Ceramic MicroTurbine Program by Ingersoll-Rand Energy Systems

MicroTurbine and Industrial Gas Turbine - Peer Review

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Climate Control

Industrial Productivity

Security and Safety

Infrastructure

IR PowerWorks

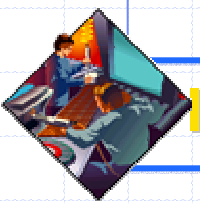
IR: A Diversified Industrial Company

Climate Control

- Transport refrigeration
- Display cases

Infrastructure

- Compact equipment
- Road pavers and compactors
- Drills
- Portable Compressors
- Golf cars and utility vehicles



Industrial Solutions

- Stationary air compressors
- Bearings
- Industrial tools and lifting equipment
- DG, Microturbines

Security and Safety

- Locks
- Exit devices
- Steel doors
- Electronic access control systems

Market Leading Brands

Climate Control

Thermo King, Hussmann

Infrastructure

Ingersoll-Rand, Bobcat, Blaw-Knox, Club Car

Industrial Solutions

Torrington, ARO, IR ASG, PowerWorks

Security and Safety

Schlage, Von Duprin, Steelcraft

PowerWorks™ Specifications

- 70kWe model
- Has 140% peaking power capacity on cold days (98 kWe)
- High efficiency
  - 30+% LHV electric
  - Up to 80% total with cogen
- Built-in heat recovery with modulation capability
- Integrated gas booster, option
- Low emissions<5 ppmv NOx @ 15% ex.O2 (natural gas)
- Noise ~ 70 dba @1 m
- Remote monitoring
- 8,000 hour maintenance interval
- Up to 80,000 hour engine life
- Leasing through IR available
- IR service contract

PowerWorks 70 kW Microturbine

Patented Recuperator/Combustor

- Critical to high efficiency
- Designed for 80,000 hour engine life

Efficiency

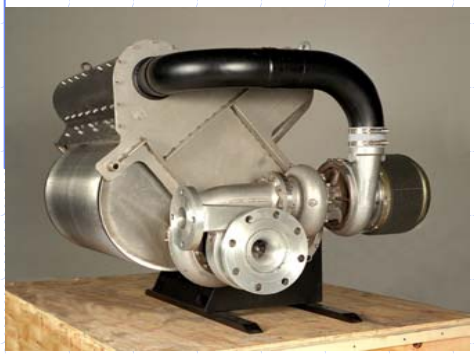
- Electric - 31% demonstrated
- Up to 80% with cogeneration

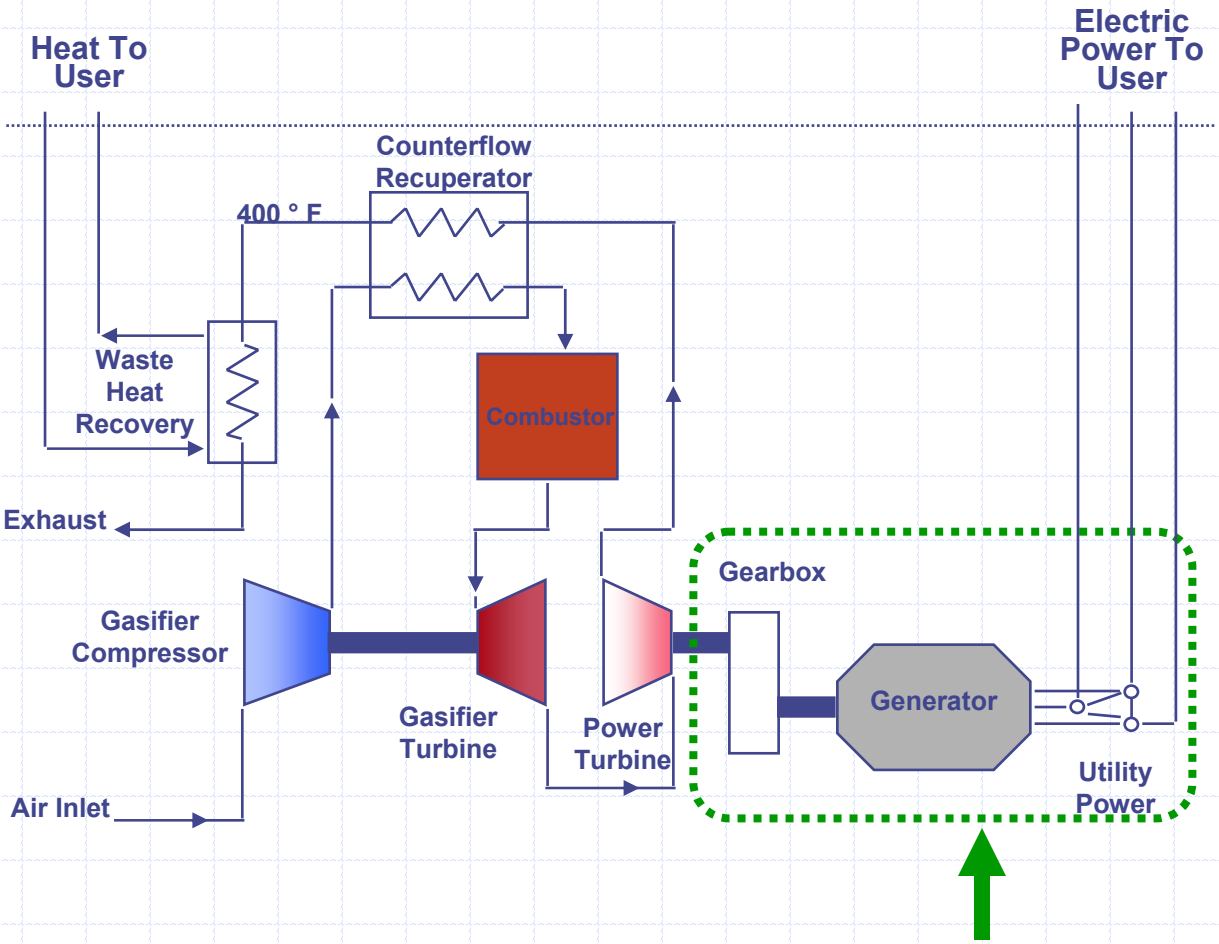
Low Emissions

- Easily meets California standards

Market leading efficiency

PowerWorks™ - Cogen





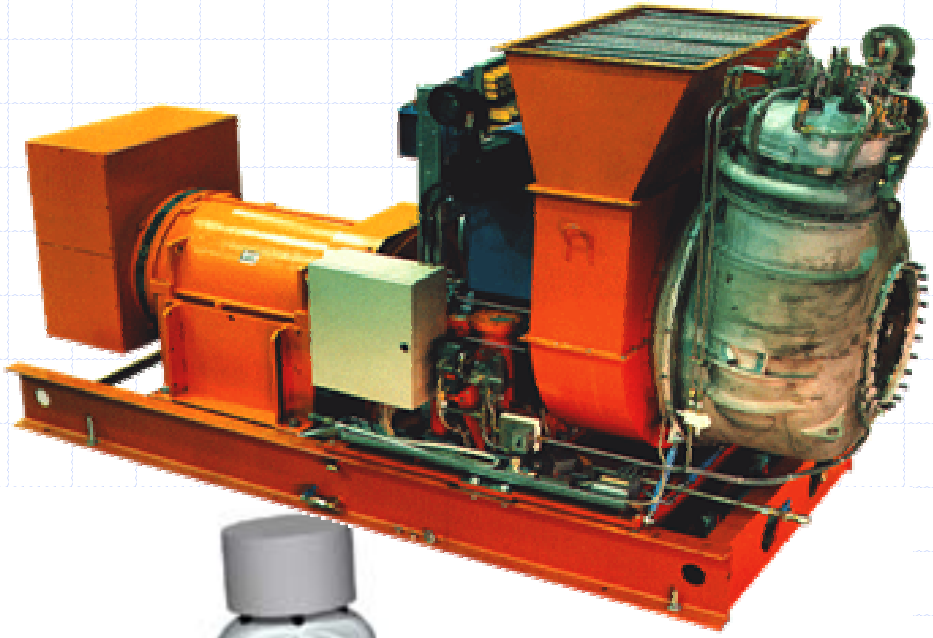
Shaft Power Loads

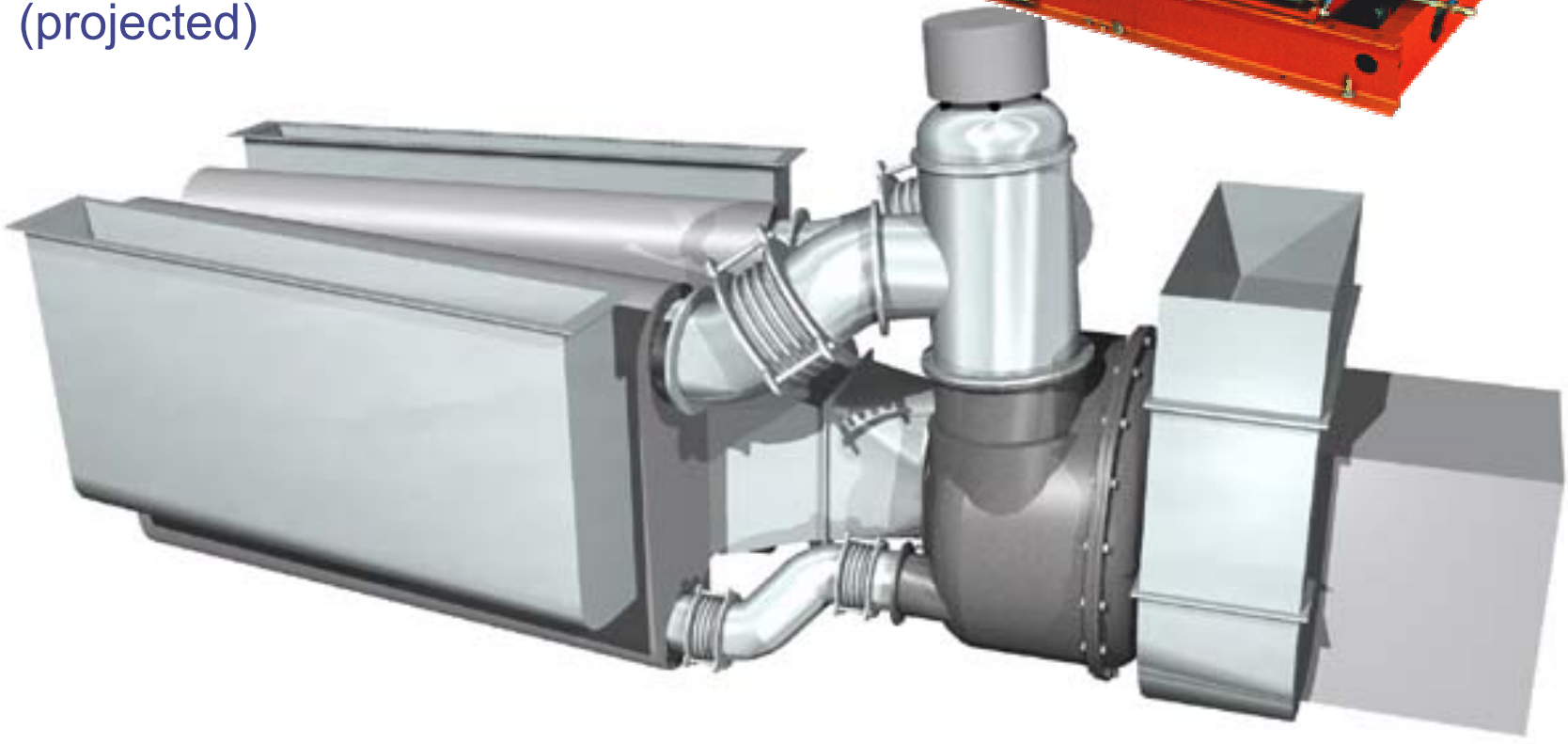
- *Generators*
- *Chiller compressor*
- *Screw compressor*

PowerWorks

Dresser-Rand KG2 - 1.7 MW

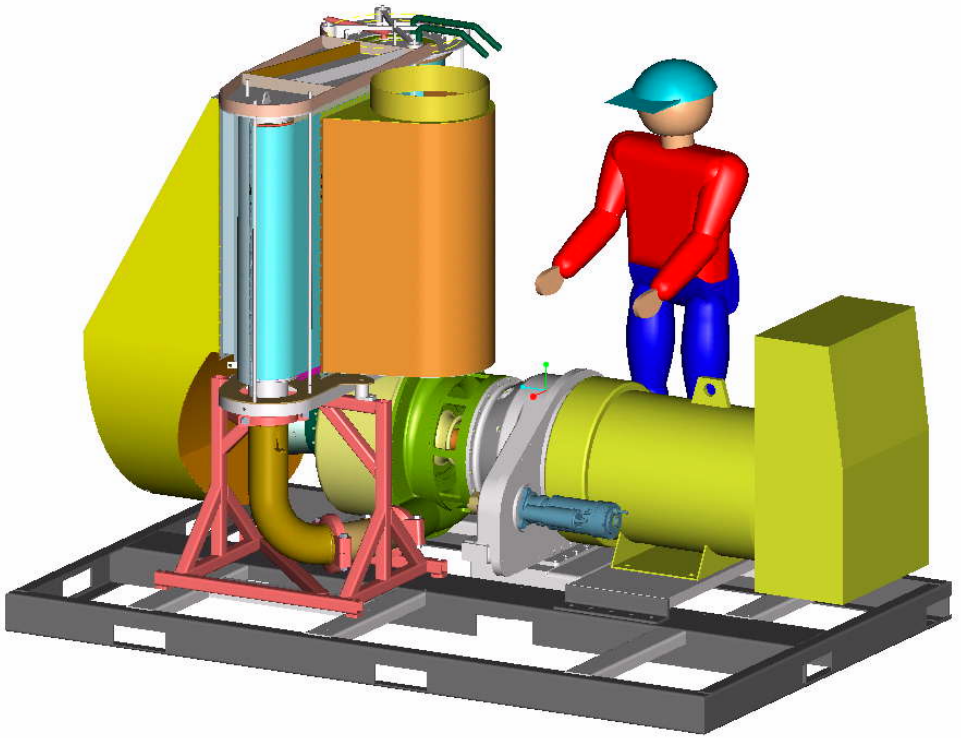
- Exceptional reliability (over 1000 units in the field)
- Single shaft, radial design
- Recuperated Efficiency >35% (projected)



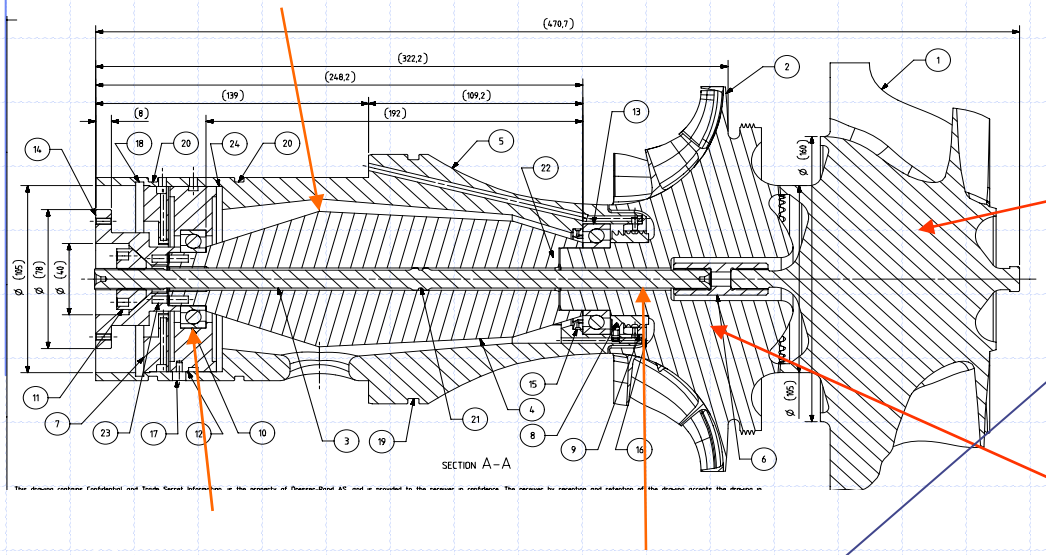


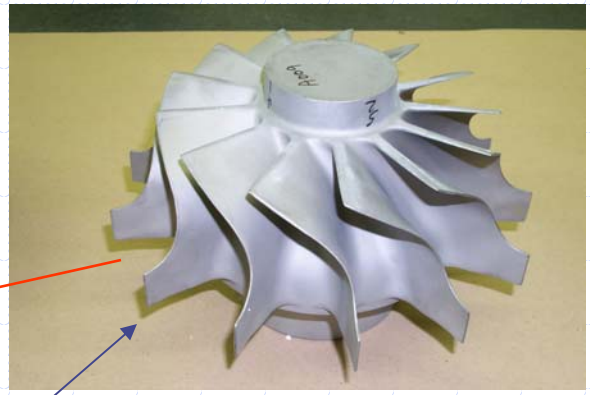
Frame 4 - 250 kW PowerWorks™

- 250kW Unit- scaled from Dresser-Rand Kongsberg KG2
- Single Frame 4 recuperator core
- 33% target efficien
- Beginning testing in 20



Core Engine Rotor Assembly





Turbine rotor 250 mm
too large for today's ceramics

Ingersoll-Rand Recuperator

Advanced Recuperator Design

- ***Three models offered to industry***
- ***Customers:***
  - ***Northrop Grumman/Rolls Royce***
  - ***TurboMeca***
  - ***Kawasaki Heavy Industries***
  - ***GE/Honeywell (LV100)***

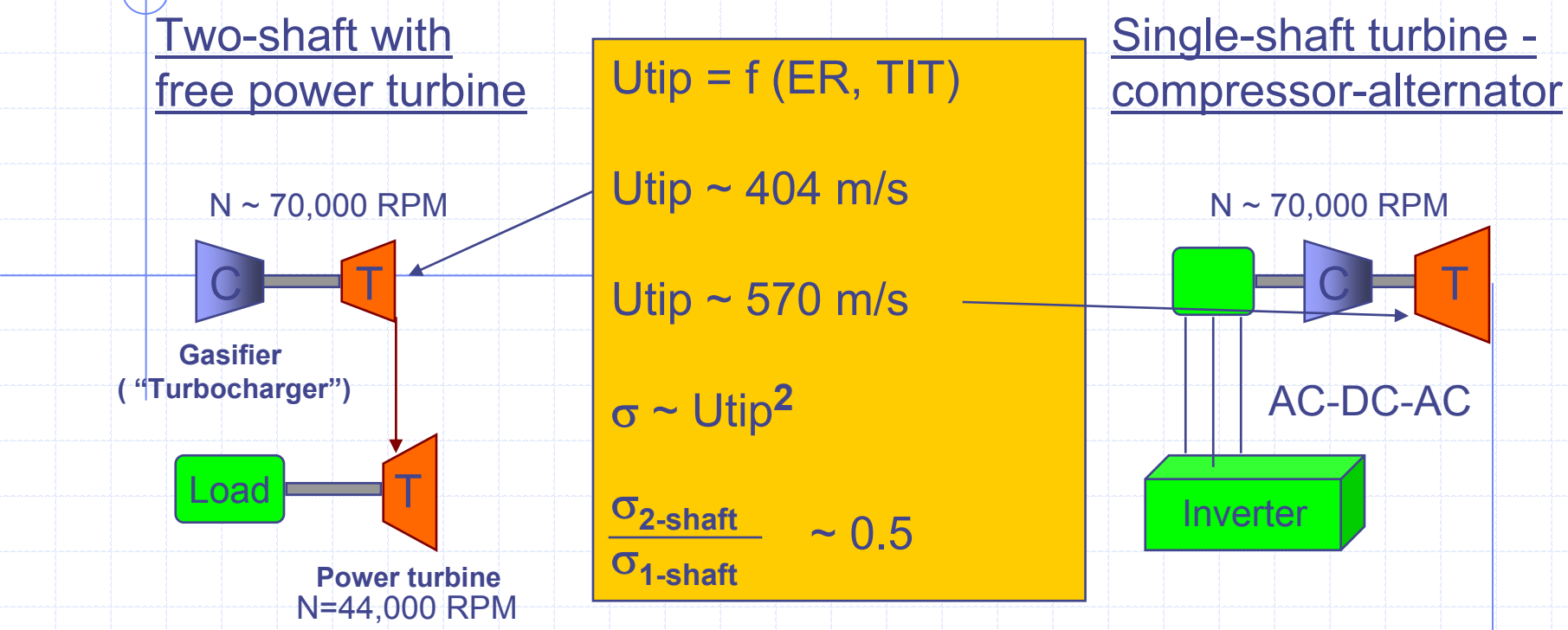
Ingersoll-Rand's **Ceramic** Microturbine Plan

- Follow a low risk development path that will yield significant performance increase for PowerWorks products in 2003
  - 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, including recuperator.

PowerWorks 70 kWe (Frame 3) is adaptable to today's ceramic rotor technology

- Silicon Nitride turbine rotors are currently in high volume production for the turbocharger industry
  - up to 20,000 /mo.
  - Moderate temp and stress
- Two shaft turbine helps keep (ceramic) rotor stresses manageable (roughly half that required for single shaft)

Two-Shaft Vs Single-Shaft Small Gas Turbine
(70 kW Example)



Load
- generator
- gearbox option
- centrifugal compressor
- pumps and other

Load
- shaft speed alternator, inverter

Two cases analyzed:

"Case 4" -

- Retain existing turbocharger/gasifier section (with SiN rotor)
- TIT limited by "super alloy" recuperator,

"Case 6" -

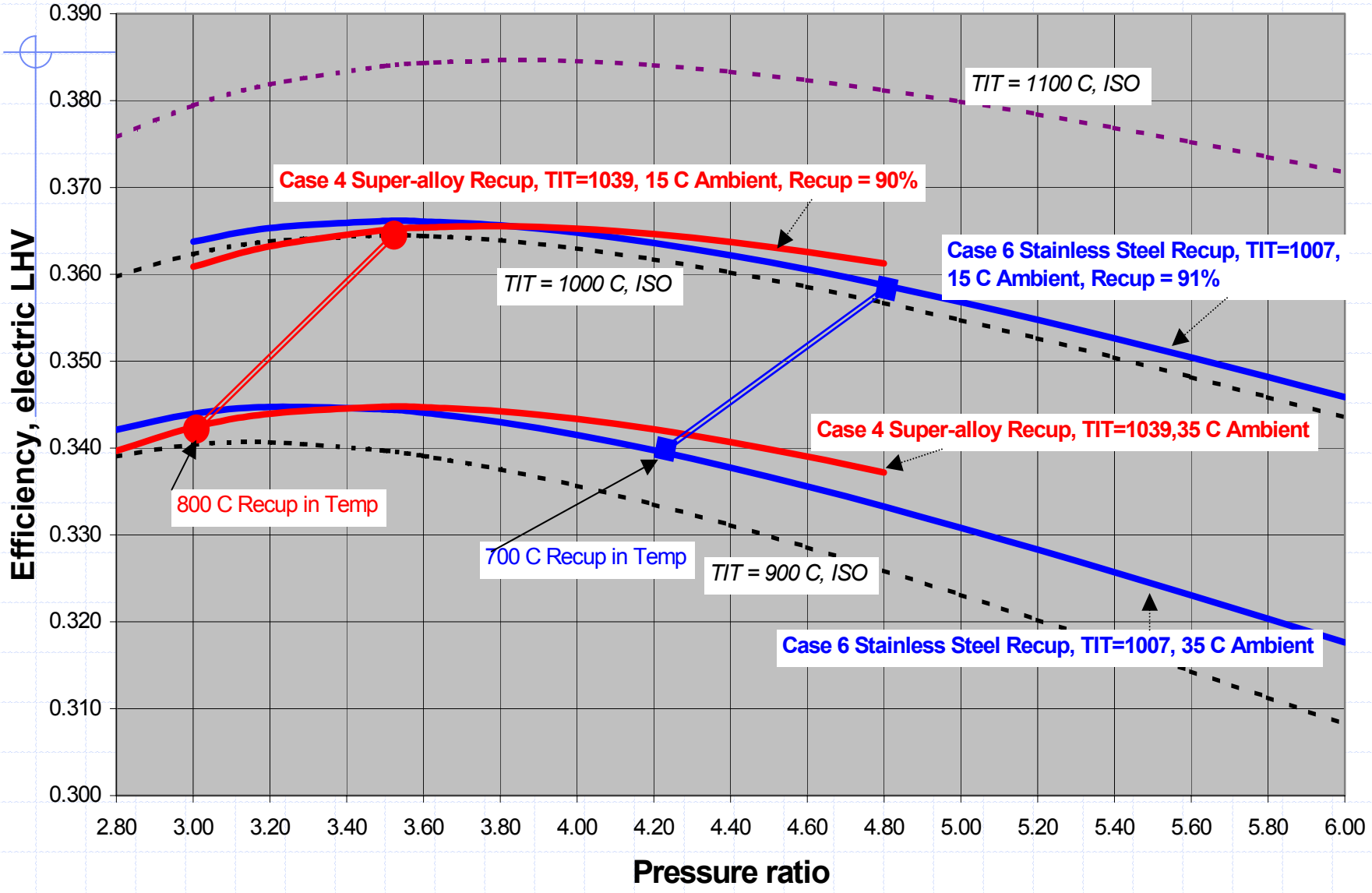
- TIT limited by stainless steel recuperator -
- Custom high pressure ration turbocharger

Preliminary Ceramic Rotor Design- case study

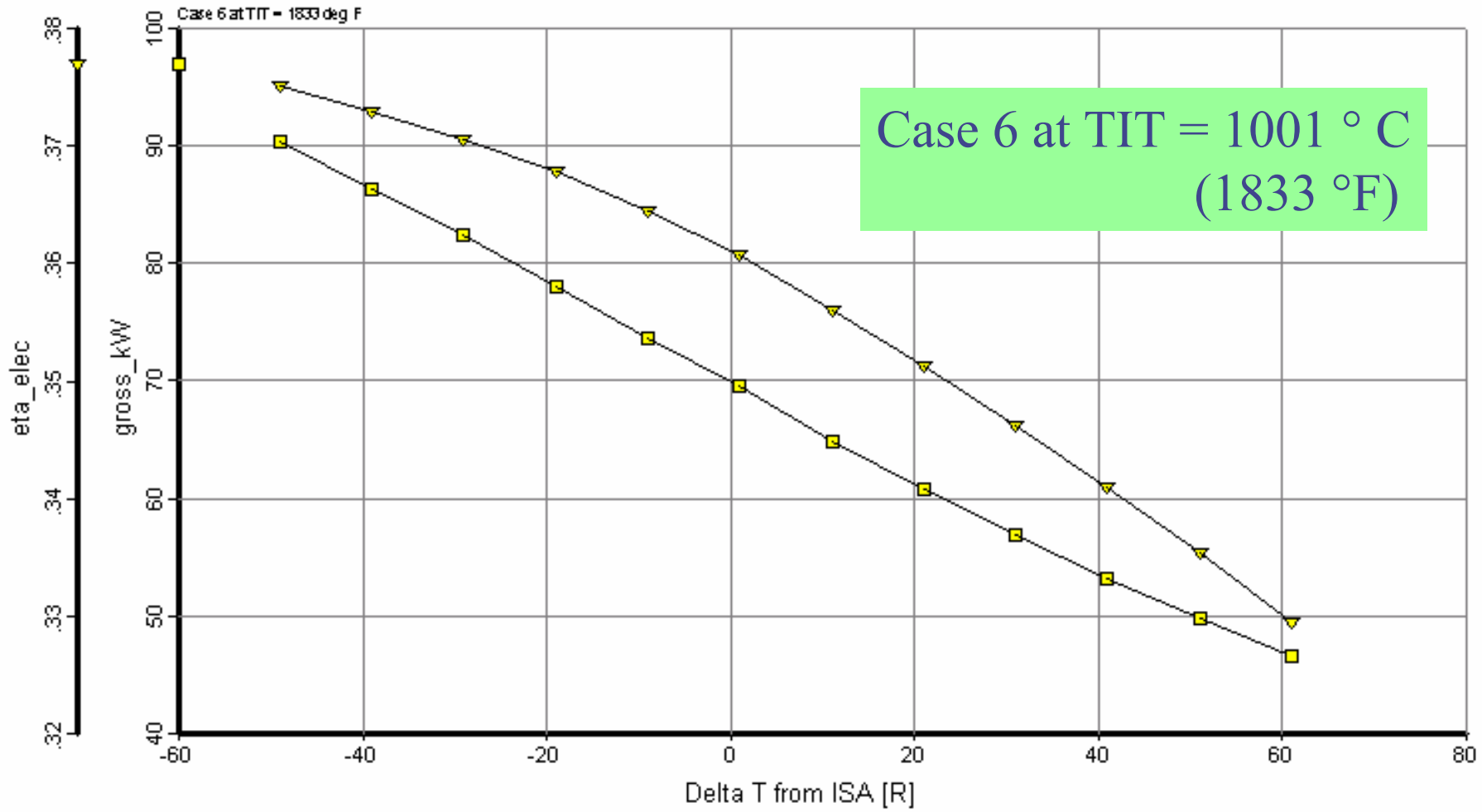
	Case 4	Case 6
Turbine inlet Temp, °C	1039	1006
Recuperator inlet Temp (at 35 °C ambient)	800	700
Pressure ratio at ISO	3.5	4.8
Ceramic rotor diameter, mm	95	95
Efficiency, LHV electric	0.370	0.359
Max stress, MPa	208	160
Rotor max temp °C(at inlet)	961	904

PowerWorks

Ceramic Turbine Cycle Analysis

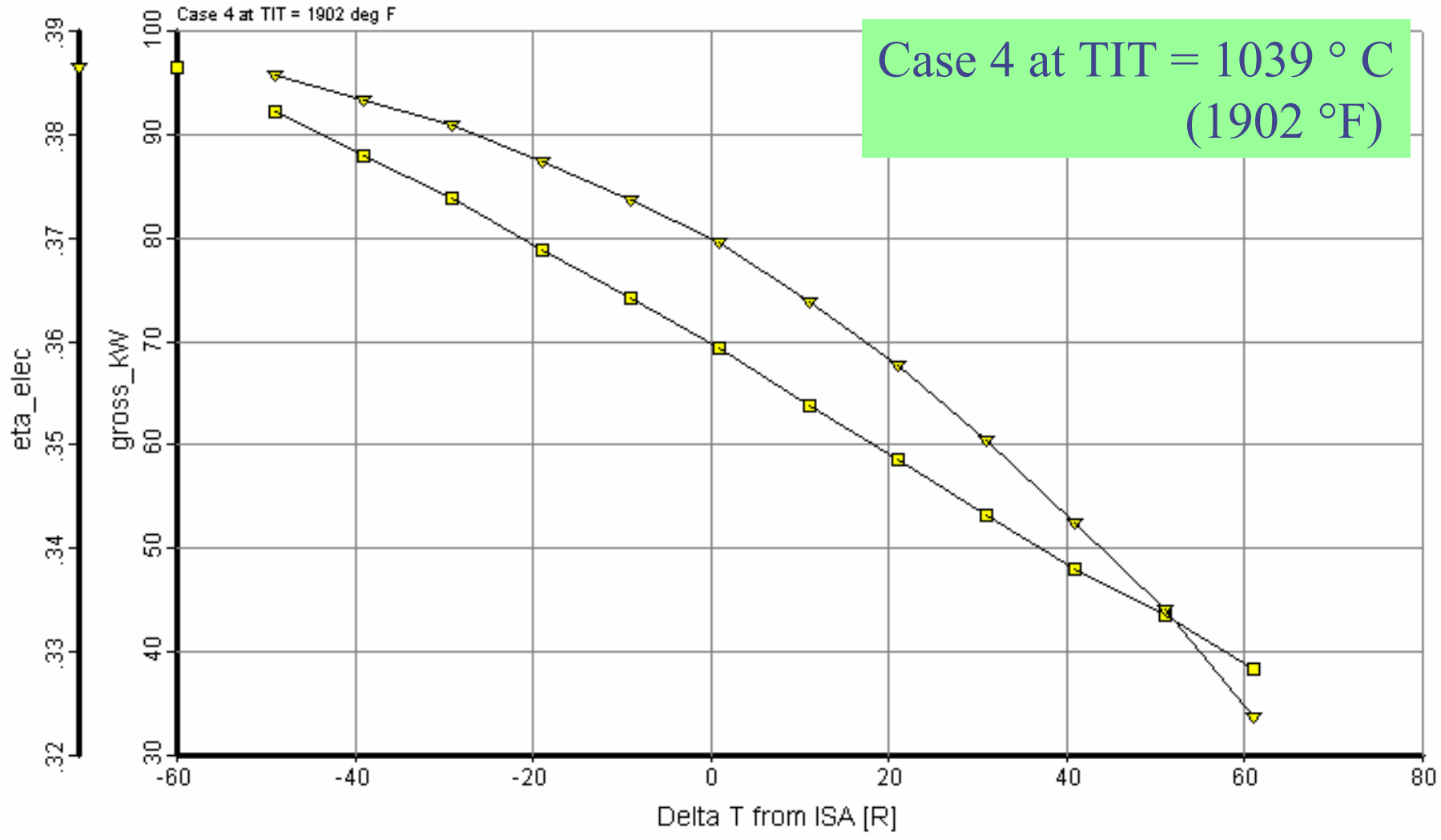


PowerWorks CMT - Case 6



Case 6 at TIT = 1001 ° C
(1833 °F)

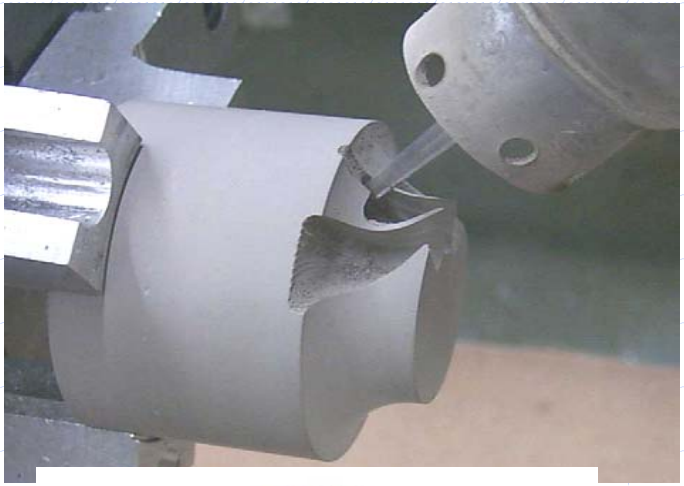
PowerWorks CMT Case 4



Case 4 at TIT = 1039 ° C (1902 °F)

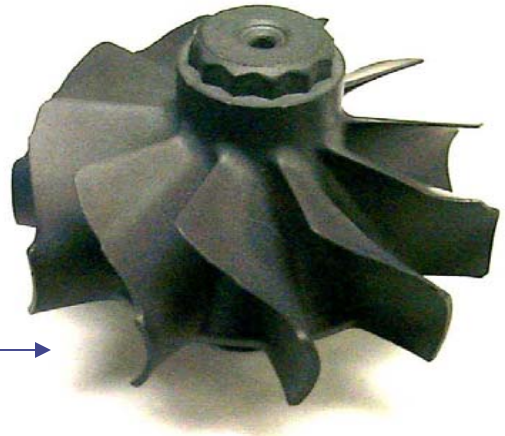
IR/NREC has worked with Kyocera since 1999

- *Performing feasibility machining trials of various "green" bisque ceramics*



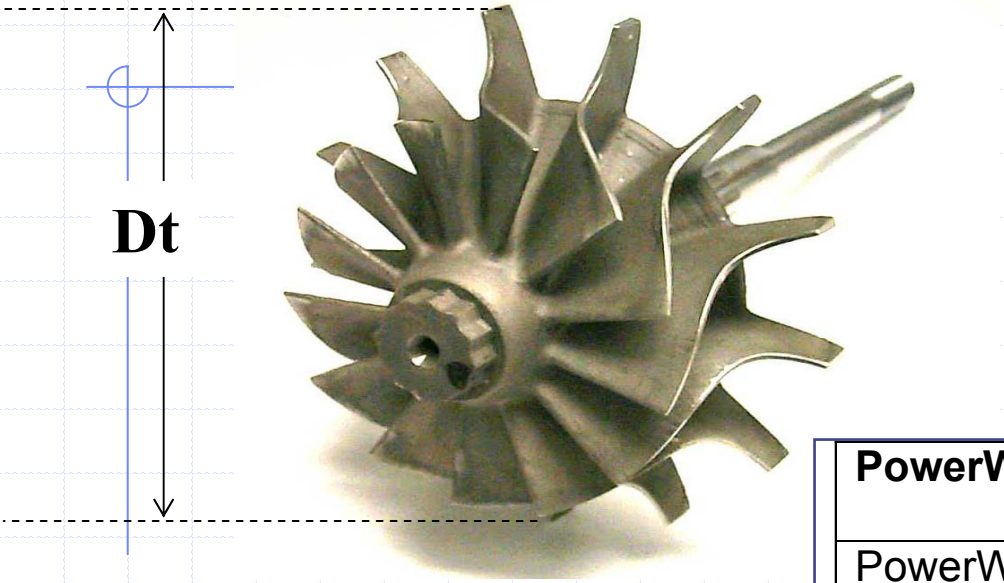
- *IR/NREC has worked with Schwitzer and IHI throughout the PowerWorks program.*

- *Kyocera rotor - designed for Schwitzer in 1990's*



We prefer to demonstrate production-like manufacturing methods, rather than quick prototyping (bisque machining)

PowerWorks



Dimensional comparison of ceramic turbine candidates

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

PowerWorks

Ceramic rotor design:

- Recession and environmental effects
- Aerodynamic analysis
  - Constrained by special ceramic design rules
- Finite element analysis
  - Ceramic design rules
- Surface temperature prediction
- CARES life prediction model
- Mechanical interface

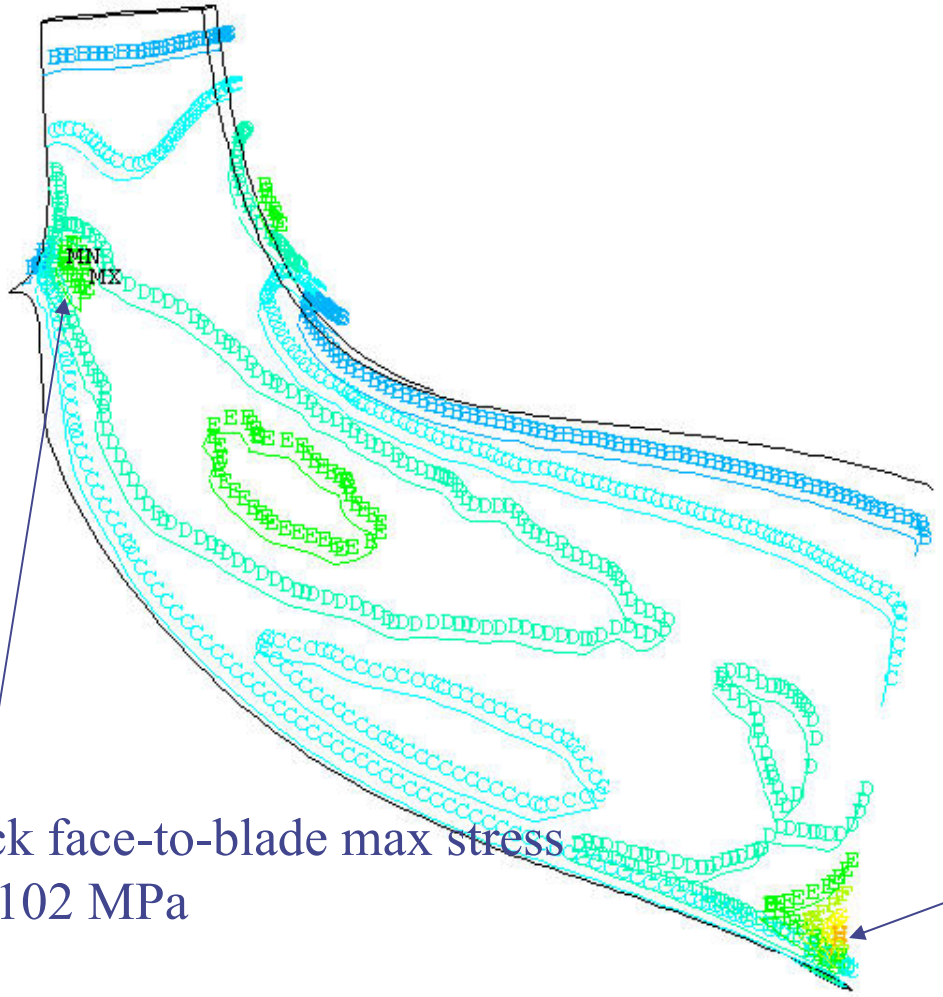
IR PowerWorks

Special ceramic design issues have been Implemented into IR design process:

- Ceramic turbine designed for durability and low cost manufacturing
  - Blade thickness allowable
  - Mold pull-ability in single piece
  - CARES "kv" coefficient to establish stress/temperature allowables
  - Shaft attachment - maximum temperature
  - Turbine hub nut for torqueing rotor group; method, geometry, and limits

Case 4 - Low pressure ratio (PRc=3.5) with Super-alloy Recuperator

Gasifier Turbine D=95-mm. The stress distribution at 88,700 rpm (rated power) TIT = 1019 C

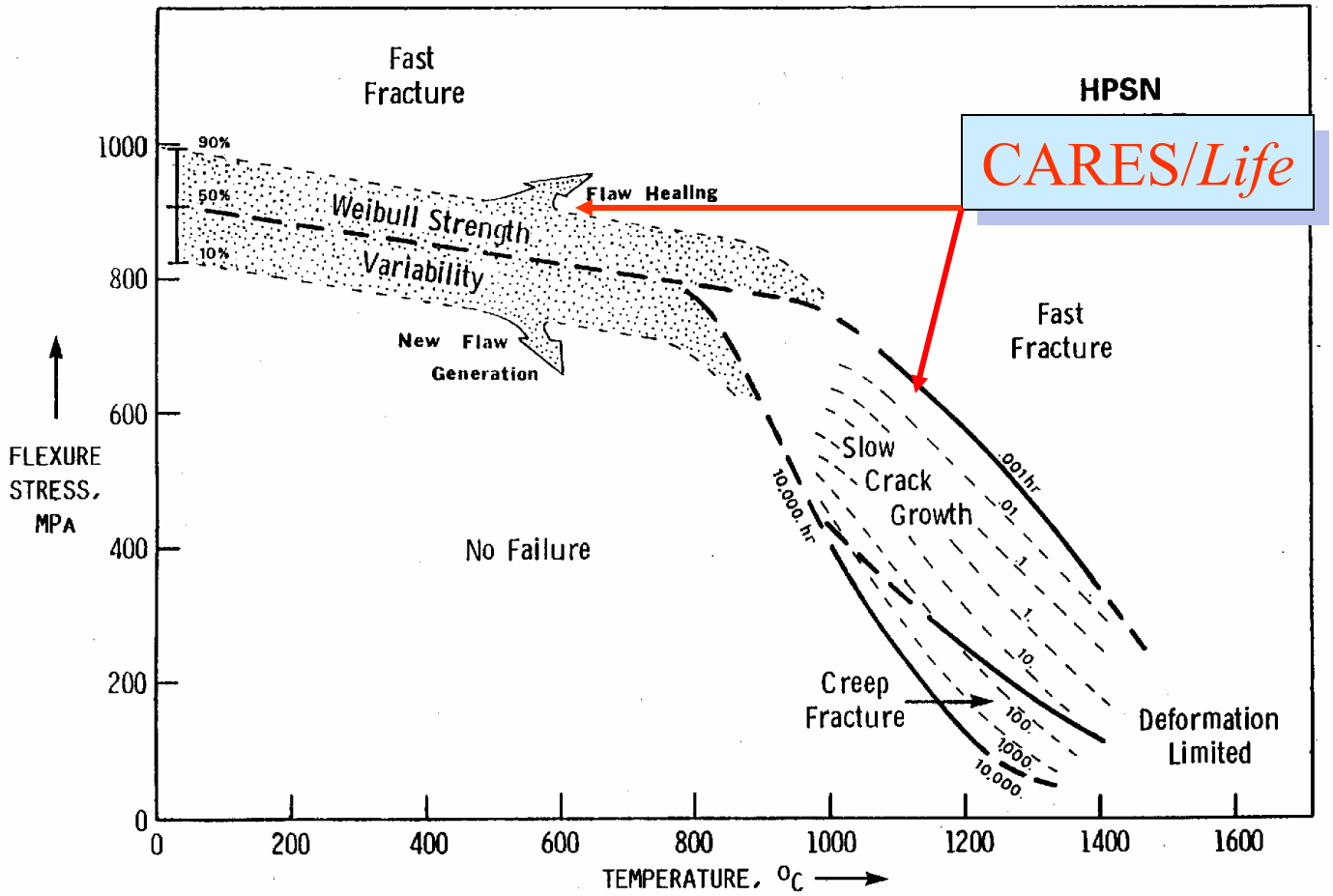


16:24:49
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
S1 (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.296E-03
SMN =-3829
SMX =45407
A =-1094
B =4377
C =9848
D =15318
E =20789
F =26260
G =31730
H =37201
I =42672

Back face-to-blade max stress = 102 MPa

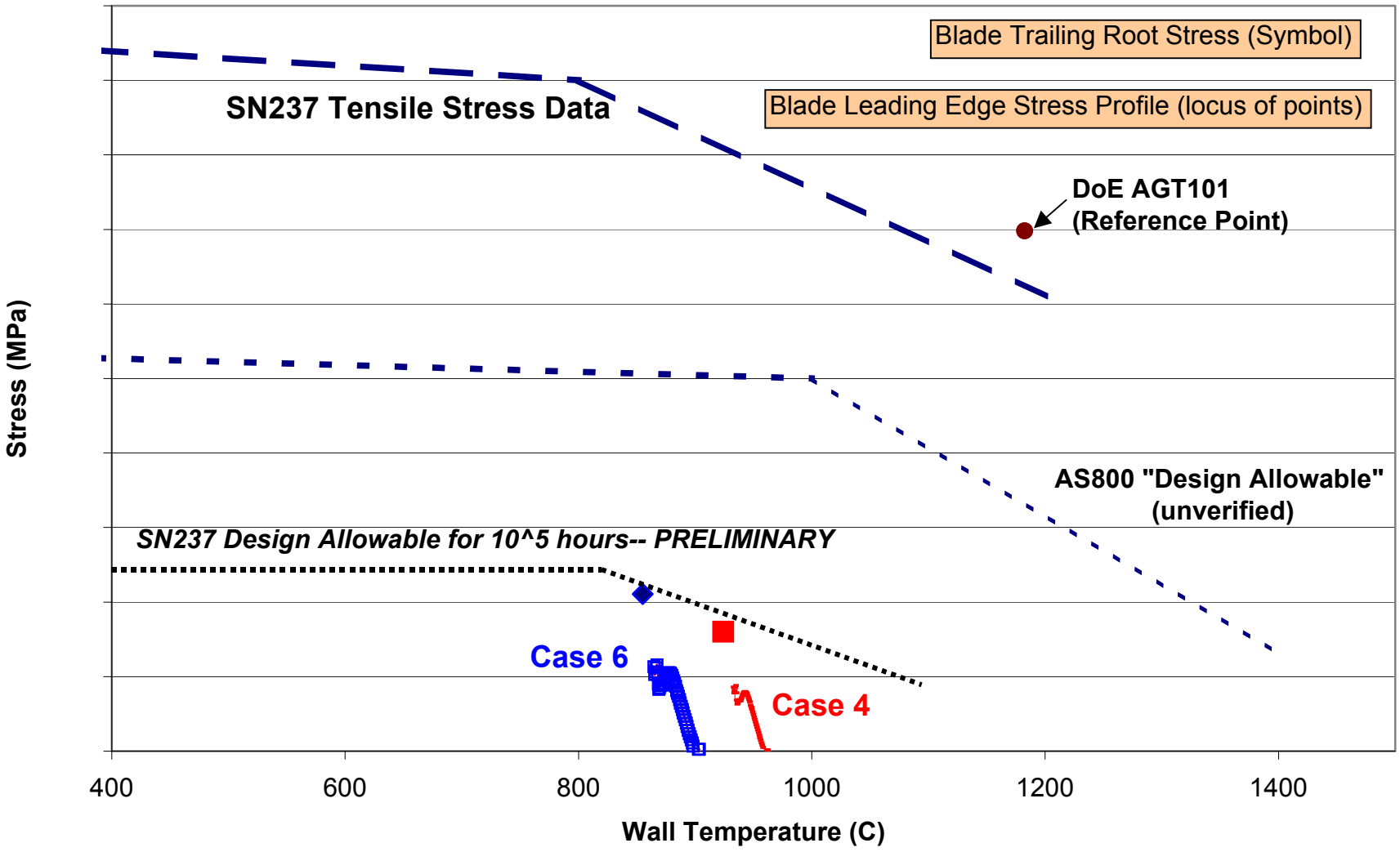
Peak Stress =150 MPa

Strength and Failure Mechanisms in Ceramics



*G. D. Quinn, Journal of Material Science, 1990.

Ceramic Rotor Design and Material Allowables



Blade Recession Analysis

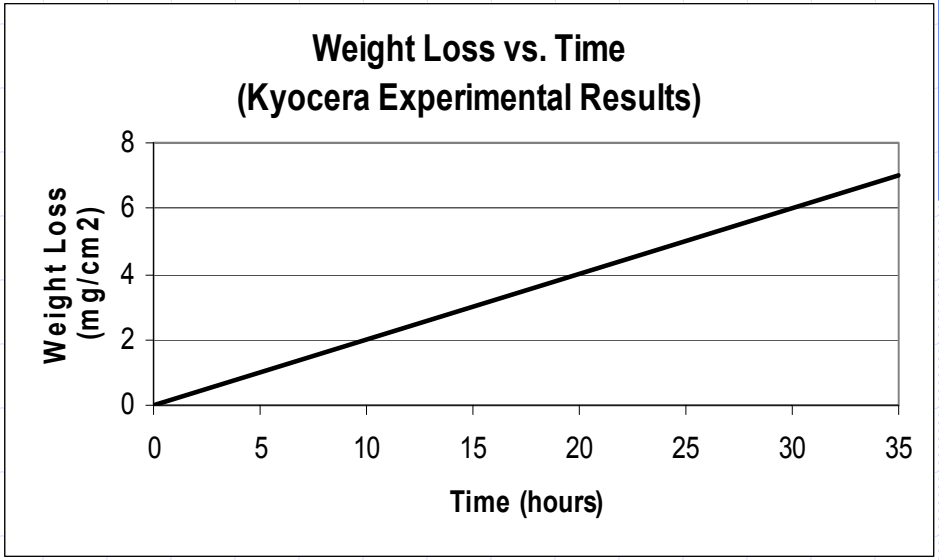
- Initial Ingersoll-Rand Recession Model based on Oak Ridge National Laboratory/NASA Results for SiC:

$$Recession\ Rate\left(\frac{\mu m}{hr}\right) = 512\exp\left(\frac{-108}{RT}\right) v^{0.5}\ \frac{P_{H_2O}^{2.0}}{P_{total}^{0.5}}$$

- All SN237 data in analyses is considered

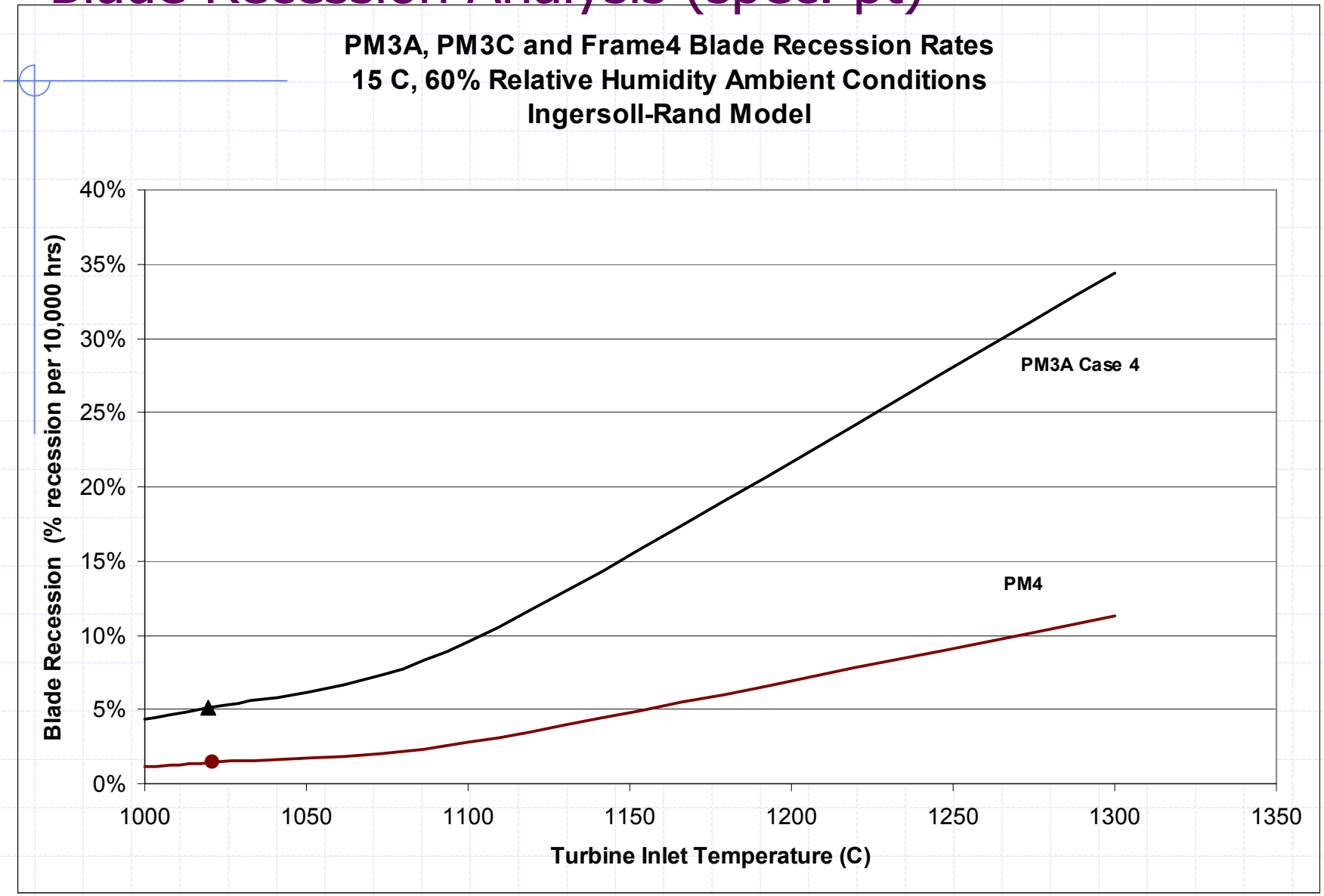
Comparison of Test Results to Model

- For Kyocera's conditions:
  - Temperature = 1250 °C
  - Velocity = 110 m/s
  - P_{total} = 1.5 MPa
  - P_{H2O} = 120 kPa
  - P_{O2} = 200 kPa

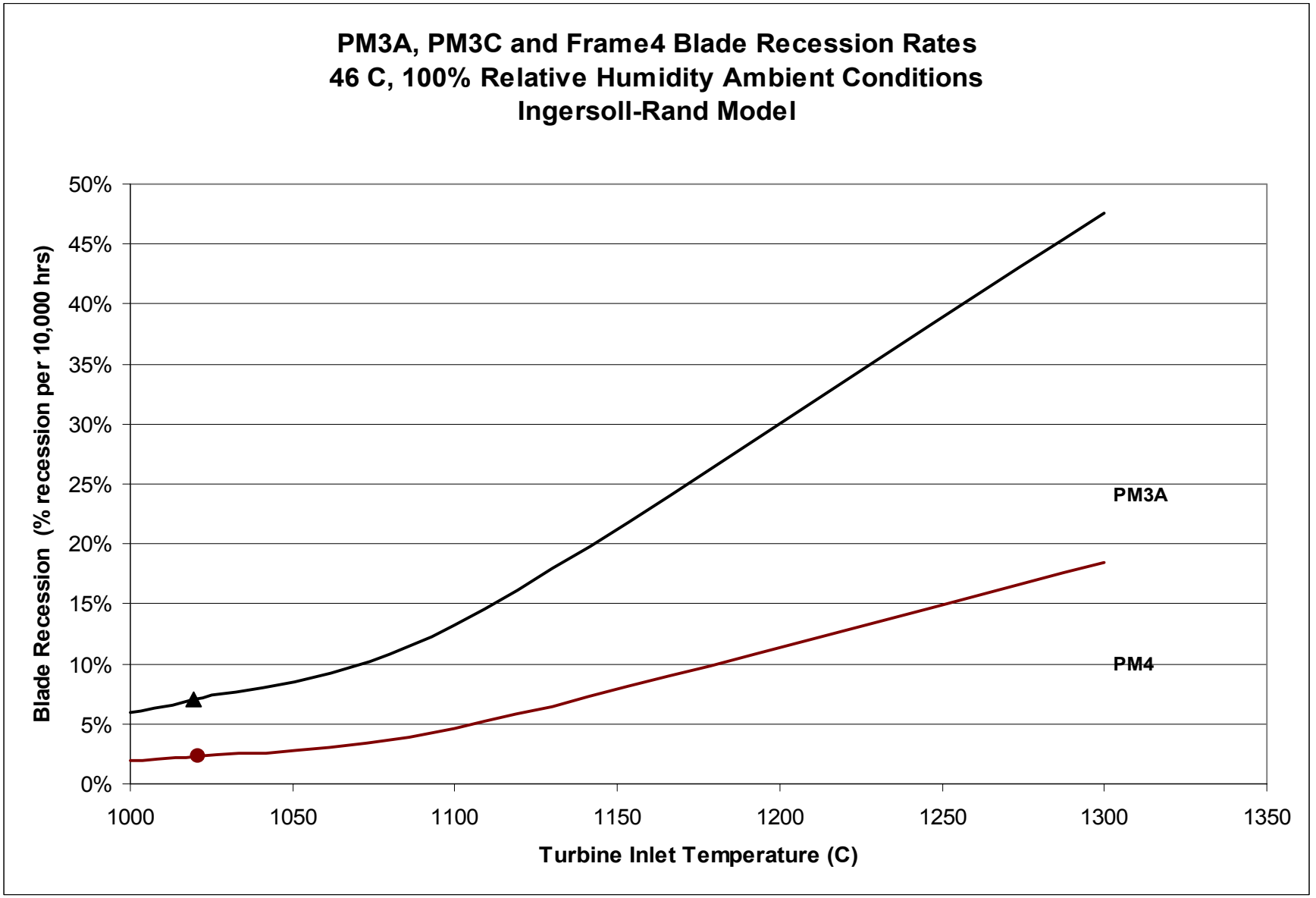


- After 30 hours, a 6-7 mg/cm^2 weight reduction was measured; this corresponds to a ~25 μm recession (based on density data provided for SN237)
- The IR model, for the same conditions used by Kyocera, predicts an 8.9-11.7 μm recession after 30 hours (depending on the adiabatic wall temperature of the tested sample)

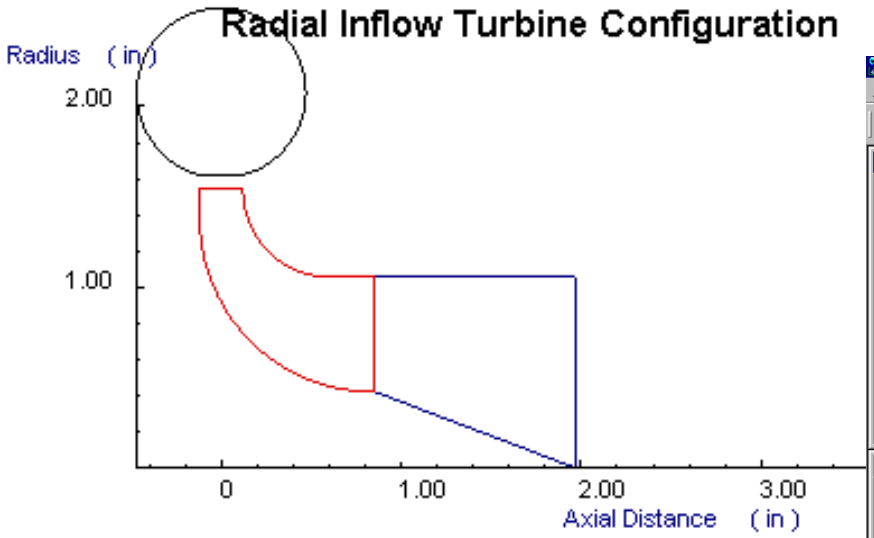
Blade Recession Analysis (spec. pt)

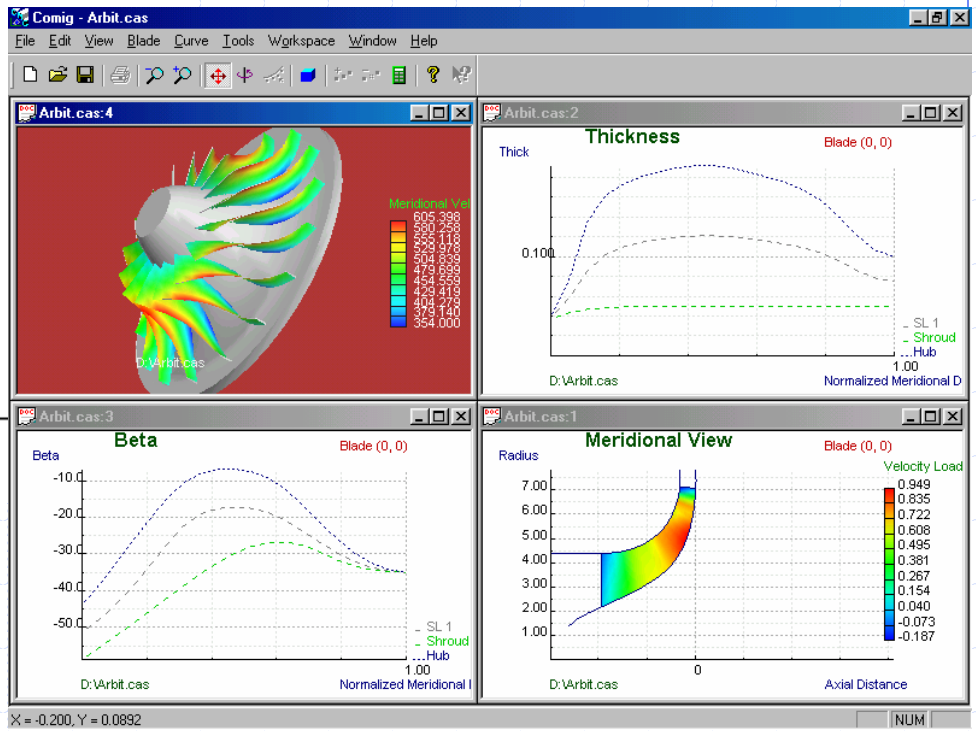


Blade Recession Analysis (worst case)



Mechanical and Aerodynamic Details of Ceramic Turbine - RITDAP™ Analysis





TURBINE DESIGN STATE POINT:

Mass Flow Rate = 0.414 kg/s
Inlet Total Temperature = 1007
Expansion Ratio = 2.1
Shaft Speed = 98,600 rpm

Aero design details

Turbine total-to-total efficiency = 0.83

COMPONENT EFFICIENCY DECREMENTS

SCROLL + VLS	0.06118
ROTOR TOTAL	0.09917
DIFFUSER (DIFFUSER + DISCHARGE)	0.02817

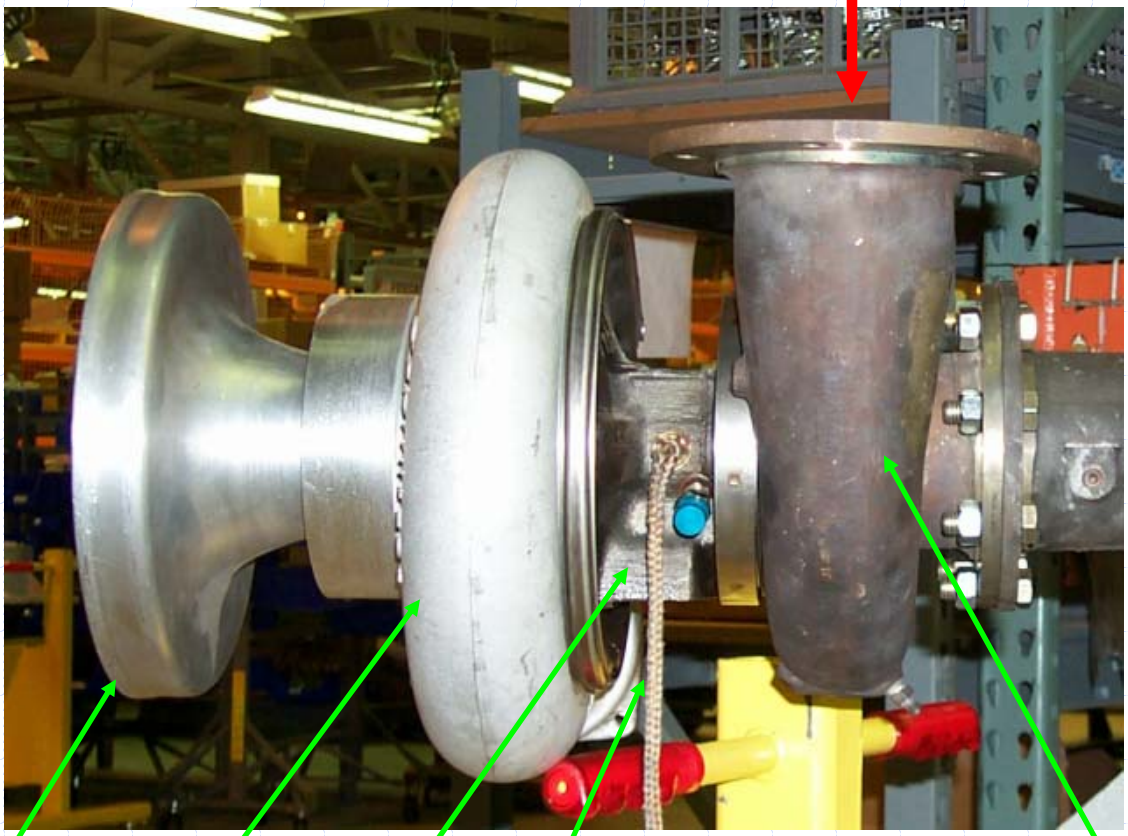
BREAKDOWN OF EFFICIENCY DECREMENTS

SCROLL FRICTION	0.05791
ROTOR INLET VANELESS SPACE FRICTION	0.00327
ROTOR FRICTION	0.00587
ROTOR LOADING	0.07637
ROTOR CLEARANCE	0.01686
ROTOR INCIDENCE	0.75821E-04
DIFFUSER	0.00311
DISCHARGE	0.02506
DISC FRICTION (WINDAGE)	0.00317

APPROXIMATE 0.5% efficiency decrement per each blade removed

PowerWorks 70KW Gasifier

Assembly Overview



CMT Development schedule

Task / Month	3/02	4	5	6	7	8	9	10	11	12	1/03	2	3
Rotor (95-mm) FEA -complete analysis													
Turbine housing design													
Design and make rotor tooling													
Fabricate turbine hoiusing													
Fabrication, rotor & shaft attachment													
Section and test sample rotors at ORNL													
Full Engine Test													