Development of Silicon Nitride Ceramic Components for Advanced Turbine and Microturbine Systems

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Outlines of Presentation

- **Background**

- **Silicon Nitride Components for Gas Turbines**
  Ceramics Stationary Gas Turbines Program
  - Solar Turbines CSGT (Centaur 50S)

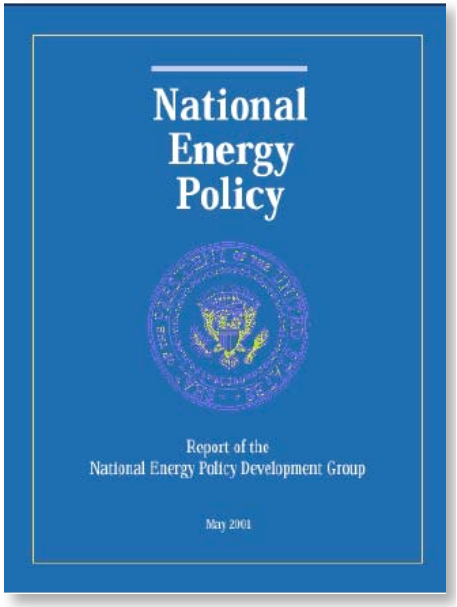
- **Silicon Nitride Components for Microturbines**
  Microturbine Program
  - Ingersoll-Rand (PowerWorks 70kW)

- **Summary**

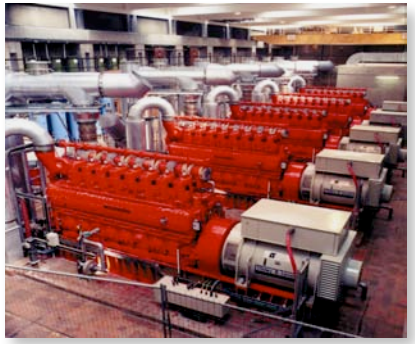
Distributed Energy Resources Provide a Secure New Energy Infrastructure for the U.S.

Vision 2020:

The United States will have the cleanest and most efficient and reliable energy systems in the world by maximizing the use of affordable distributed energy resources.



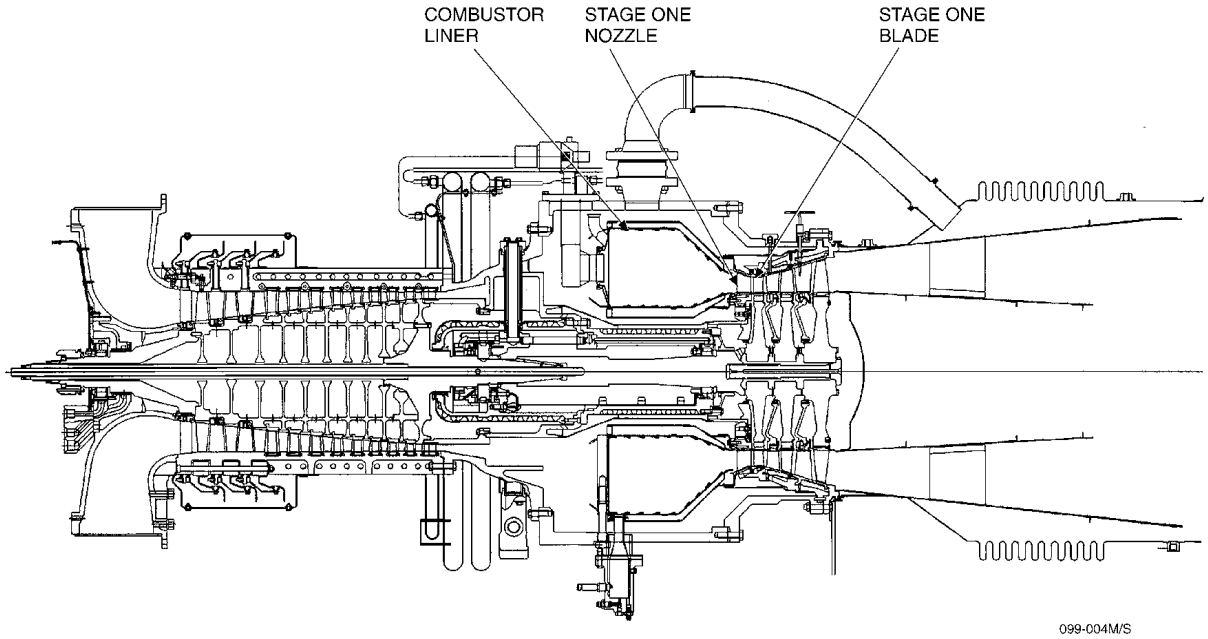
- *Diversity of energy supplies*
- *"Fuel independent" technologies*
- Flexible electric power grid
- Distributed on-site locations
- Advanced communications and controls
- Alternative transportation fuels



Solar Turbines Ceramic Stationary Gas Turbine (CSGT) Program

Goals:

- Increase turbine inlet temperature (TIT) from 1010°C to 1121°C
- Increase the electric thermal efficiency by 5.6%
- Increase the electric output from 4.1 MW to 5.2 MW (~26%)
- Decrease NOx emission down to 10 ppm or lower.

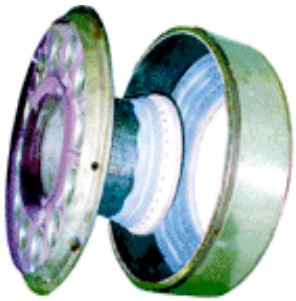


Program awarded in 1992

Solar Turbines' Centaur 50S Gas Turbine (4.1 MW, 29.6%)

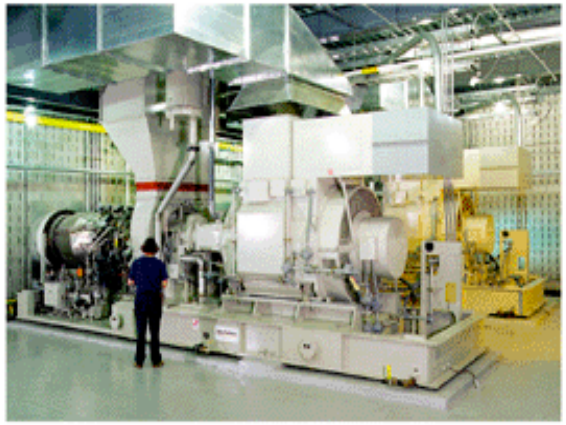
Solar Turbines
A Caterpillar Company

CSGT Hot Section Ceramic Components



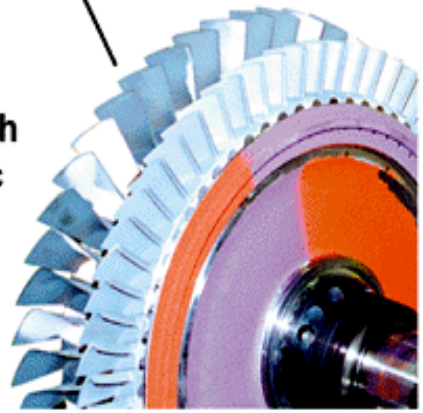
Combustor with
Ceramic Liners

Ceramic
Nozzle
Assembly

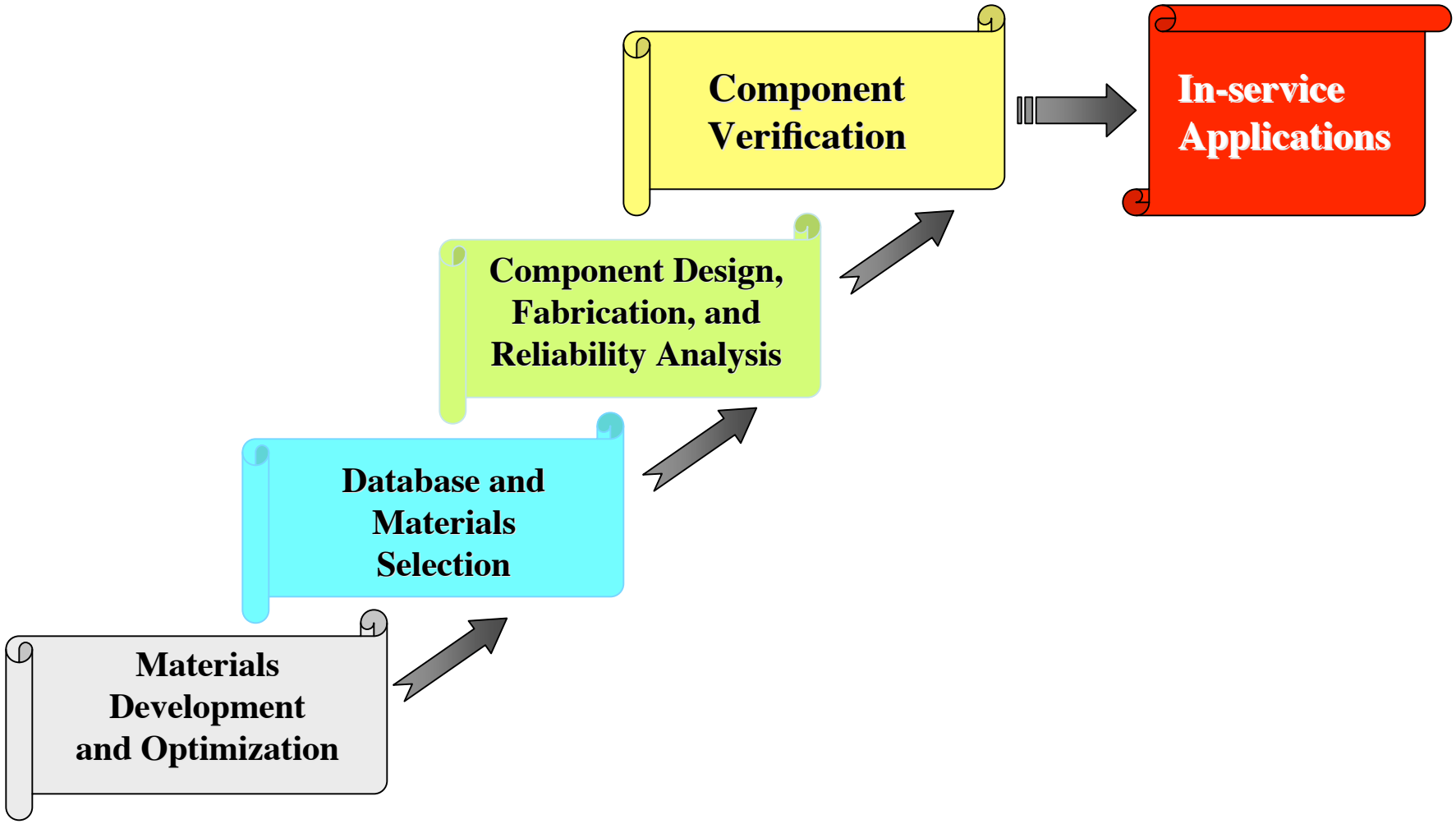


CSGT Field Test Site
Centaur 50 SoLoNOx
Textile Mill
Lawrence, Massachusetts

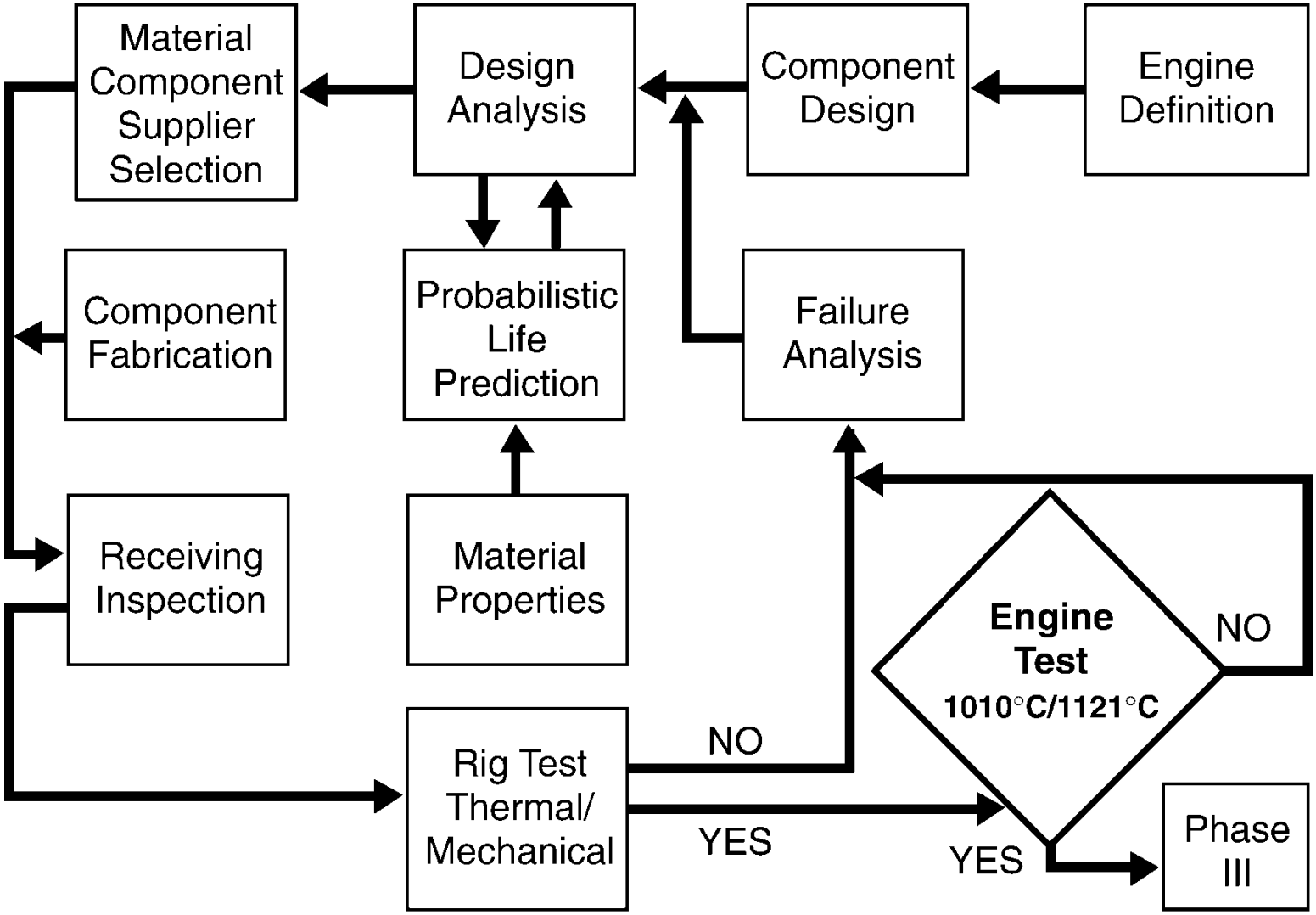
Disk with
Ceramic
Blades



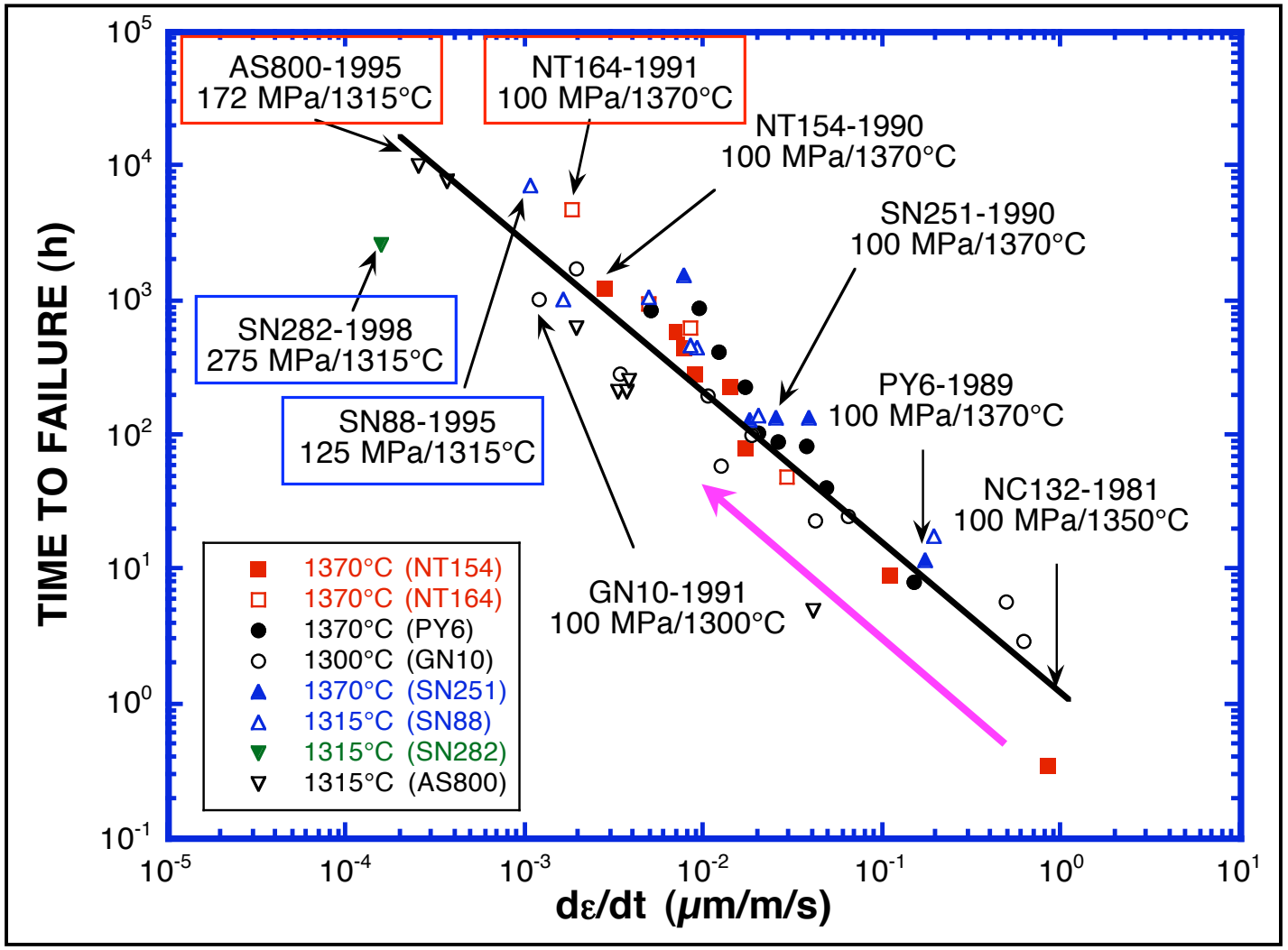
Mechanical Properties are an Important Measure of Performance for Structural Ceramic Components



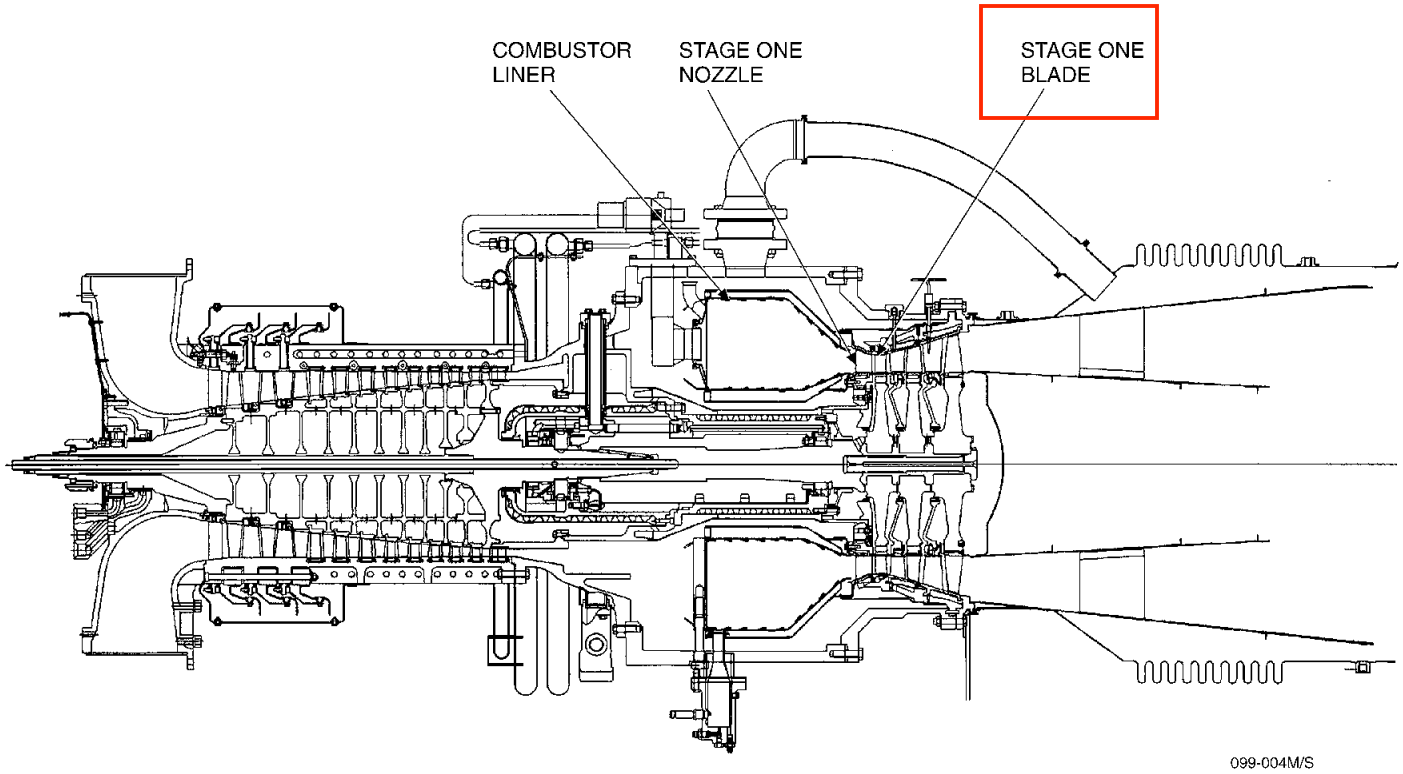
Solar Turbines CSGT Design/Materials/Test Strategy



High-Temperature Mechanical Performance and Reliability of Si_3N_4 Ceramics Substantially Improved



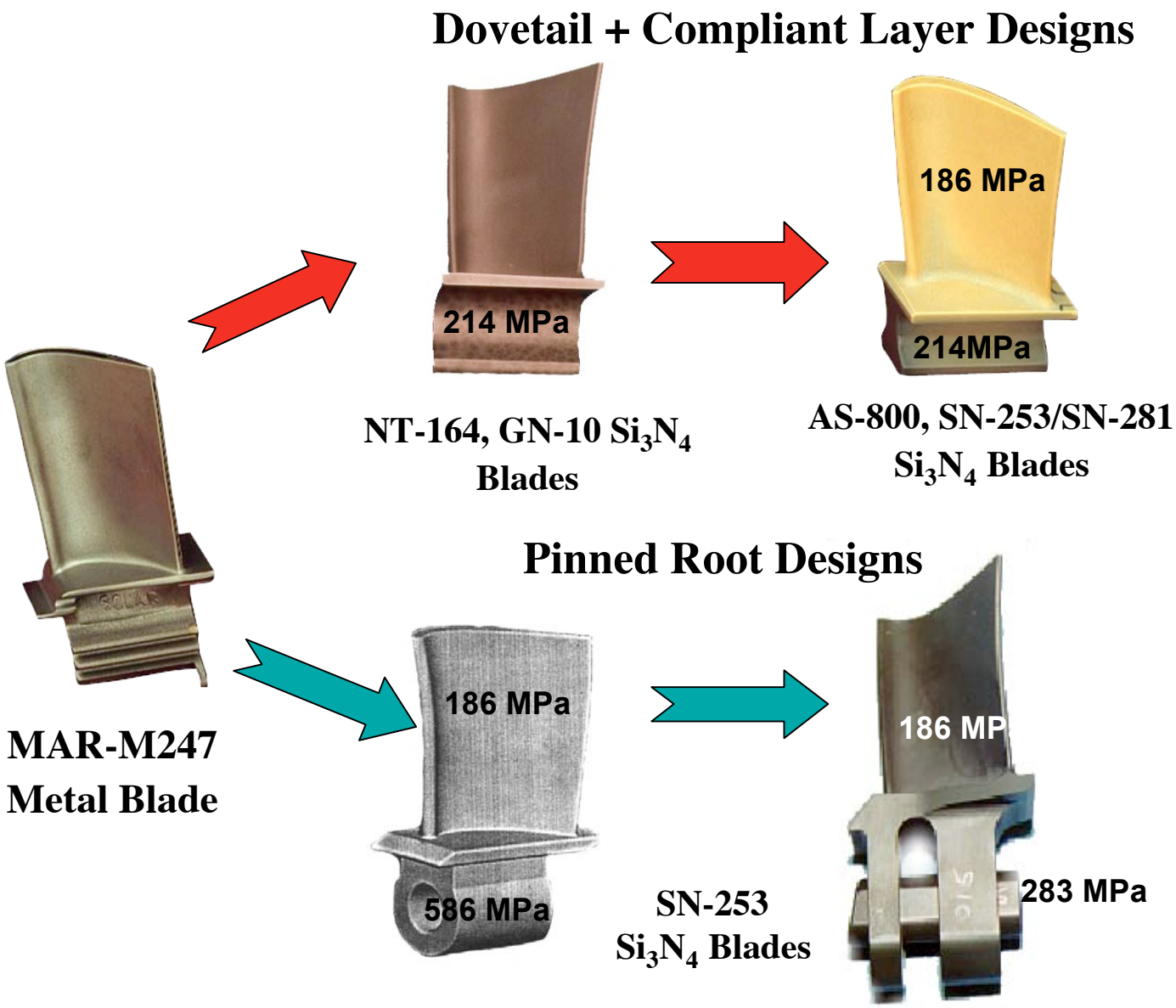
Monolithic Ceramic Blades



Candidate Monolithic Blade Suppliers and Materials

- Norton Advanced Ceramics
  - NT154 and NT164 Si_3N_4
- Honeywell Ceramic Components
  - GN10 and AS800 Si_3N_4
- Kyocera Industrial Ceramics Corporation
  - SN252, SN253, and SN281 Si_3N_4
- NGK Insulators, Ltd.
  - SN88 Si_3N_4

Solar CSGT Ceramic Blade Design Evolution



Solar Ceramic Blade Life Prediction

SPSLIFE, NASA CARES/Life - Fast Fracture, Slow Crack Grow (the key life limiting factor)

- 186 MPa airfoil stress
- 1121°C TRIT
- 30,000 hrs life target

Si_3N_4	POS (Blade)	POS (Set)
NT164	0.96355	0.10004
AS800	0.99999	0.99976
SN253	0.99993	0.99567
SN88	0.99998	0.99908

Ceramic Blades - In-House Engine Testing

- Short 1-20 hour tests
  - Blades had passed cold spin test
  - Steady state full load
  - Start-stop and trip transients
  - NT164 (NAC) and GN10 (HCC)
- First 100 hour test
  - AS800 Blades (HCC)
  - 2 Compliant layer systems:

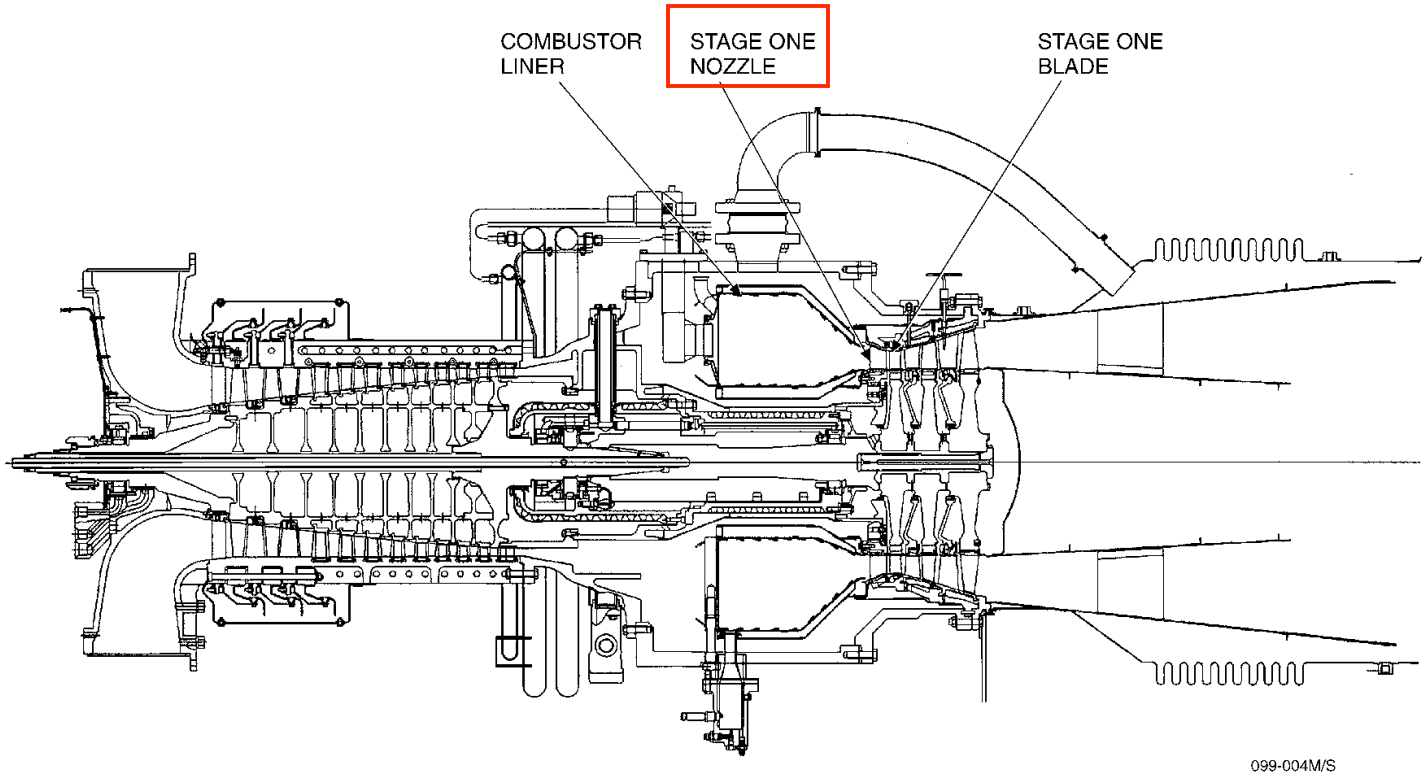
    Ni-alloy + BN, ~~***Ni-alloy + Pt***~~
  - Blades failure after 58 hours

CSGT Ceramic Blade Field Testing

- Texaco (Formerly ARCO Western Energy), Bakersfield, California
- Steam and electricity cogeneration
- 1,300 total Hours of full-load field operation

- 1st field test: AS800 Blades - Terminated after 948 Hours (FOD)
- 2nd field test: AS800 Blades - Terminated after 352 Hours (FOD)
- *Compliant layer system (Ni-alloy + BN) intact*
- ***Need for a more impact resistant design***
- ***Need higher fracture toughness Si_3N_4***

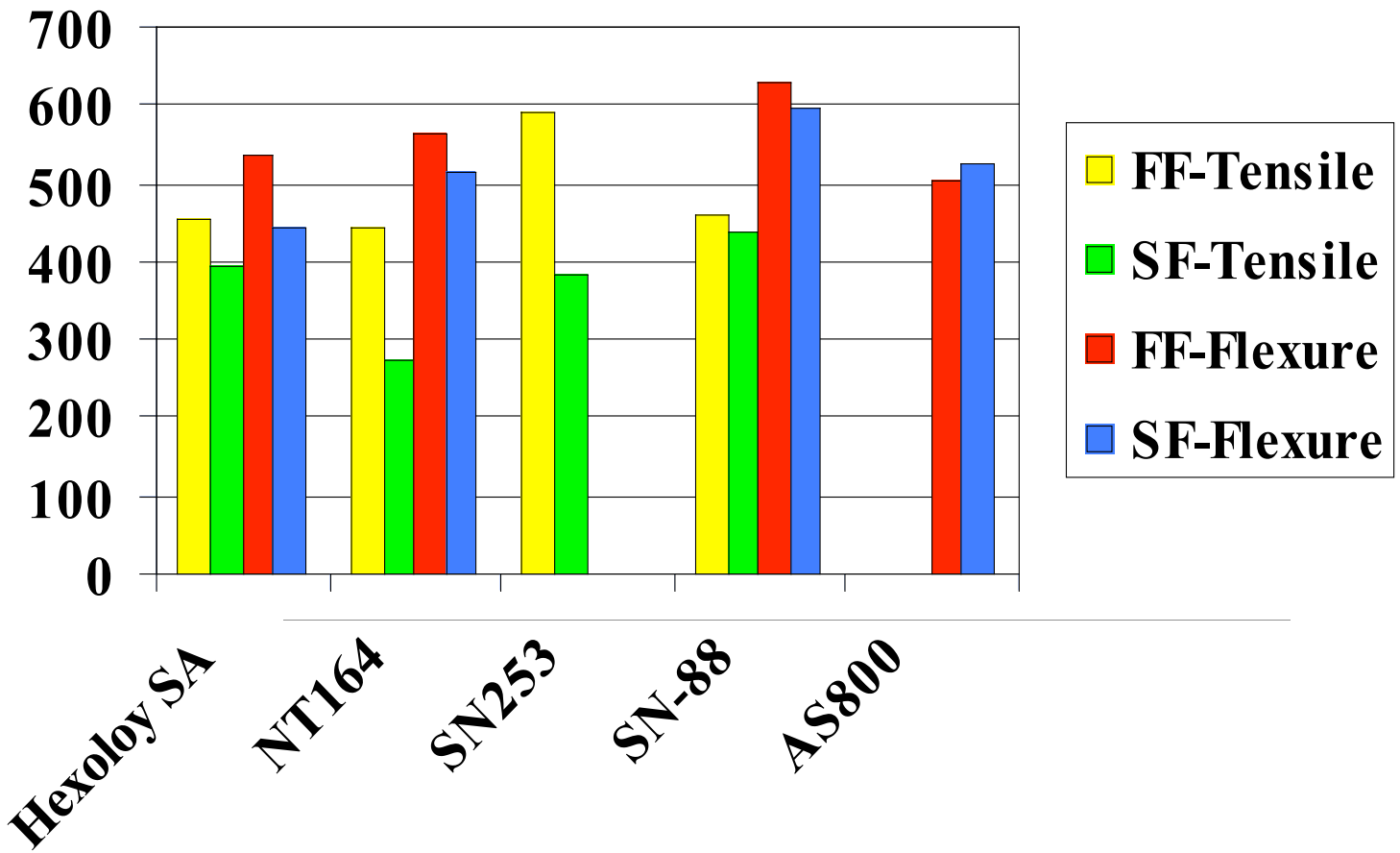
Monolithic Ceramic Nozzles



Candidate Monolithic Nozzle Suppliers and Materials

- Norton Advanced Ceramics
  - NT154 and NT164 Si_3N_4
- Kyocera Industrial Ceramics Corporation
  - SN252, SN253, and SN282 Si_3N_4
- NGK Insulators, Ltd.
  - SN88 Si_3N_4
- Carborundum
  - Hexoloy SA SiC

Dynamic Fatigue Testing at 1288°C in Air



Flexure Testing
FF: 4 x 10^{-3} cm/s
SF: 4 x 10^{-5} cm/s

Tensile Testing
FF: 4 x 10^{-2} cm/s
SF: 4 x 10^{-6} cm/s

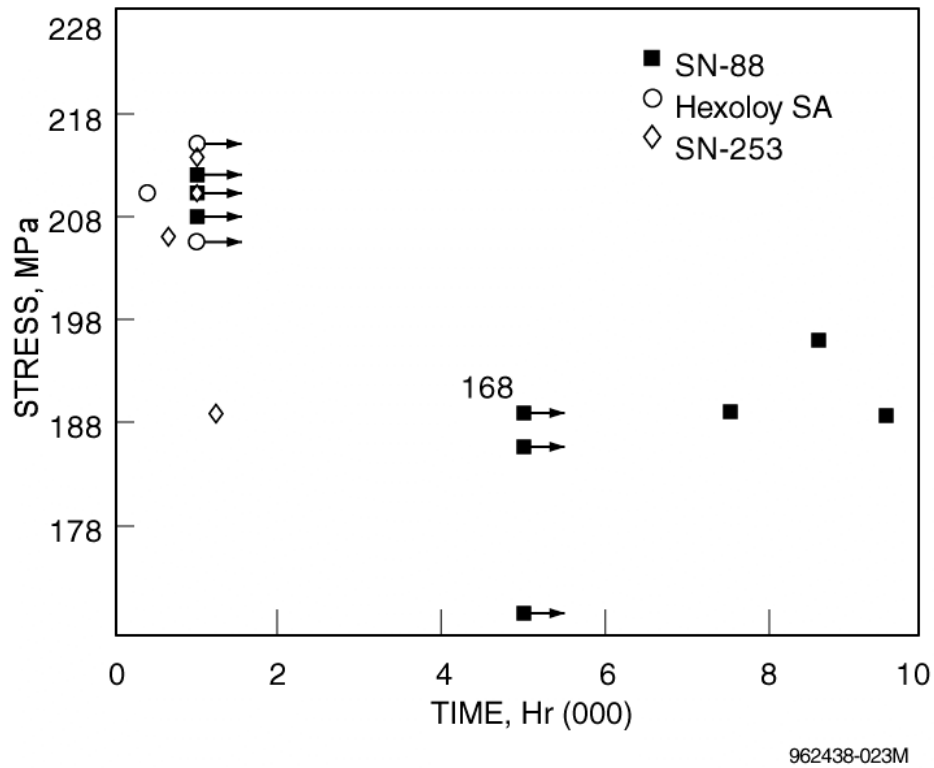
Solar Ceramic Nozzle Life Prediction

- SPSLIFE, NASA CARES/Life - Fast Fracture, Slow Crack Grow (key life limiting factor)
  - 186 MPa airfoil stress
  - 1121°C TRIT
  - 30,000 hrs life target

Si_3N_4	POS (Set) Surface	POS (Set) Volume
NT164	0.1505	0.983
SN253	0.9993	1.000
SN88	0.9939	1.000

- Eliminated NT164 due to its SCG issue

NGK SN-88 exhibited superior creep life and was selected for nozzle fabrication



Evolution of Ceramic Nozzle Design

Aim to reduce the SS max. principal stress developed

Bowed Ceramic Nozzle

221 MPa

211 MPa

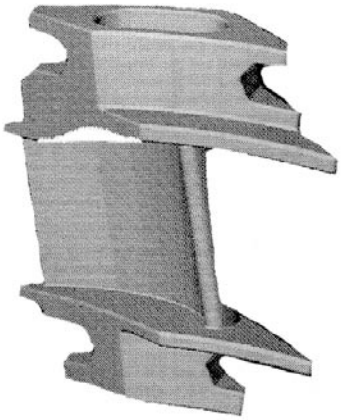
SN-88 Si_3N_4

SN-282 Si_3N_4

FS-414 Metal Nozzle

480 MPa

172 MPa

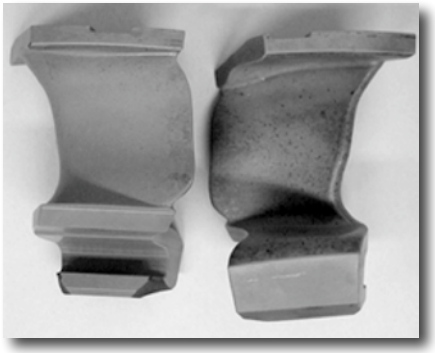


Uncooled Ceramic Nozzle

Cooled Ceramic Nozzle

Silicon Nitride Nozzle Proof Testing

- Thermal gradient rig
  - RT-> 1190ºC in 18s
  - 113% of max. SS stress
- Mechanical proof test rig
  - Load on nozzle suction side
  - Simulates aerodynamic load

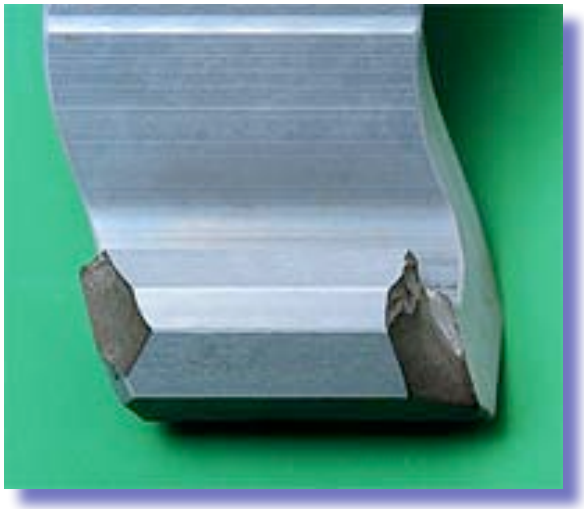


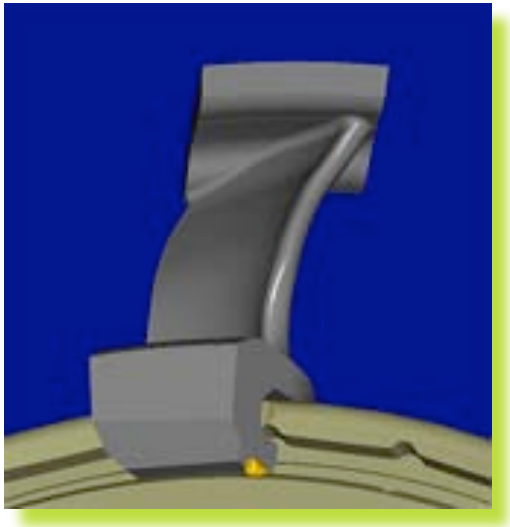
Pressure side **Suction side**

Nozzles that pass both tests are then used for engine testing

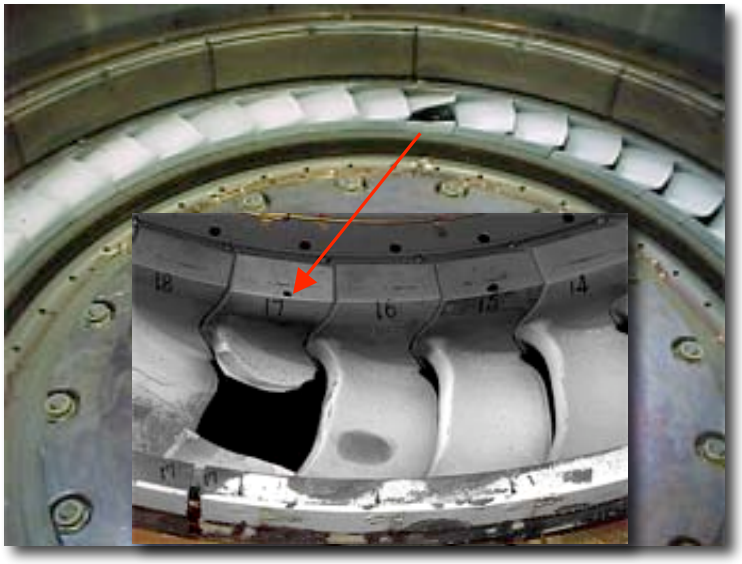
First SN88 Si_3N_4 Nozzle Engine Test

- **Short one hour test at full load Nozzle airfoil performed well**
- **Chipping in nozzle attachment and outer shroud**
- **Redesigned attachment structure**
- **Chipping eliminated in 2nd one hour full load test**
- **100 hour engine test - steady state, transients**



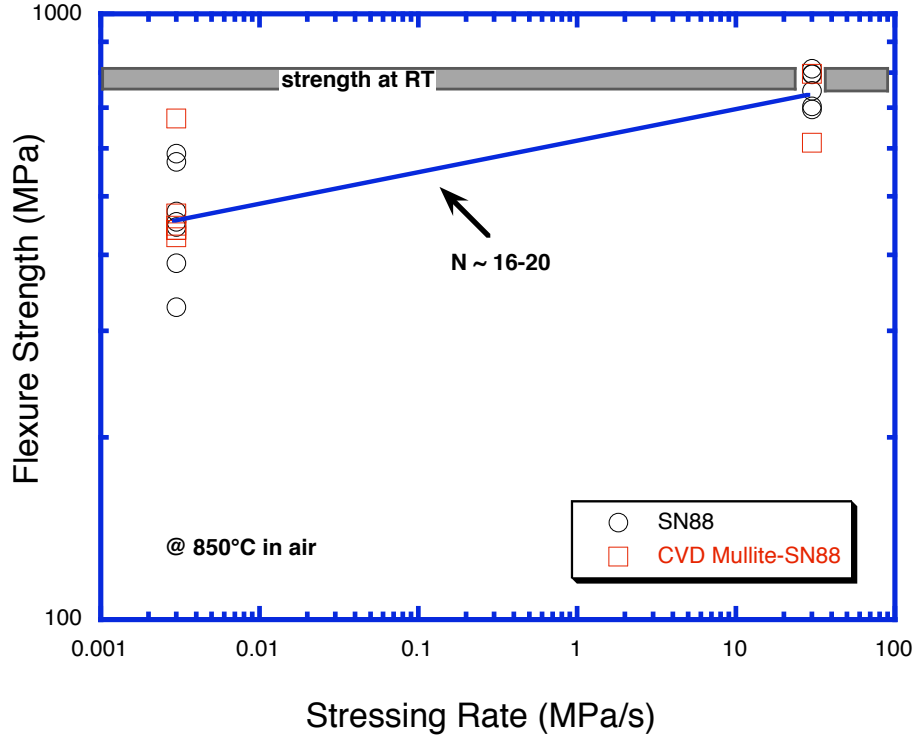


Second SN88 Si_3N_4 Nozzle Engine Test



- **White deposit on all airfoils**
- **Cracks on 9/11 nozzles in 120° Arc**
- **Cracks originated from trailing edge: 3(OD), 6 (ID), 2 (OD+ID)**
- **OD and ID attachment in good condition**

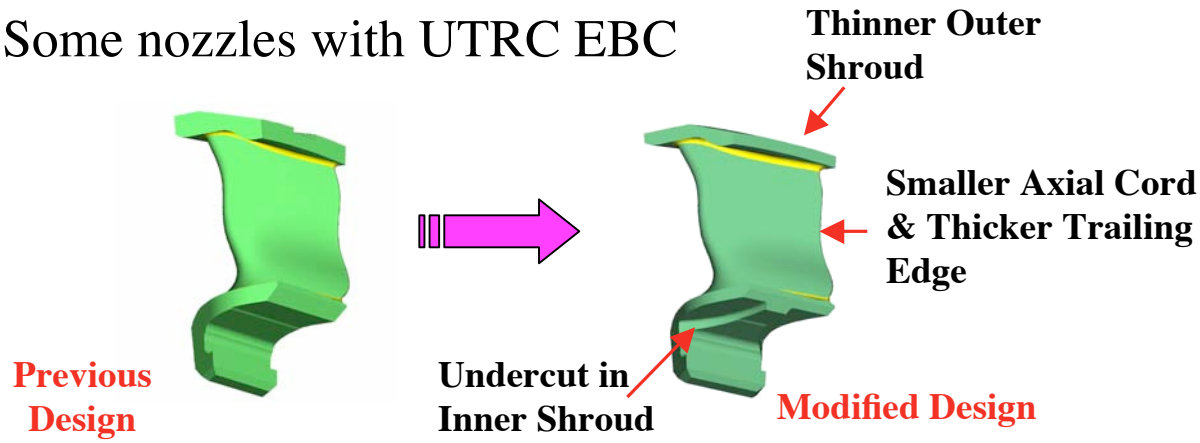
- **Planned 100 hr engine test**
- **Test halted after 68 hrs**
- **Materials degradation and stress state in service**
- **850°C: Protective SiO_2 Layer Removed and change in J-phase to $Yb_2Si_2O_7$ plus Yb_2SiO_5 => large tensile residual stress and failure of nozzles**



Ceramic Nozzle Redesign and Test

- Instrumented engine test
  - Boundary conditions at nozzle and secondary hardware
- Redesigned airfoil and attachment
- ***SN282 nozzles (KICC)***
  - Improved oxidation resistance
  - Excellent creep resistance ($Lu_2Si_2O_7$)
- Thermal gradient rig testing
  - Some nozzles with UTRC EBC

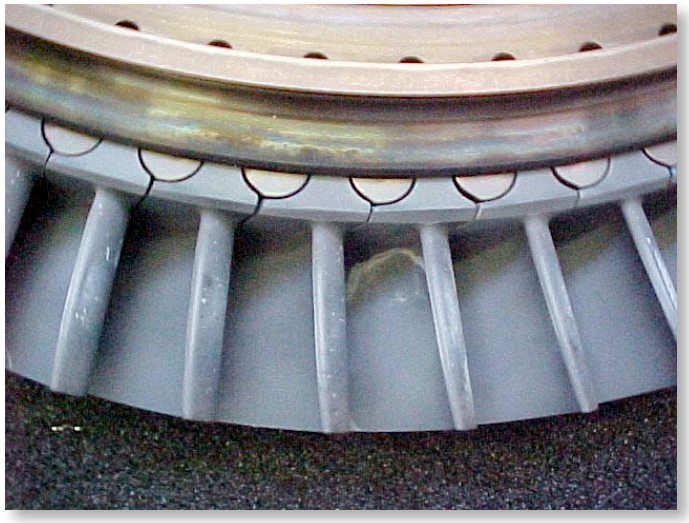
Bisque Machined and Sintered Nozzles



Nozzle With EBC

Blades and Nozzles After Recent 100 Hr Engine Test

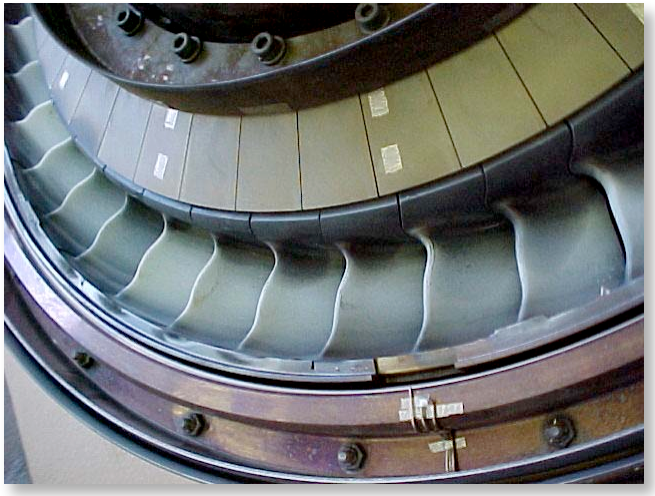
- Blades & nozzles in good condition
- White oxide deposit observed
- No evidence of cracks on airfoil
- No chipping at attachment



Kyocera SN281 blades (62)

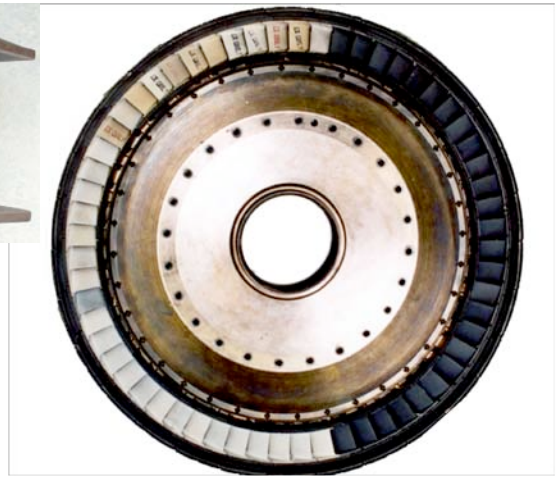
Kyocera SN281 blades (62) and CFCC combustor liner were also employed in the last 104h engine test (final Phase III demonstration).

Both nozzles and blades were tested without EBC.

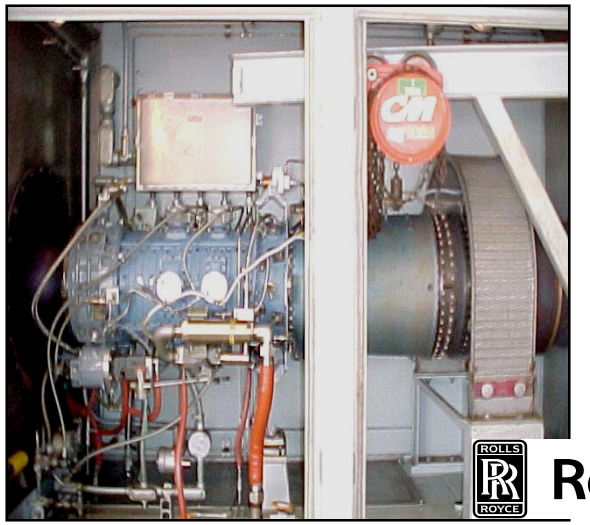


Kyocera SN282 nozzles (42)

Other Successful Si_3N_4 Components Development and Demonstration



1st stage vane

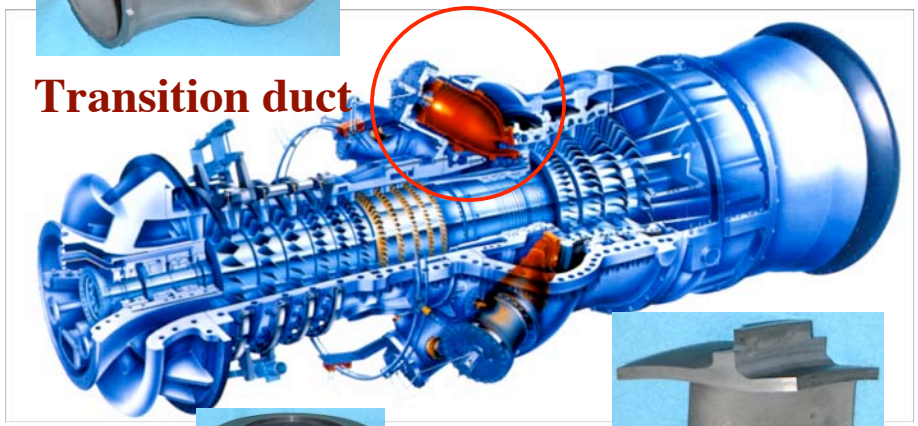


Rolls-Royce

~ 2500 hrs field test
Rolls-Royce Allison vane program

KYOCERA

Transition duct



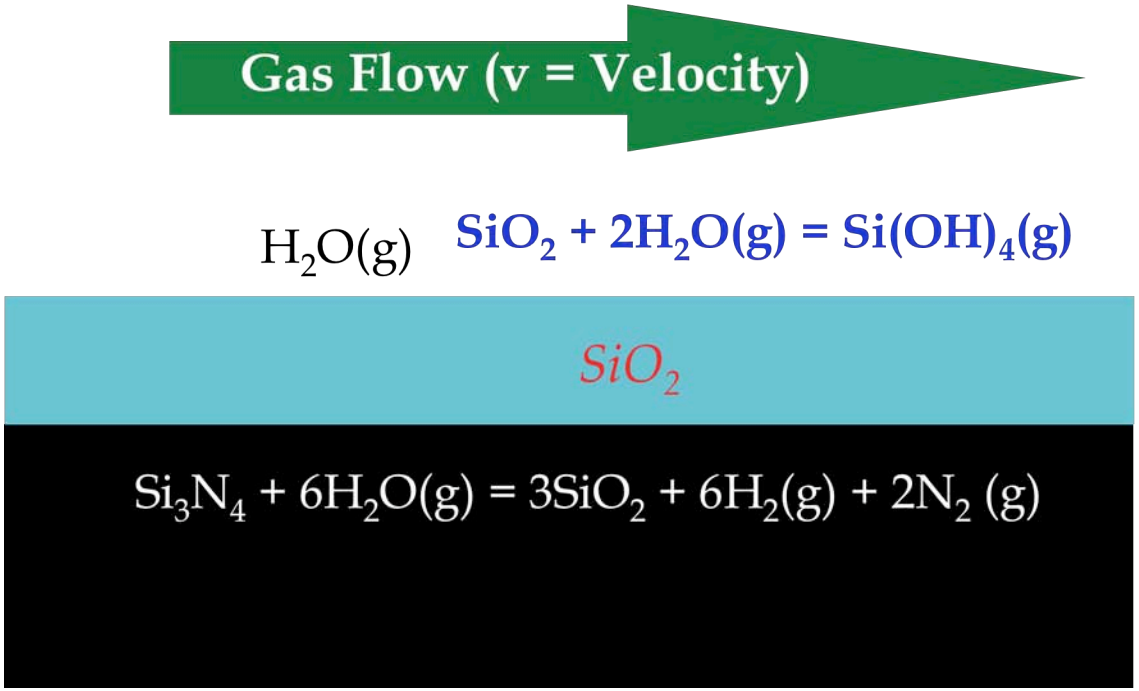
1st stage vane

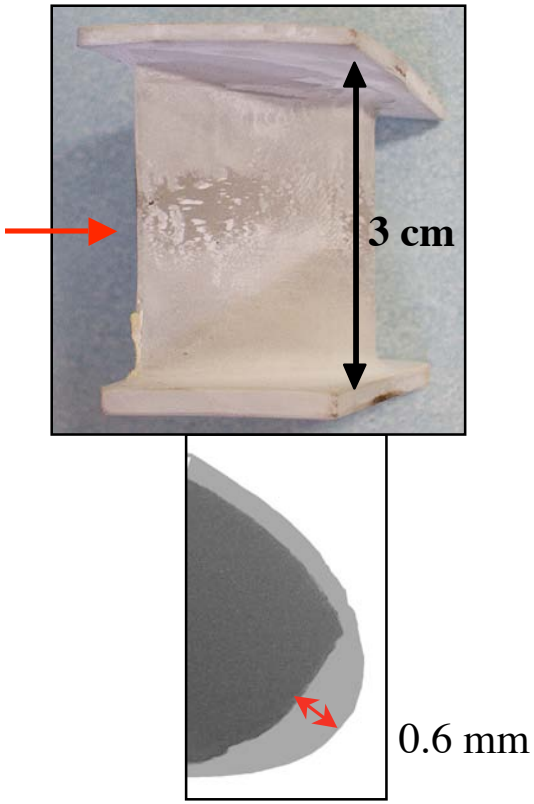
Combustor liner

1000 hrs
Kyocera HGT Program

Significant Material Recession of Airfoils Could Lead to Dimension Instability and Component Failure

Volatilization Rate $\propto v^{1/2}\, P(H_2O)^2/(P_{total})^{1/2}$,

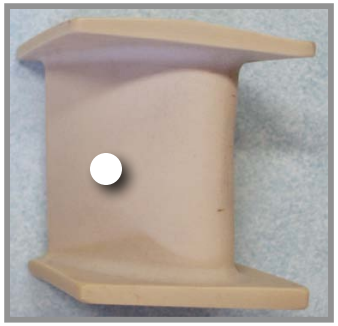


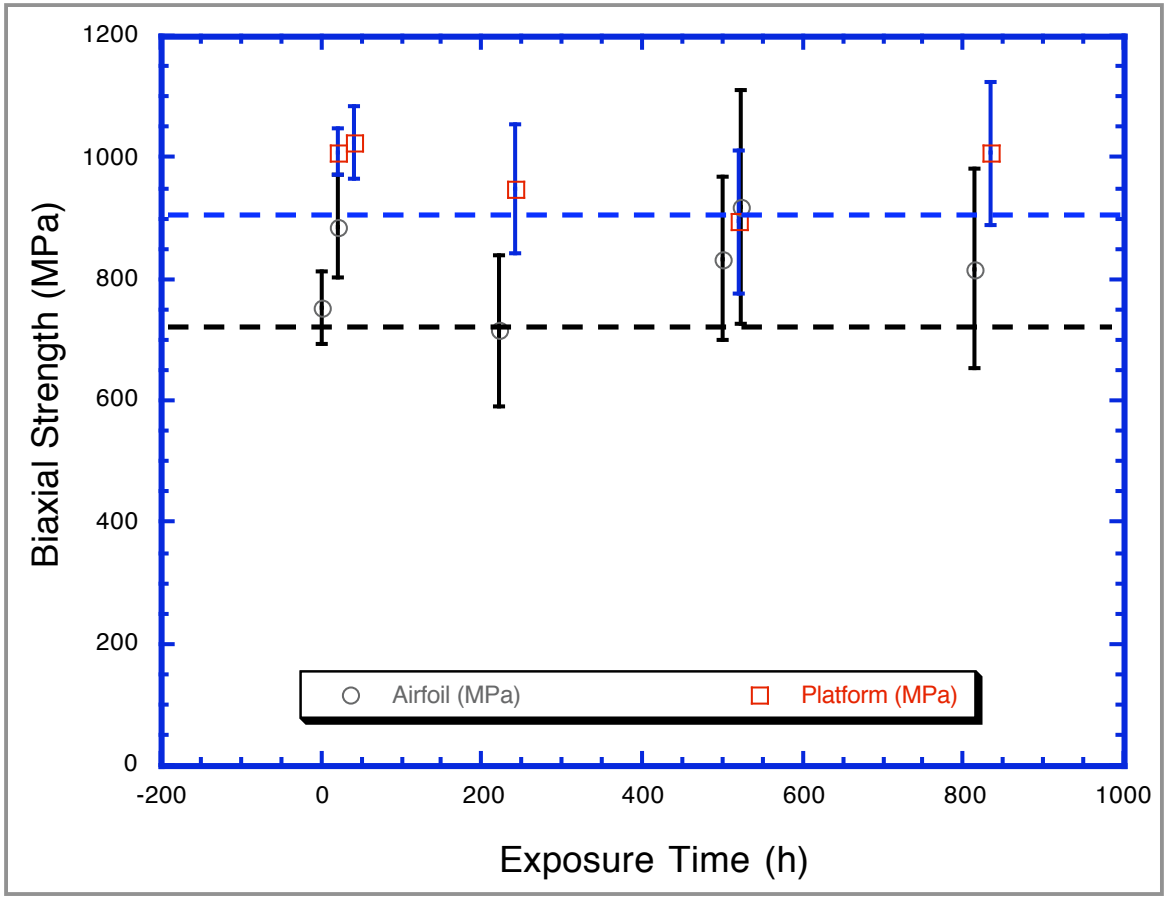


Cross-section: 815 h field test

Effective environmental barrier coatings need to be developed to protect Si_3N_4 components in gas turbine environments

Mechanical Property of Material From Airfoil Section is Relatively Insensitive to Combustion Exposure





Scatter in strength data from airfoil sections increases with exposure time

Advanced Microturbine Program Goals

Six year program (FY 2000 - 2006), $60+ million Govt. investment

Next generation advanced microturbine system by 2006

- **High Efficiency** - Fuel-to-electricity conversion efficiency of at least 40%
- **Environmental Superiority** - NOx < 7 ppm (natural gas)
- **Durable** - 11,000 hours of reliable operations between major overhauls and a service life of at least 45,000 hours
- **Economical** - System costs < $500/kw, costs of electricity that are competitive with the alternatives (including grid) for market applications
- **Fuel Flexible** - Options for using multiple fuels including diesel, ethanol, landfill gas, bio-fuels

Advanced Microturbine Program

2000

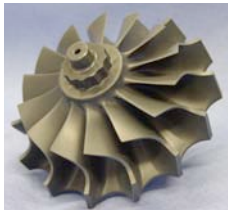
- 17-30% Efficiency
- Double digit ppm NO_x

2006

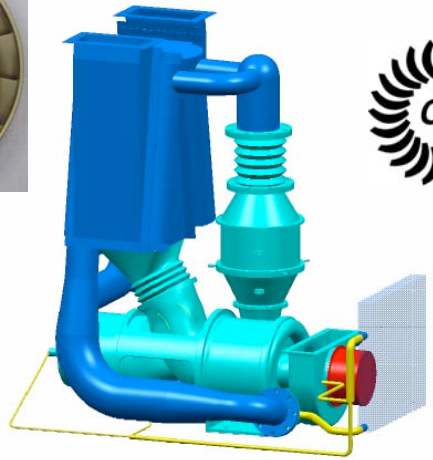
- 40% Efficiency
- Single digit ppm NO_x

FY00 – 5 Awards

- *Ingersoll-Rand*
- UTC
- GE
- Capstone
- Solar Turbines



PowerWorks



Capstone

United Technologies Research Center

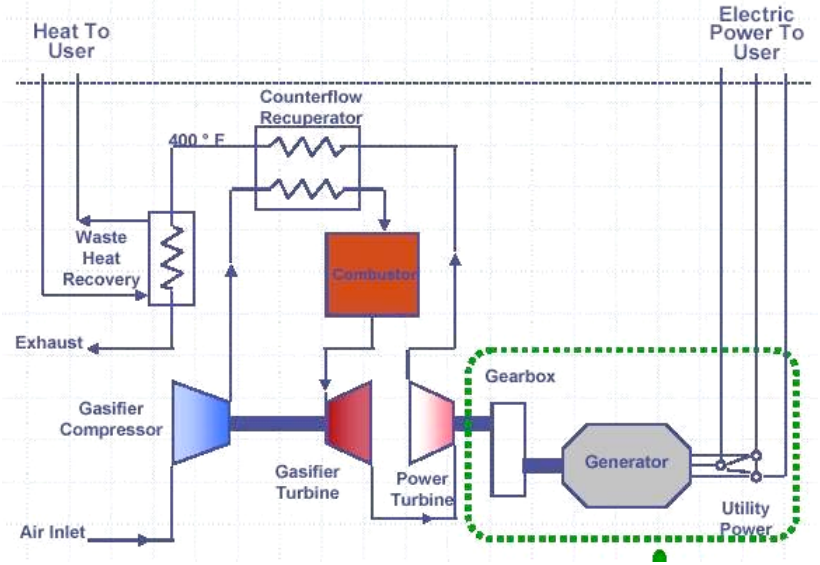
Ingersoll-Rand Advanced Microturbine Program

- PowerWorks 70kW model
- Efficiency:

- 30% demonstrated

- up to 80% total with cogeneration

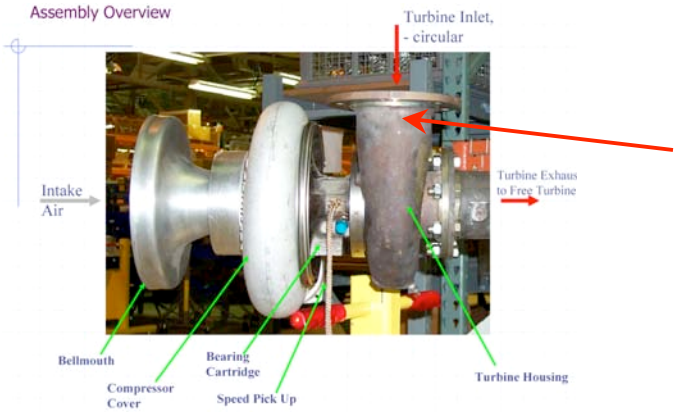
- Low emission - 5 ppm Nox
- 8,000 hour maintenance interval
- 80,0000 hour engine life



Ingersoll-Rand's Ceramic Microturbine Plan

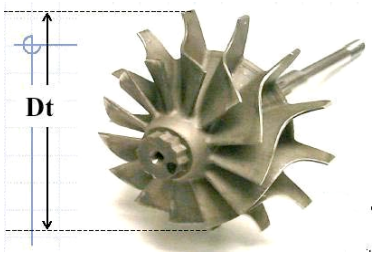
- Introduce ceramic turbine rotor to operate within proven limits of today's technology
  - * Size and manufacturing limits
  - * Temperature
  - * Stress

- Use metallic alloy for turbine housing and down-stream section (e.g., recuperator)
- Silicon nitride turbine rotors are in high volume production for the turbocharger.
- Small turbocharger rotors are low in cost, and operate at temperatures above that of uncooled metallic candidates.



Application of Today's Silicon Nitride Technology to Microturbines to Achieve Near-Term Product Success

- Apply Kyocera silicon nitride rotor technology
- Mechanical database of SN237 silicon nitride meet the application conditions



PowerWorks Product	Dt, mm	status
PowerWorks air compressor	78	Feasible
30 RT chiller-ceramic	62	Feasible
Frame 3-100 kWe-ceramic	112	Future
Frame 3-70 kWe-ceramic	**95**	**Recommended for new focus**
Frame 4 250 kW - ceramic	228	Too challenging

1000

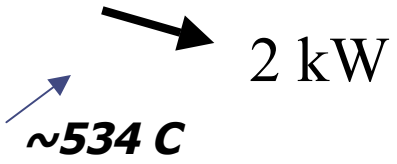
500

100

CMT Rotor Steady State Temperatures

- TIT = 1000 C
- Maximum adiabatic Wall Temperature = 905 C
- Maximum rotor temperature difference = 60 C (excluding cooled attachment)*

* low rotor temp gradients characteristic of low expansion ratio and high thermal conductivity - both serving lower thermal stress



CMT Rotor Steady-State Stresses (Principle)

- **Kyocera stipulated design target of 200 MPa for SN237**
- **Steady state critical stress location is at back wall fillet**
  - **currently evaluating to 275 MPa (at bore)**
  - **can be further alleviated with larger fillet, if necessary**

All blade and root is below 200 MPa

CMT Rotor Worst Case Stresses

- **Worst Cases:**
  - **Vane**
    - **234 MPa @ 38 sec. into Cold Start**
  - **Bore**
    - **282 MPa @ 54 sec. into Cold Start**
  - **Back Wall**
    - **278 MPa @ Steady State**

CARES Model Results

SN 237 - 2001 Vintage Material

	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000000000747451		0.000001514190000		0.000001025080000	
Reliability	0.999999999252549	(9 nines)	0.999998485810000	(5 nines)	0.999998974920000	(5 nines)
Failure Rate	1337880343		660419		975534	

SN 282 - 2001 Vintage Material

	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000000032730000		0.000075857000000		0.000034566800000	
Reliability	0.999999967270000	(7 nines)	0.999924143000000	(4 nines)	0.999965433200000	(4 nines)
Failure Rate	30553009		13183		28929	

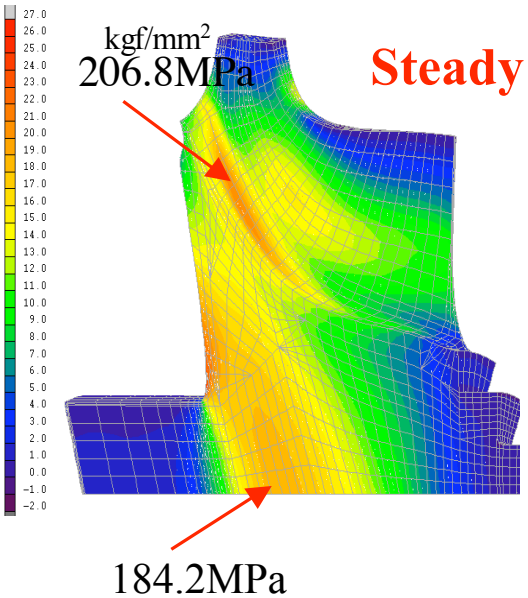
AS 800 - 1995 Vintage Material

	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000000021028900		0.000017031300000		0.000008595400000	
Reliability	0.999999978971100	(7 nines)	0.999982968700000	(4 nines)	0.999991404600000	(5 nines)
Failure Rate	47553605		58715		116341	

NT 154 - 1989 Vintage Material

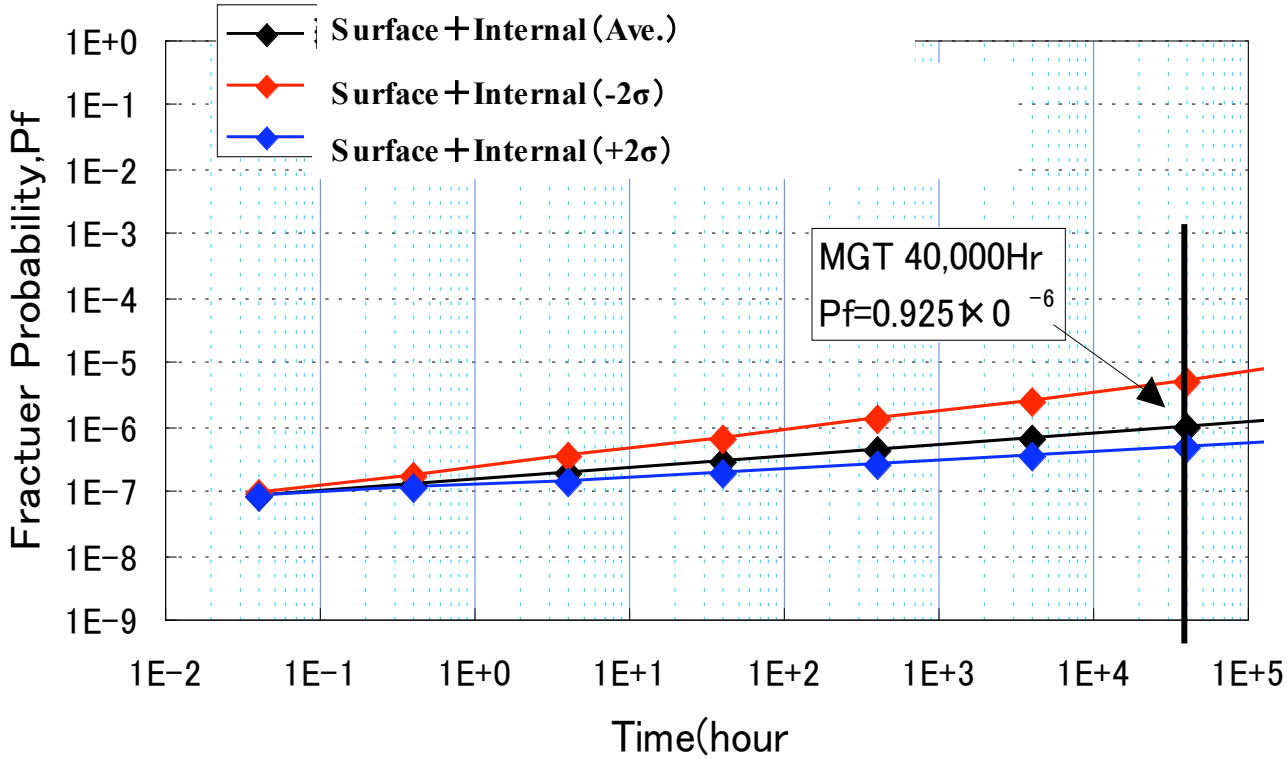
	Steady State		38 Seconds		54 Seconds	
Probability of Failure	0.000237266000000		0.011407100000000		0.008427090000000	
Reliability	0.999762734000000	(3 nines)	0.988592900000000	(1 nine)	0.991572910000000	(2 nines)
Failure Rate	4215		88		119	

Stress Analysis - Reliability Analysis



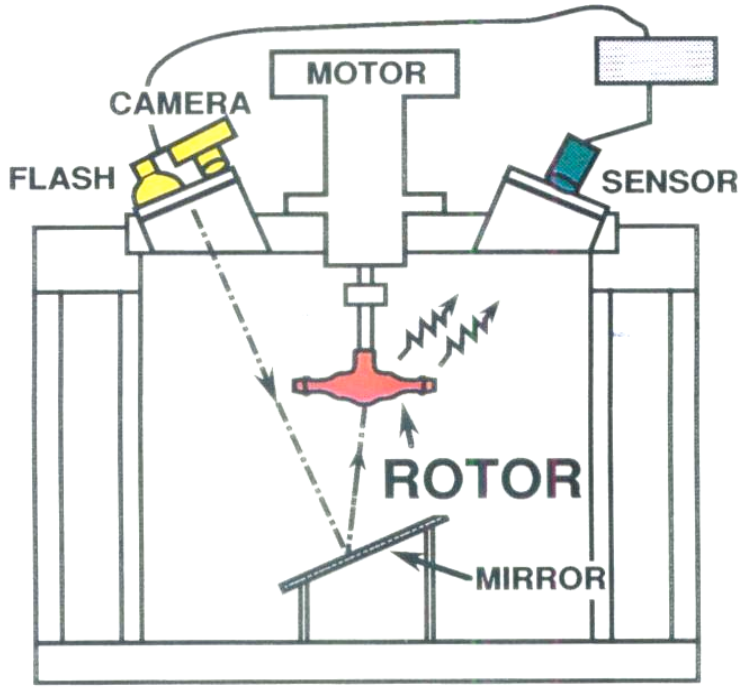
Steady State (97,500 rpm)

Fracture Probability of Rotor(SN237)

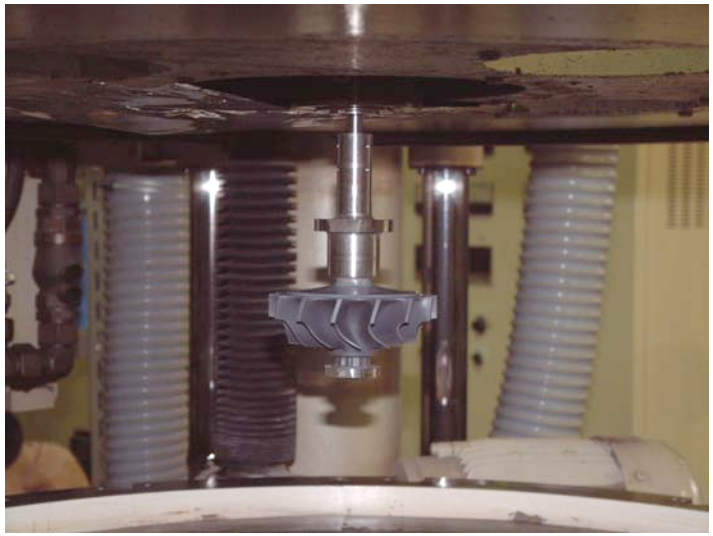


Component Evaluation Development

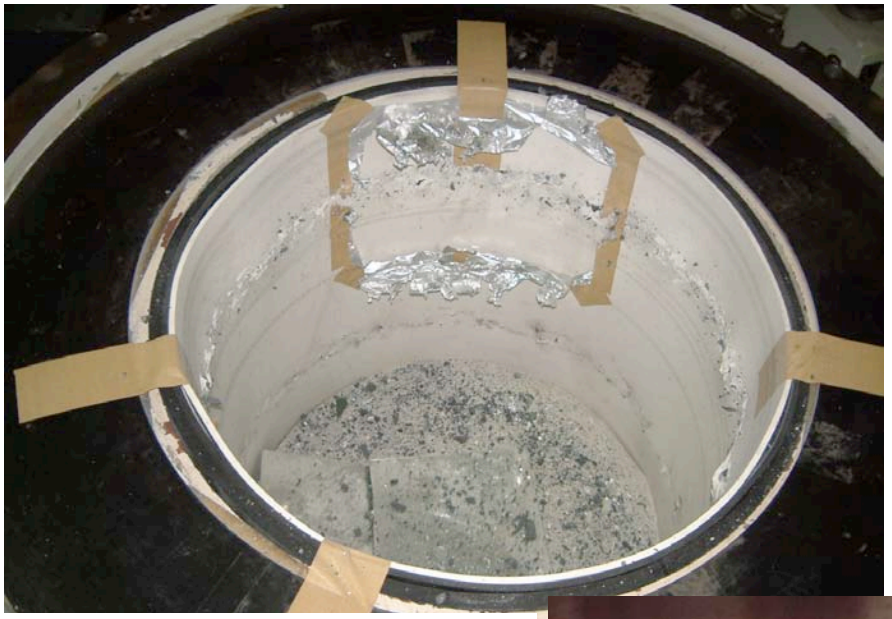
Cold spin test equipment



Cold spin system

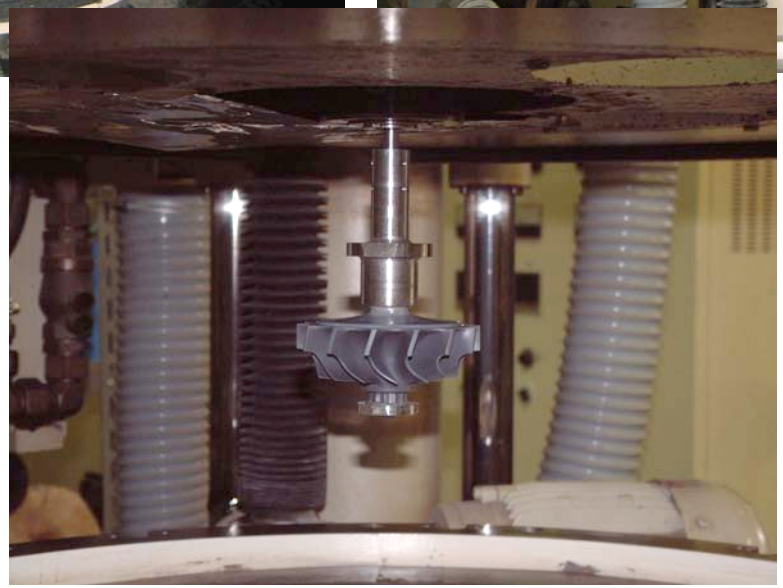


SN237 Rotor Fractured at 167,197 RPM



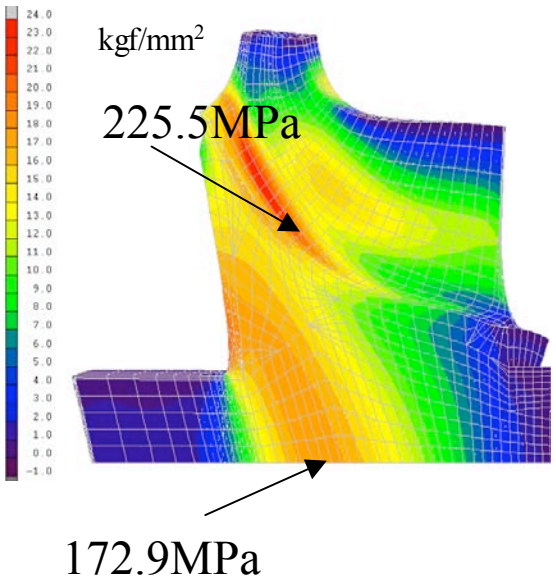
SN237 rotor fragments

Rotor-less spindle



Designed speed: 97,500 rpm

Rotor Cold Spin Test Results



Room temperature, Material :SN237

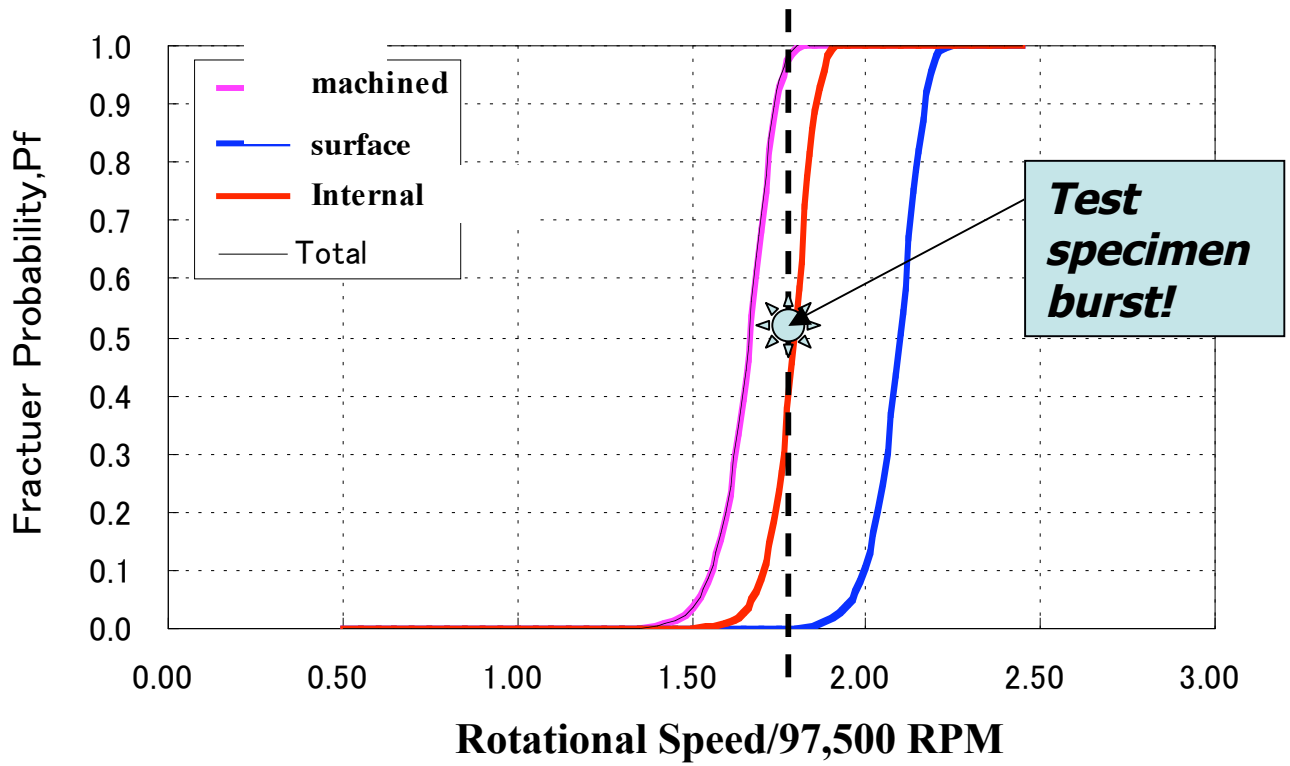
Design Speed :97,500rpm

Burst Speed = 167,197 (sample #1)

Burst Speed ratio = 171% (Burst/Design)

Burst Stress factor (N^2) = 2.9

Fracture Probability of Rotor(SN237)



IRES internal business decision terminated the microturbine field demonstration

Summary

- Advanced silicon nitride components provide low emission, high efficiency, and fuel flexibility for distributed energy applications.
- Integrated efforts on database generation, probabilistic design, and life prediction are required prior to the final field applications/demonstrations.
- Various successful gas turbine field demonstrations have been achieved. However, higher toughness Si_3N_4 ceramic is needed to overcome the issue of foreign object damage (FOD) introduced failure.
- Field tests showed that substantial material recession in gas turbine environments would limit the long-term reliability and lifetime. Environmental barrier coating (EBC) thus is needed to protect components from environments and achieve designed lifetime performance.
- The FOD and material recession may not be the critical issues for microturbine systems due to its relatively closed system and lower operation conditions.