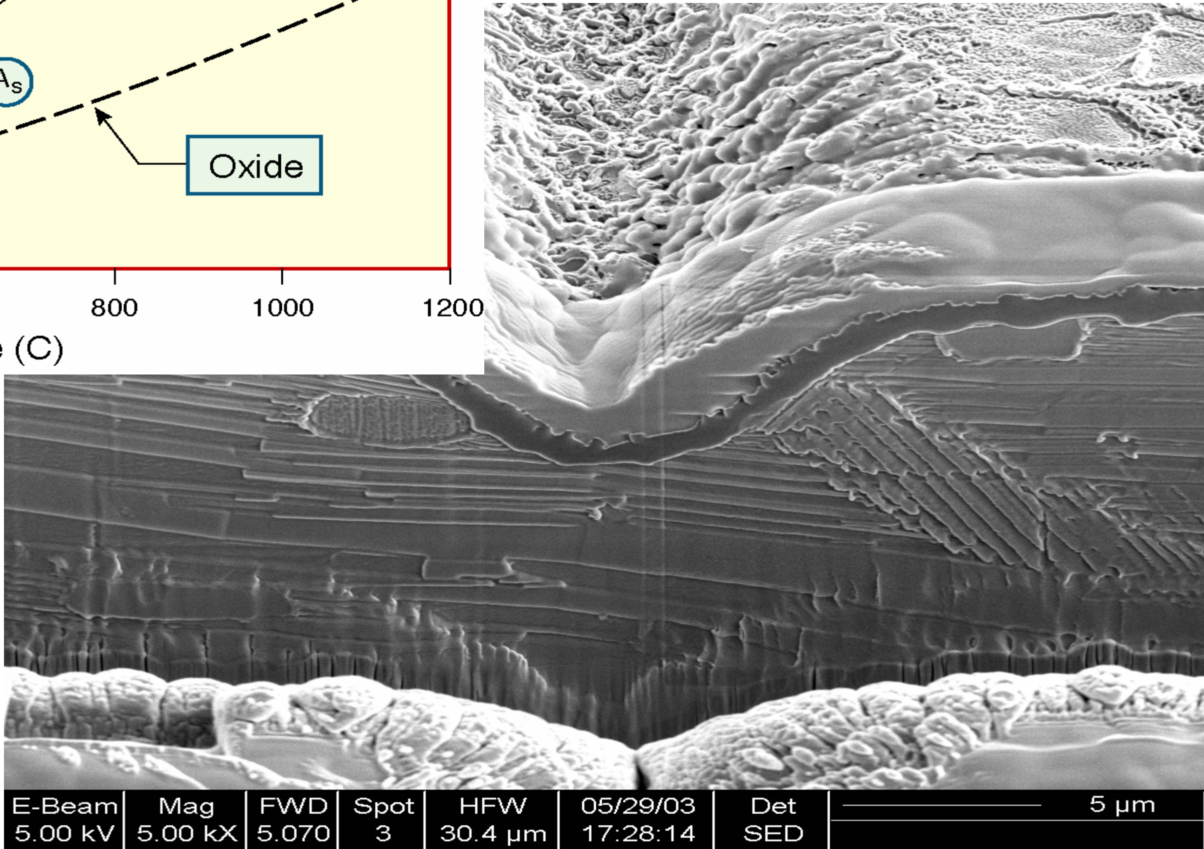
- •Thermal Expansion
- •Martensite
- •Swelling
- ➢ "Soften" Bond Coat

STRAIN MISFITS: MARTENSITE TRANSFORMATION

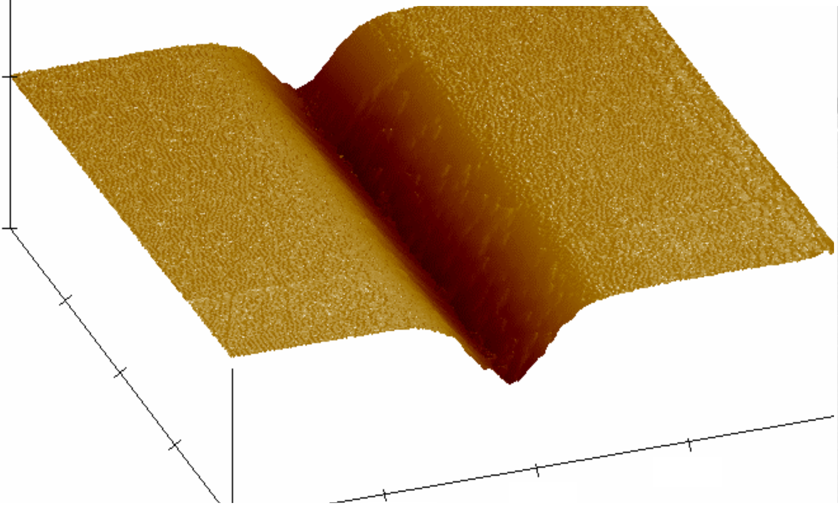


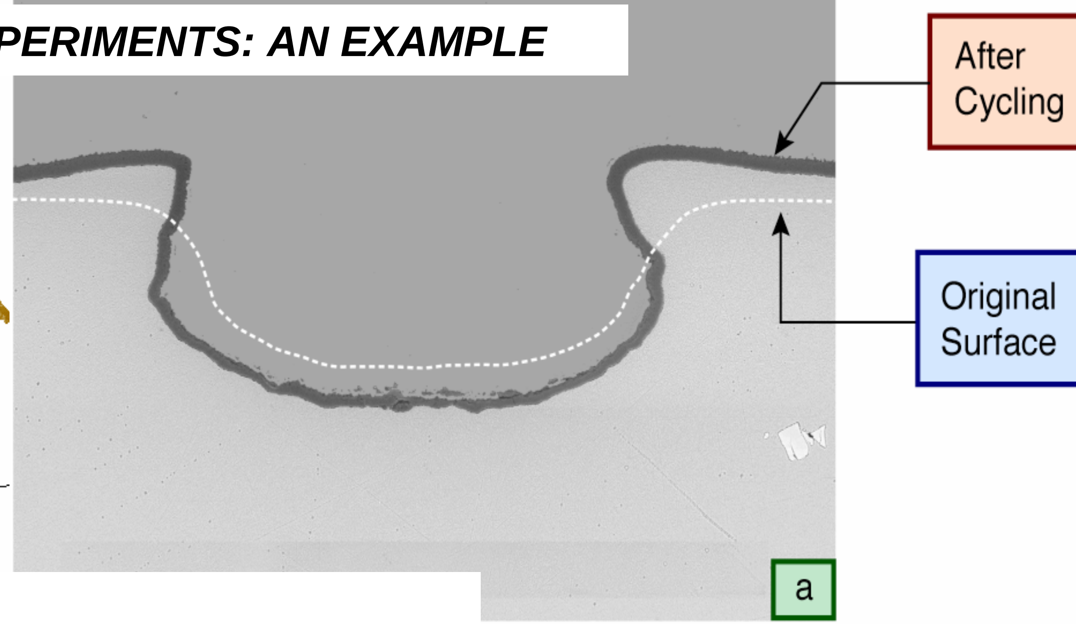




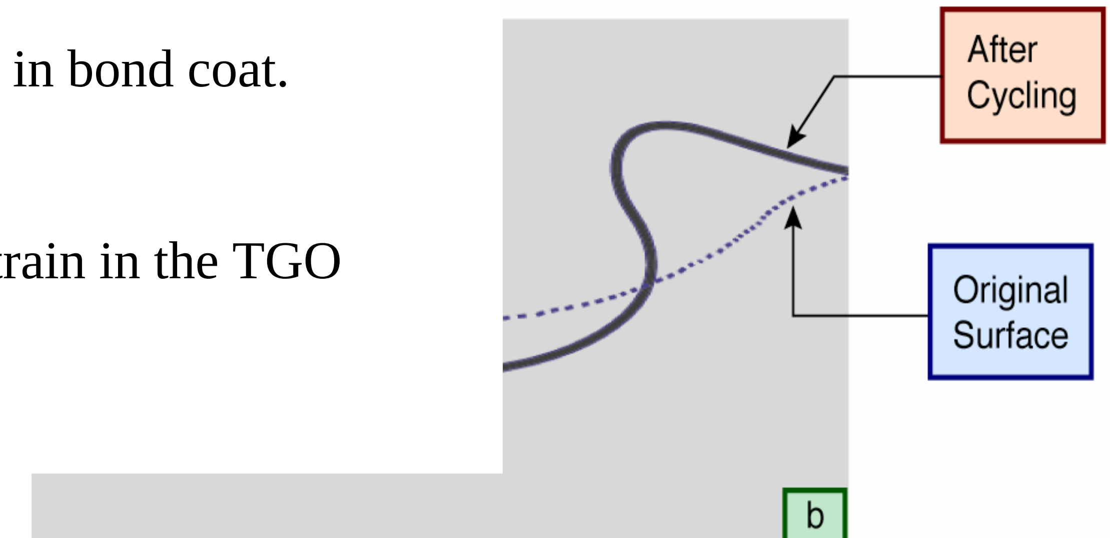


VALIDATION EXPERIMENTS: AN EXAMPLE



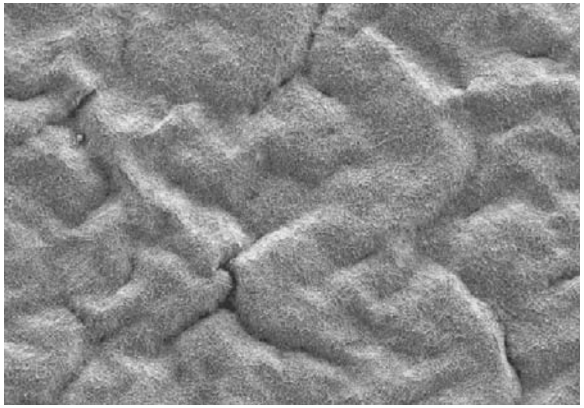


1. Elastic properties of constituents
2. Thermal expansion mismatch between layers.
3. Power-law creep.
4. Reversible phase transformation in bond coat.
5. Growth stress in TGO.
6. Thickening and lateral growth strain in the TGO
7. Initial Interface Imperfections



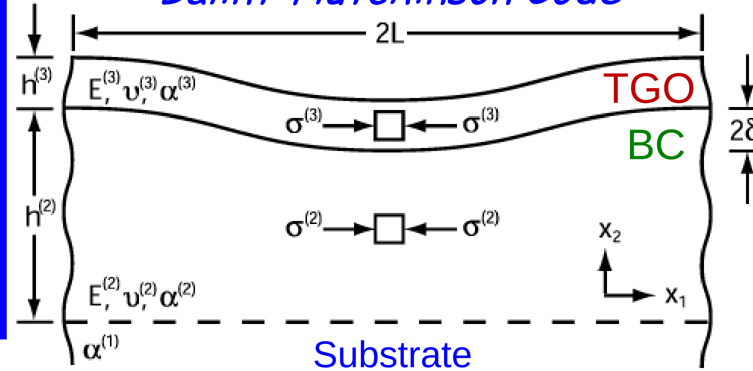
ANIMATION OF TGO DISTORTION AND ELONGATION

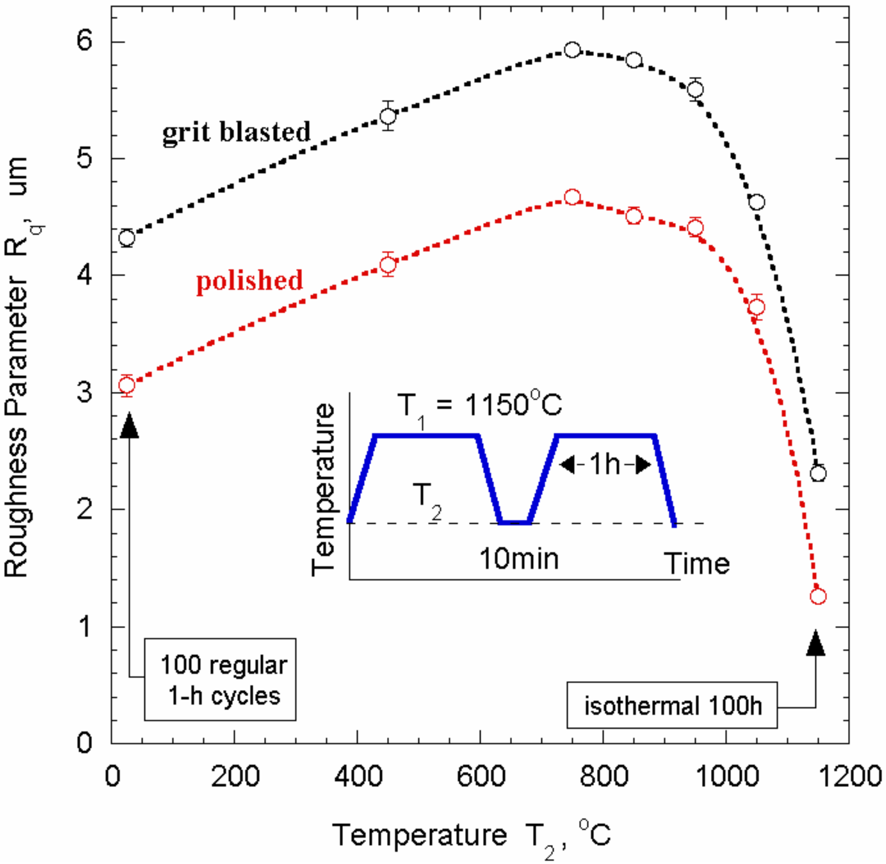
QuickTime™ and a
GIF decompressor
are needed to see this picture.

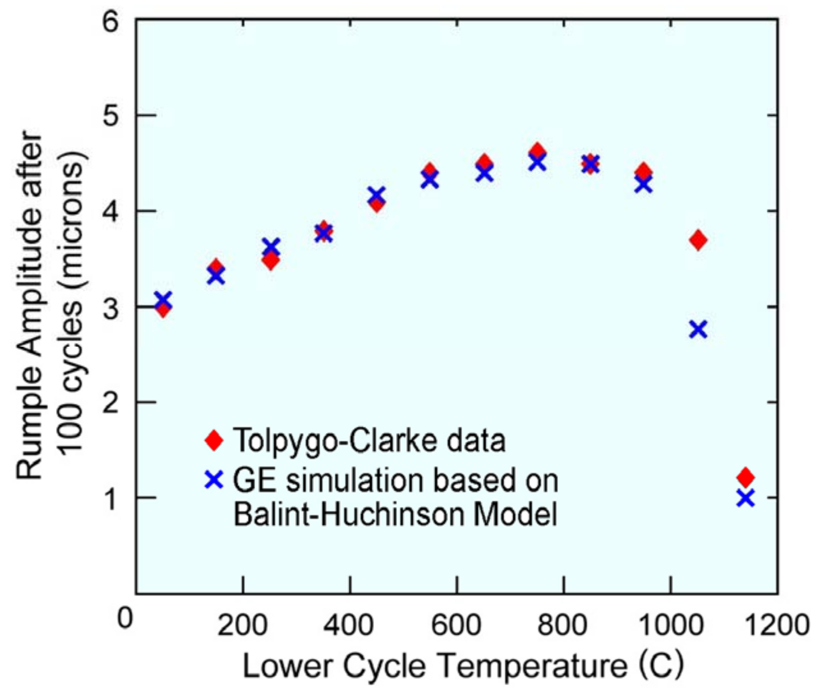


Model Validation: Transition to GE

Balint-Hutchinson Code

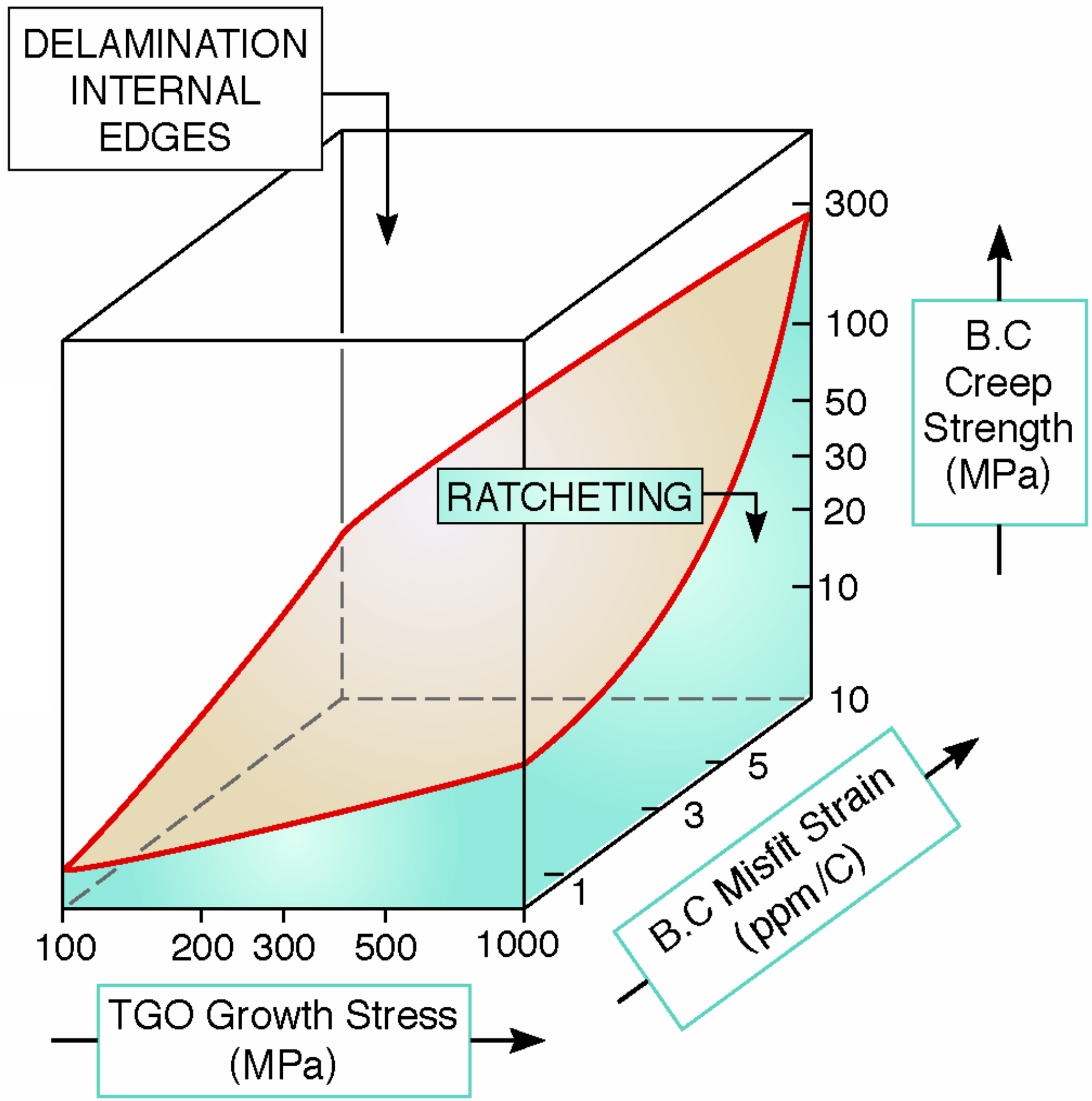


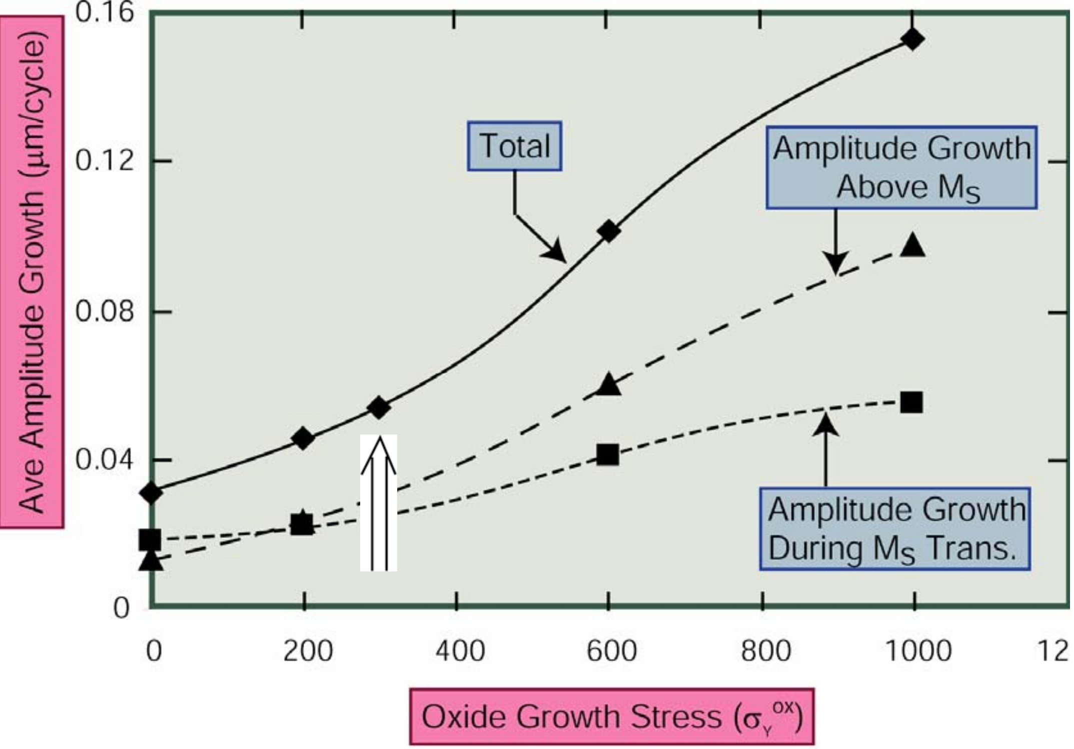


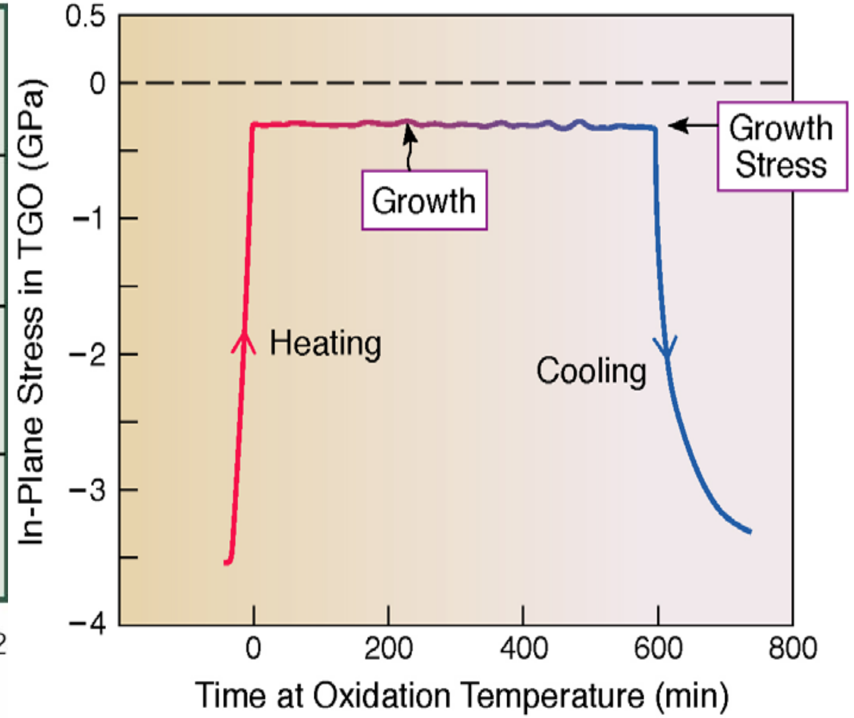


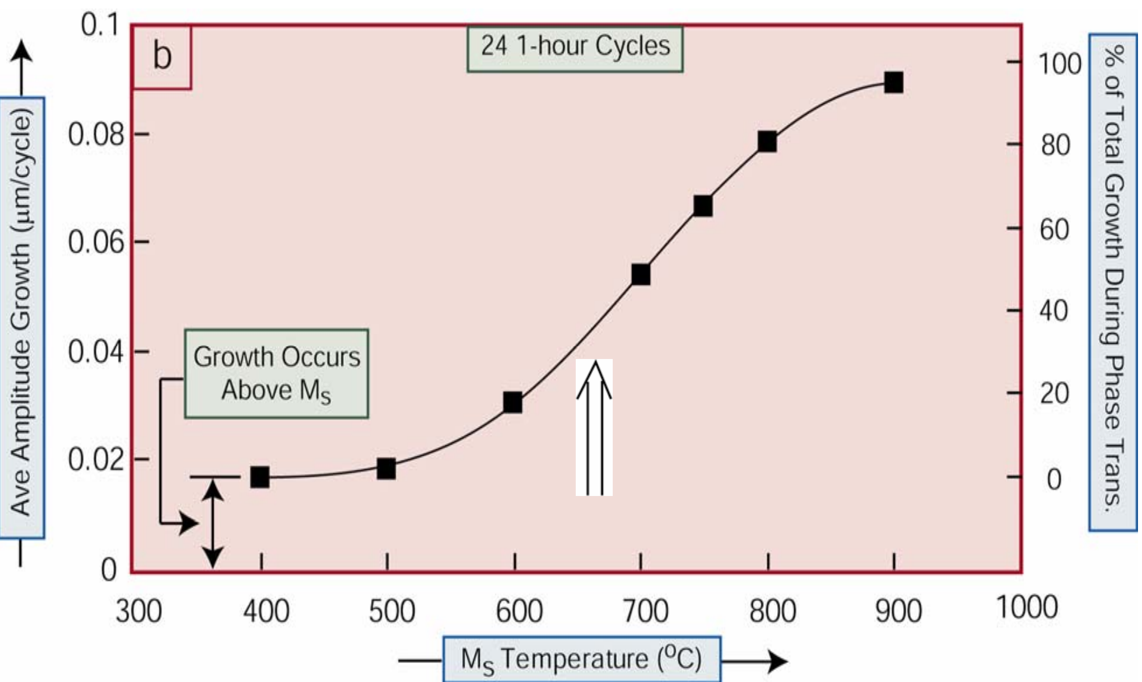
Code now in use at GE

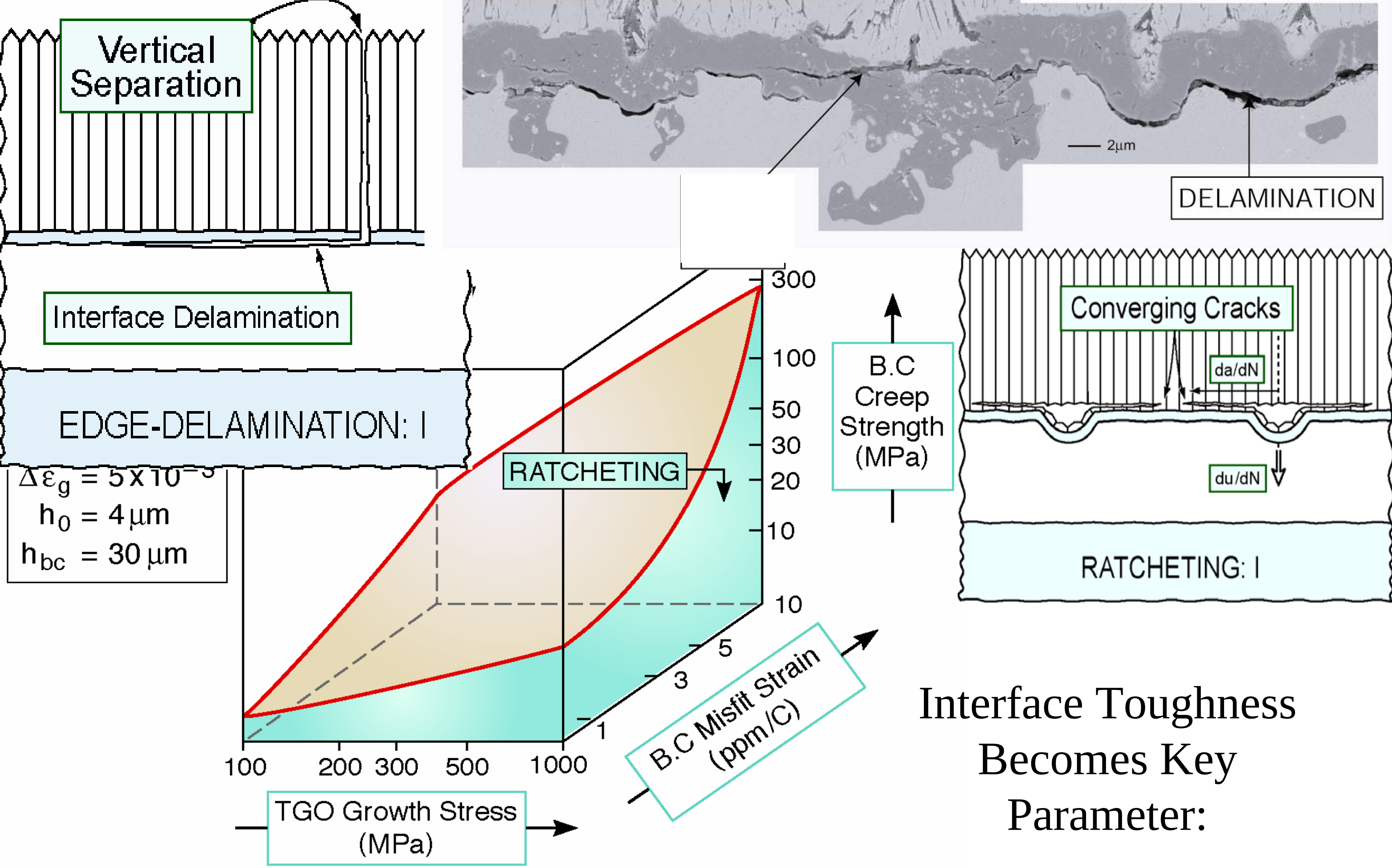
SENSITIVITY STUDY USING MECHANISM MAP: CAN MECHANISM BE SUPPRESSED?




Ave Amplitude Growth (μm/cycle)
0.16
0.12
0.08
0.04
0
Total
Amplitude Growth Above M_S
Amplitude Growth During M_S Trans.
0
200
400
600
800
1000
12
Oxide Growth Stress (σ_Y^{ox})


In-Plane Stress in TGO (GPa)
0.5
0
−1
−2
−3
−4
Growth Stress
Growth
Heating
Cooling
0
200
400
600
800
Time at Oxidation Temperature (min)


b
24 1-hour Cycles
Ave Amplitude Growth (μm/cycle)
0.1
0.08
0.06
0.04
0.02
0
Growth Occurs Above M_S
% of Total Growth During Phase Trans.
100
80
60
40
20
0
300
400
500
600
700
800
900
1000
M_S Temperature (^{0}C)



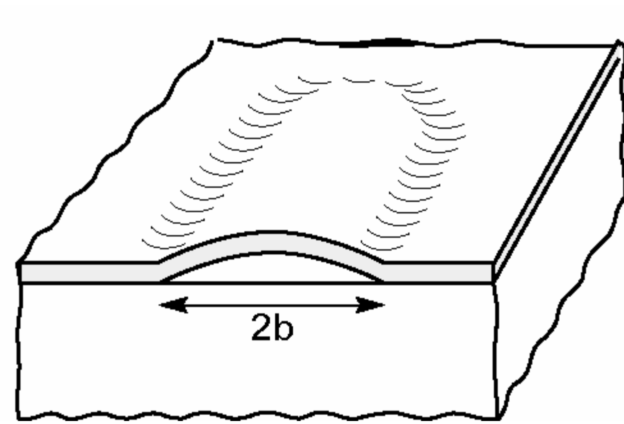
Interface Toughness Becomes Key Parameter:

NEW INTERFACE TOUGHNESS TEST

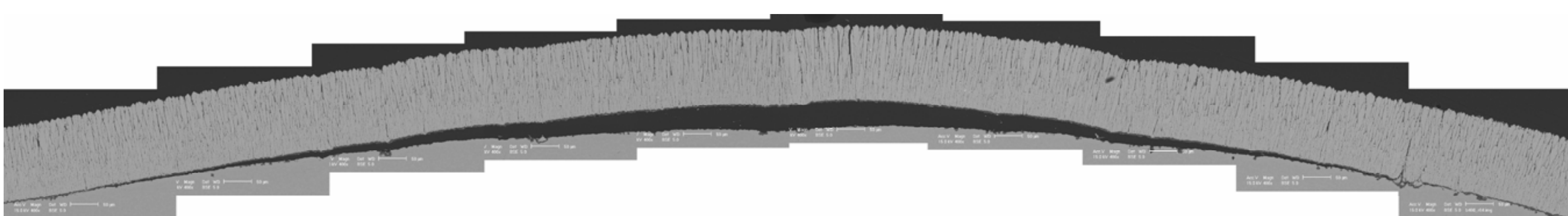
f=0.26

f=1.0

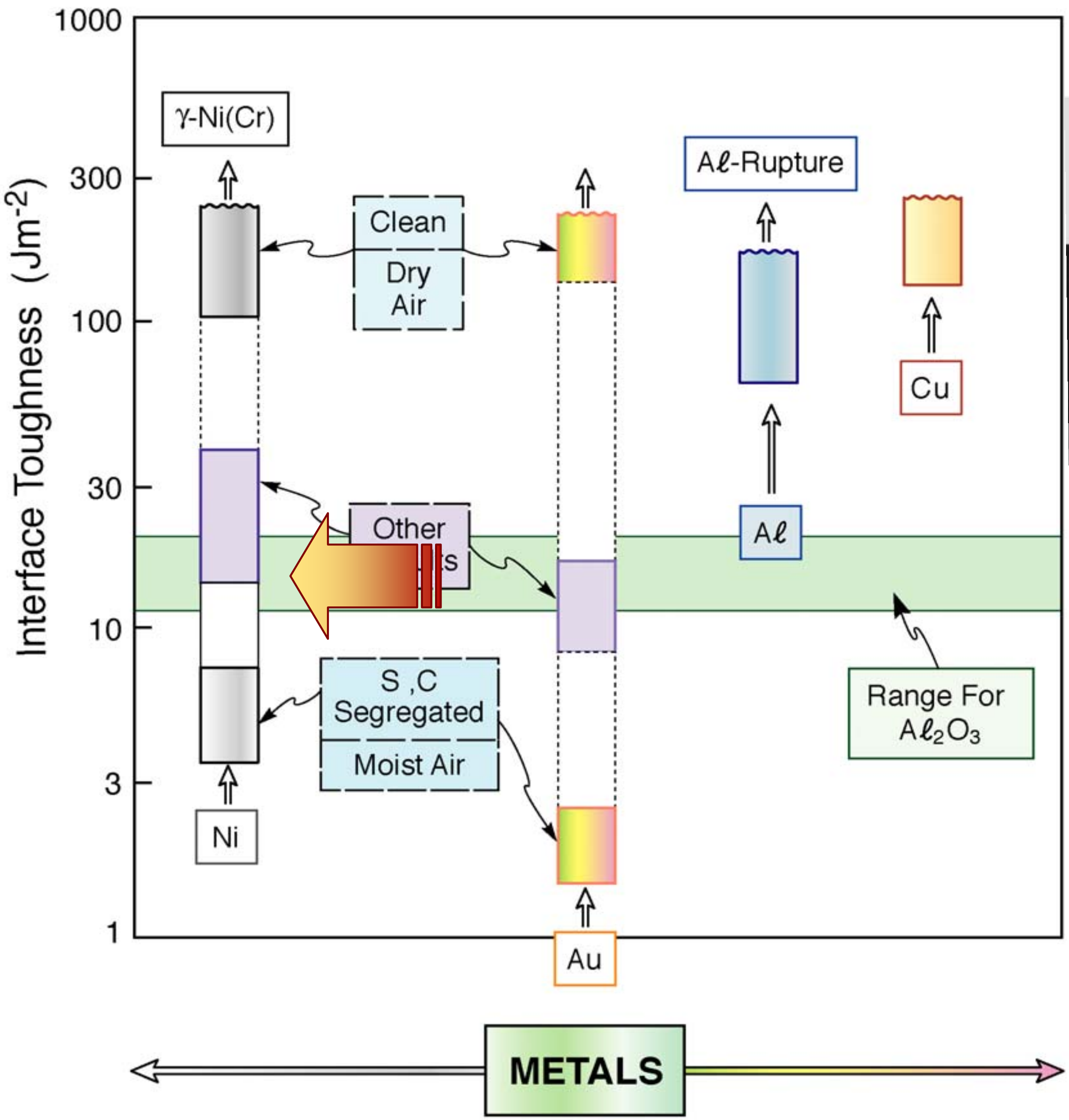
$$G_{side} = \frac{1}{2} S \left(\frac{\pi}{4}\frac{\delta}{b}\right)^4 + 2D\left(\frac{\pi}{b}\right)^2\left(\frac{\pi}{4}\frac{\delta}{b}\right)^2$$

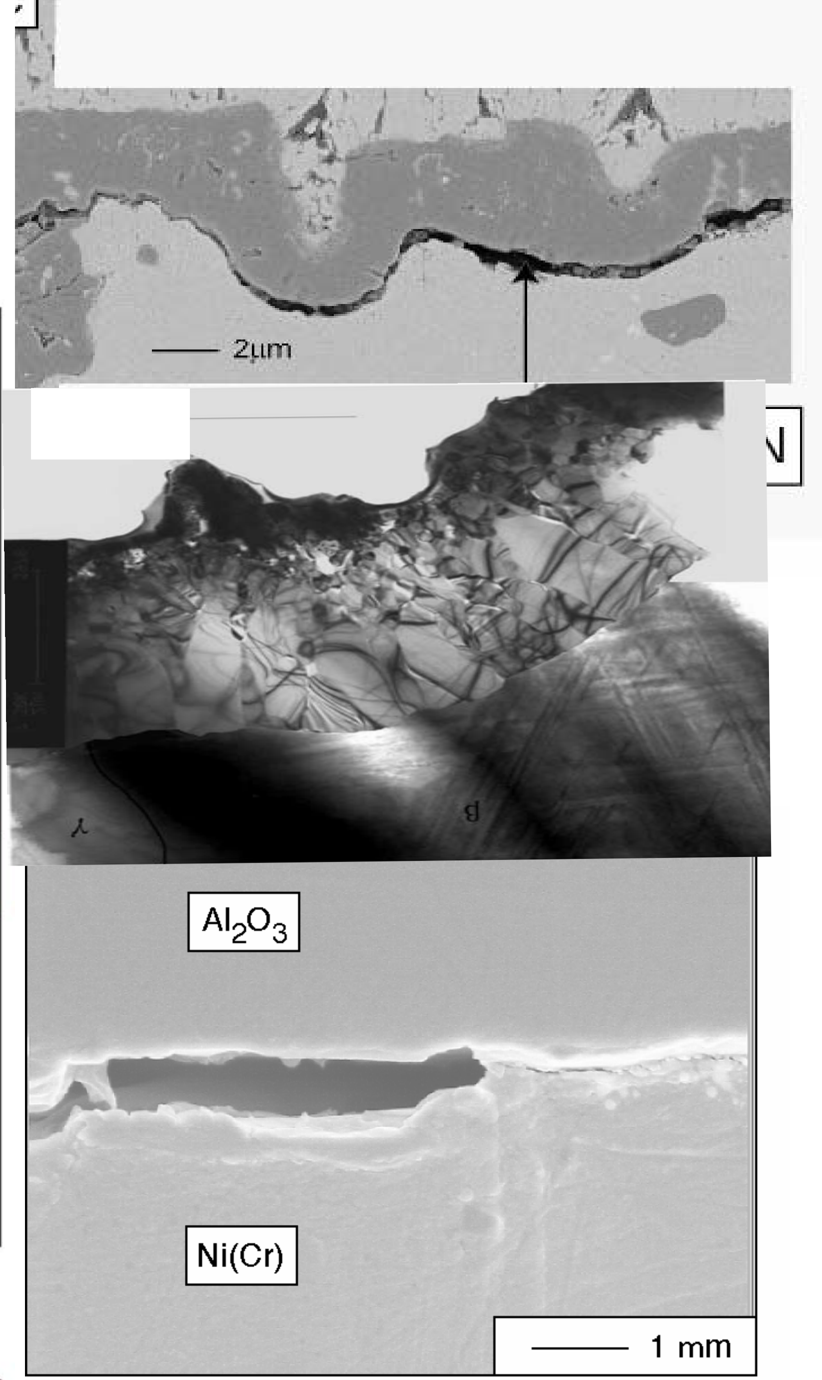


$\Gamma = 20\text{Jm}^{-2}$



Mode I Adhesion Energy of Metal / Alumina Interfaces





Work of Separation: Ni/Al_2O_3 interfaces

Expt.

TBC $Ni(Al)/Al_2O_3$ interface:

Fracture at interface

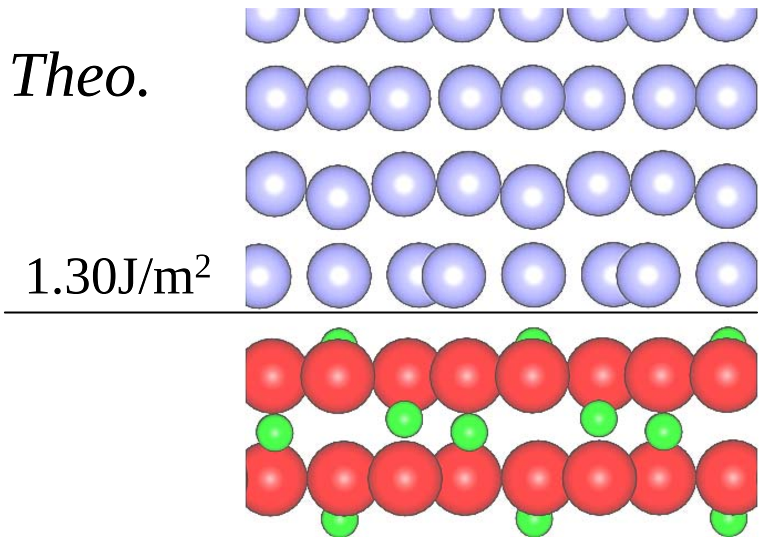
Mode I toughness ~ 20 J/m^2

Pure Ni/Al_2O_3 interface:

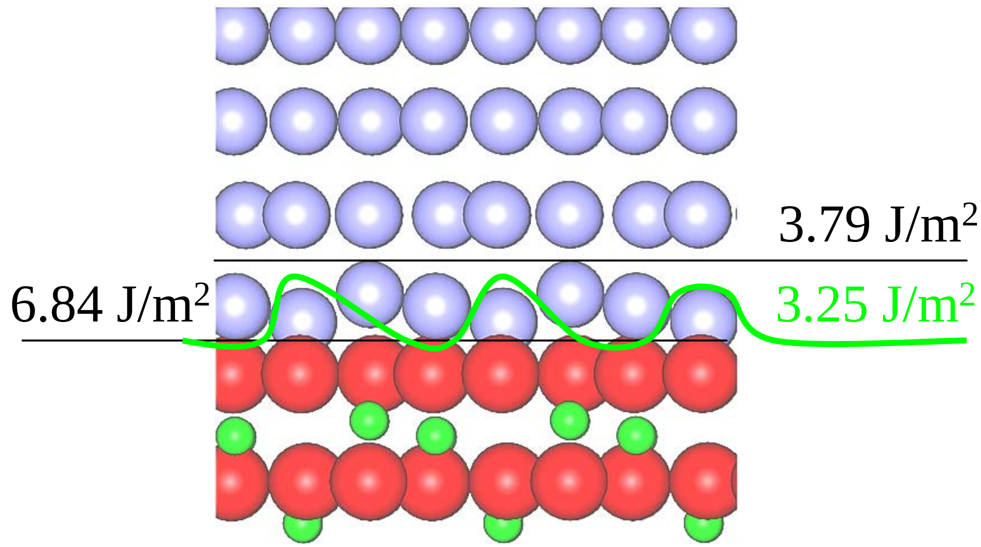
Fracture in Alumina

Mode I toughness > 300 J/m^2

Theo.



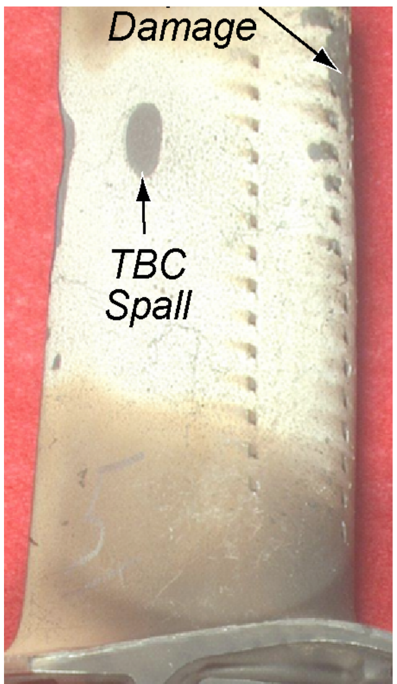
Al-termination

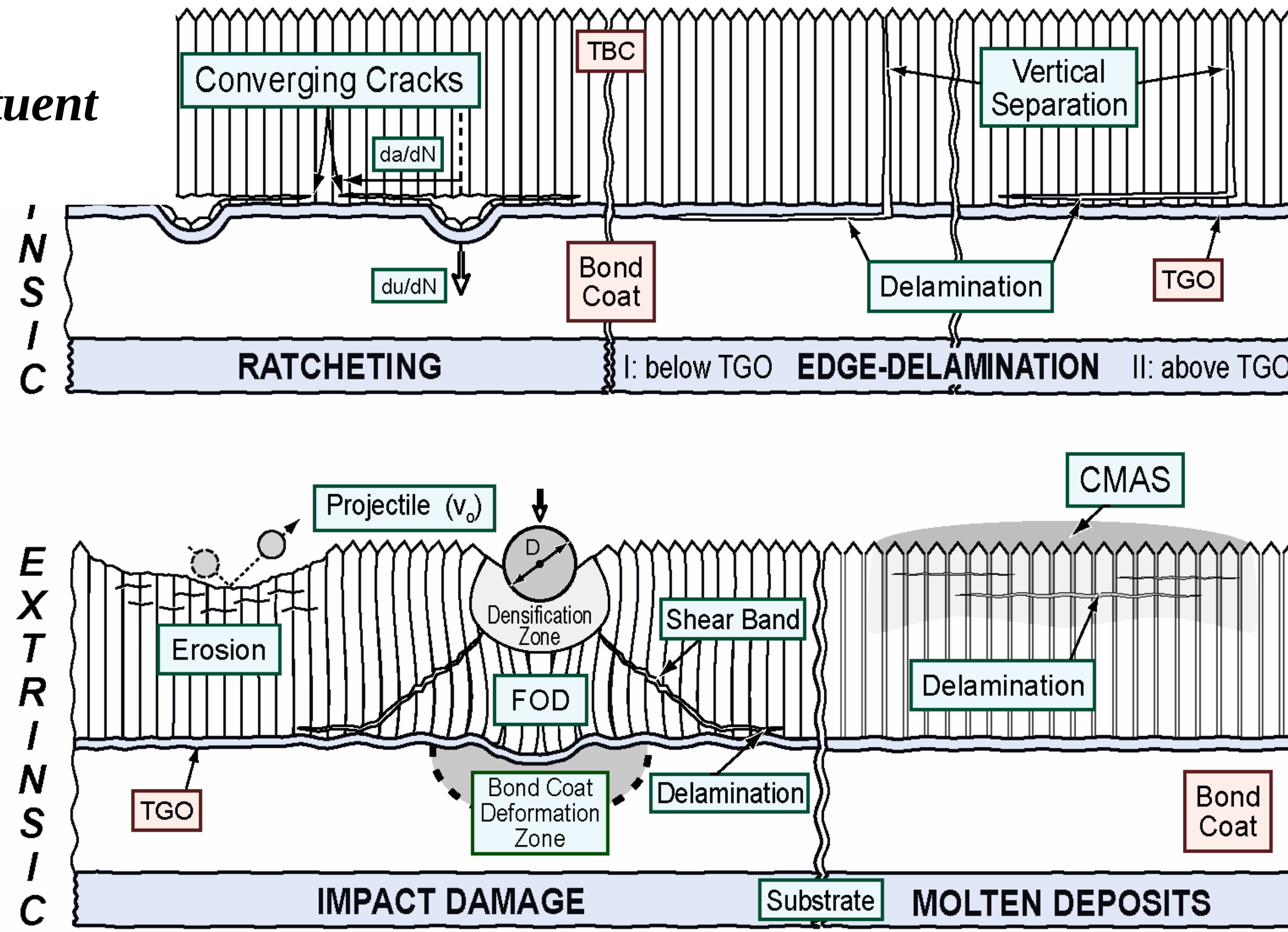


O-termination

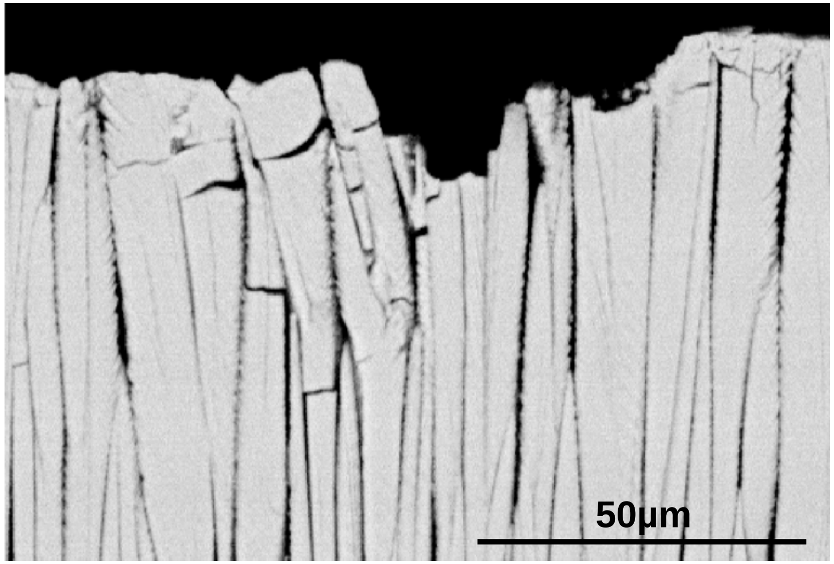
Failure Modes After Engine Test

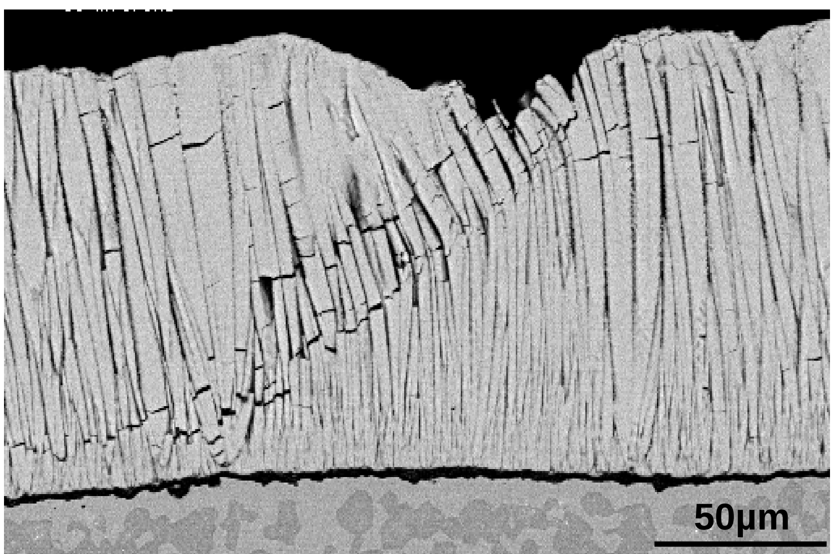
***Delay Spalling
By Understanding
Mechanisms
And
Adjusting Constituent
Properties***



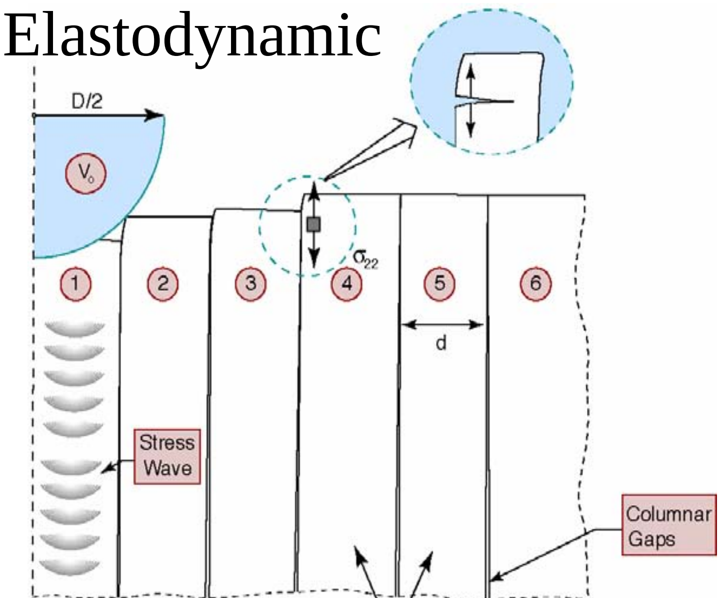


Two Basic Erosion and FOD Mechanisms

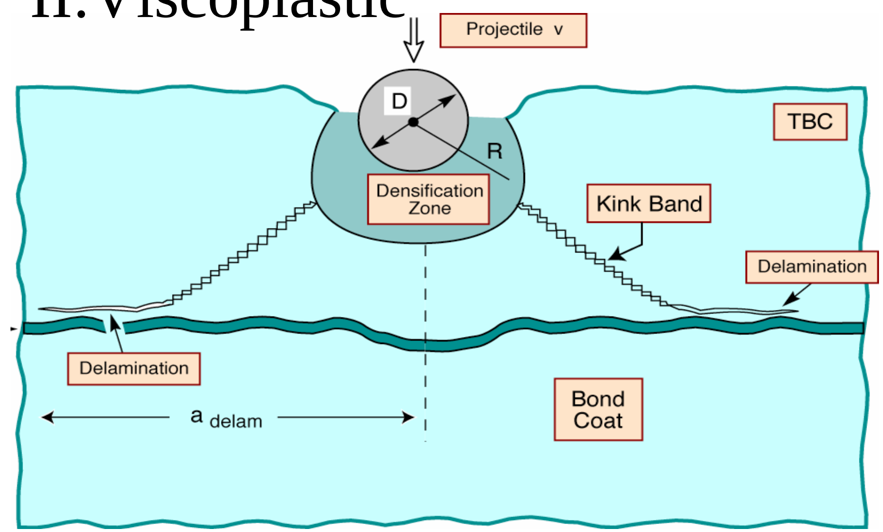




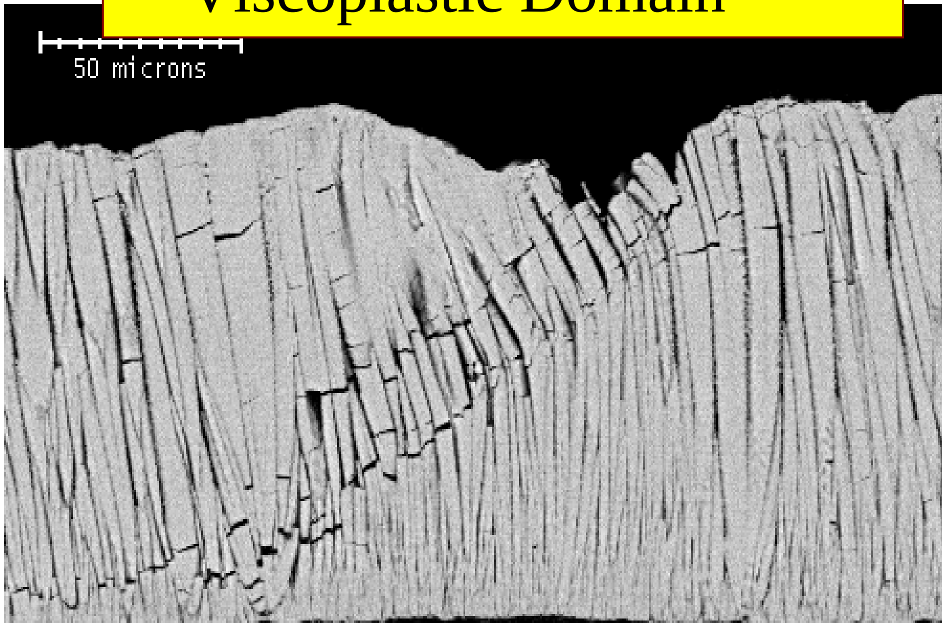
I:Elastodynamic

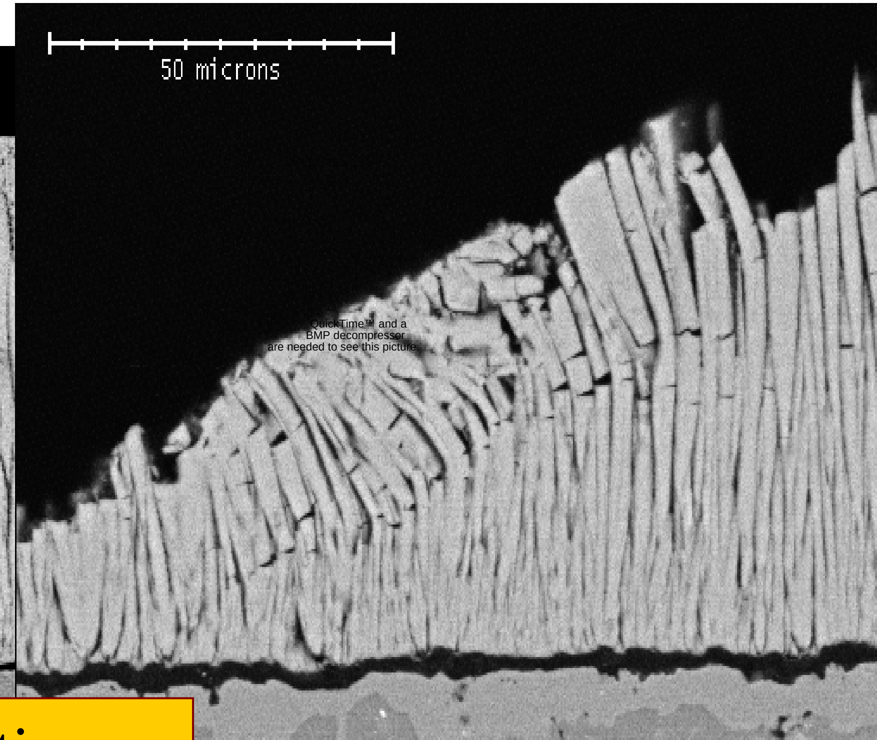


II:Viscoplastic

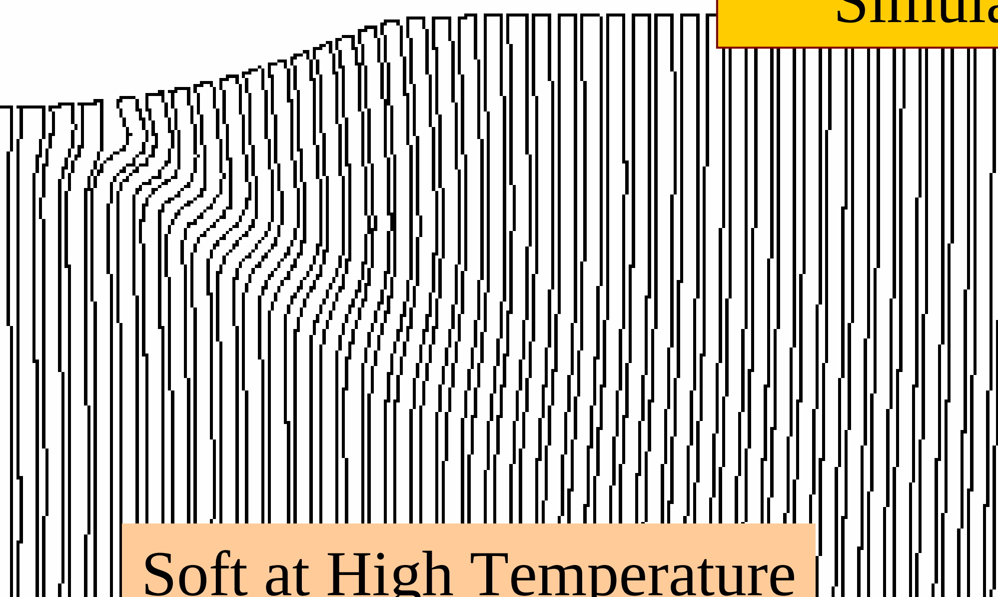


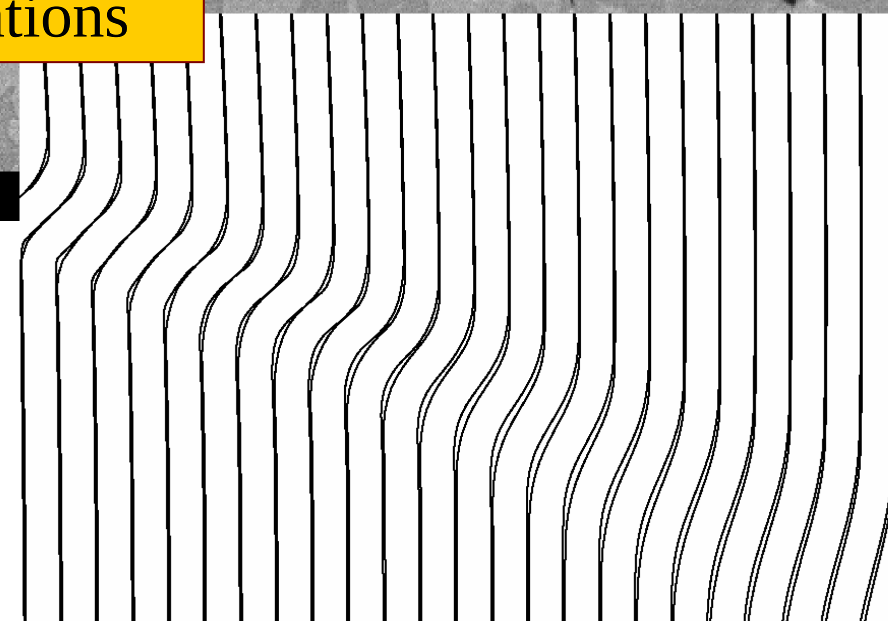
Viscoplastic Domain





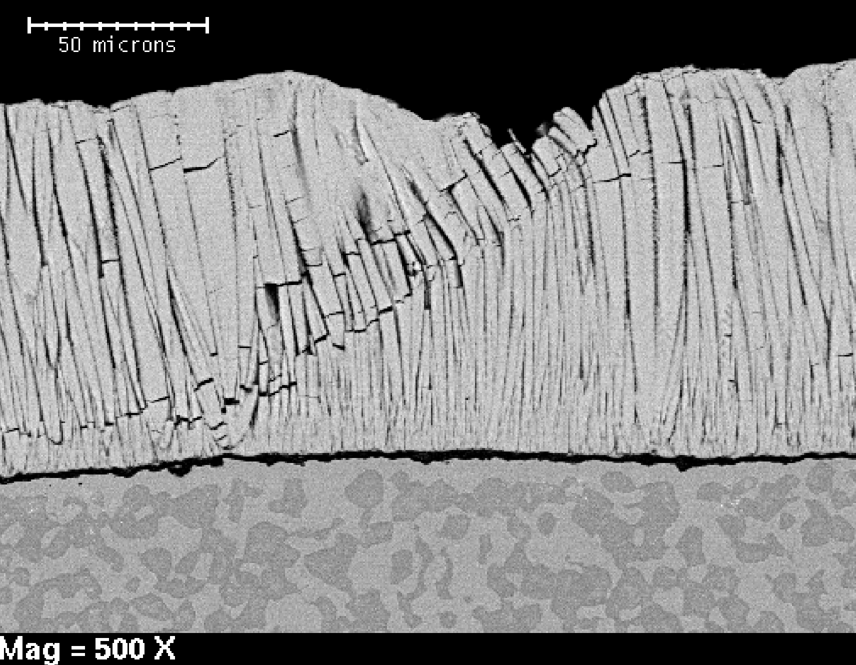
Simulations

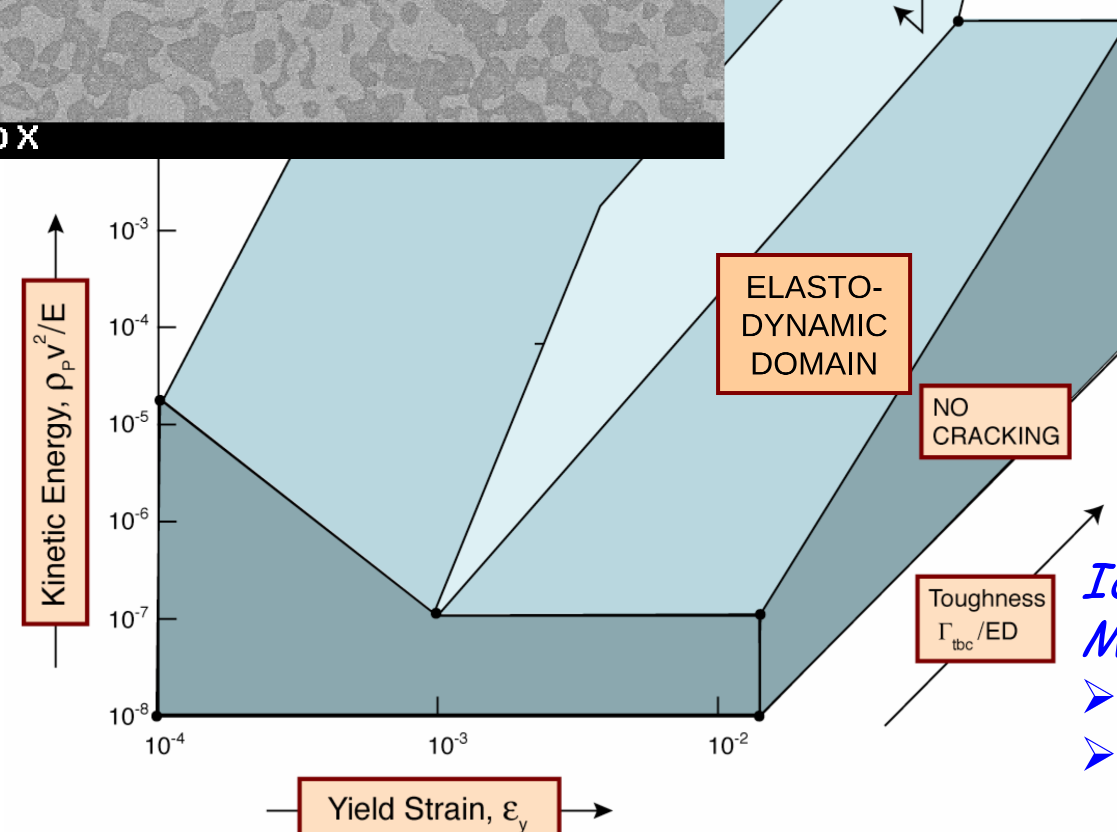


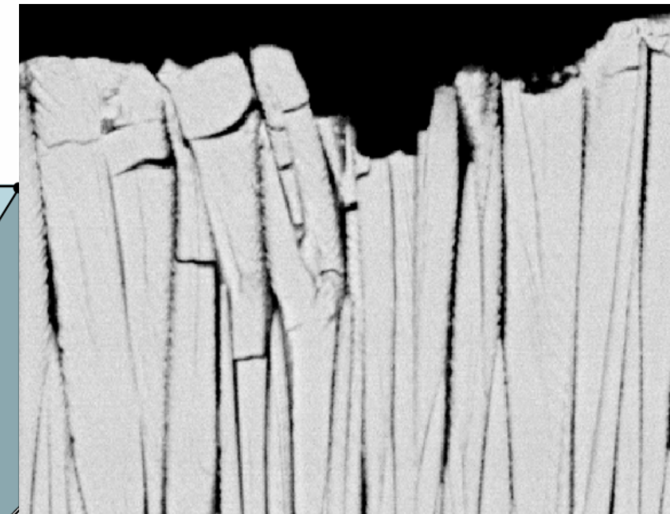


Soft at High Temperature

Erosion Threshold Map







Identify Importance of Material Properties:

- *High Toughness*
- *Soft at High Temperature*