FINAL REPORT

November 8, 2005

DoE Advanced Ceramic Microturbine

Report Prepared for

U.S. Department of Energy
National Energy Technology Laboratory
Attn: Donald W. Geiling
3610 Collins Ferry Road
Morgantown, WV 26507-0880

IR Energy Systems
30 New Hampshire Ave
Portsmouth, NH 03801

Project
"Cooperative Research and Development For Advanced Microturbine Systems"
Cooporative Agreement No. DE-FC2G-00CH-11059

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Table of Figures

Program Summary

In July 2001, Ingersoll-Rand began work on this program. Its objective was to introduce ceramic hot section components into the IR family of microturbines to permit higher operating temperatures and hence improved efficiency.

The IR microturbine product line combines a novel application of industrial turbocharger equipment, our commercially successful recuperator, and proven industrial gas turbine design practices. The objective of the joint development program is to combine the high production success of the Si_3N_4 turbocharger rotors, largely from Japan, with the IR turbocharger-based microturbines.

The IR "Ceramic Microturbine" (CMT) program has been configured to use the most practical ceramic rotor, considering size, geometry, proven manufacturing methods, and physical material limitations. Performance predictions indicate that 36% LHV electric conversion efficiency could be attained at a Turbine Inlet Temperature (TIT) of nominally 1000°C. The initial 72kW engine is being designed to have comparable life and costs to our current product. The package power rating is expandable to 100kW with this equipment by slightly increasing pressure ratio flow and TIT.

This program was initially planned as five major tasks. In Task 1 a comprehensive analysis of the state of the art ceramics and their applicability to microturbines was performed. Milestone 1 was achieved with the joint DoE/IR decision to concentrate on our 70kW microturbine, with elevated turbine inlet temperature and pressure ratio. This preserved the ability of the engine to utilize the standard IR recuperator and the majority of the microturbine subassemblies. A commercialization report, projecting the market size, was also completed as part of this task.

Task 2's detailed design of the special hot-section components has been completed. The two critical milestones, #3 and #4, associated with the detailed design of the monolithic silicon nitride turbine rotor and the release of the purchase order for this critical component were accomplished in Task 2.

Task 3 focused on the design and release of the other non-ceramic components, including the gas generator turbine housing, the power turbine and housing, the combustor, and a new compressor section. On September 4, 2002, Milestone #4 was completed with a Detailed Design Review of the 72 kW "Ceramic Microturbine". The customer's concurrence at that design review triggered the release of critical components for manufacturing (Milestone 5).

In Task 4, the principle components of the CMT were fabricated and delivered to our Portsmouth facility. Manufacturing was mostly completed with the exception of the final machining of the GT and PT housings, the machining of the compressor diffuser, and the fabrication of the compressor cover.

However, at this point Ingersoll-Rand has mutually terminated the program with the Department of Energy (DoE). Although IR certainly agrees with the long-term performance benefits of incorporating ceramic technology into a microturbine engine, IR must meet today's market-critical requirements in order to

1.0 Technical Summary of Accomplishments

The principle elements of the Ceramic Microturbine (CMT) have been successfully designed and manufactured. The new components that distinguish the CMT from the standard 70kW microturbine are confined to the hot section of the engine, and summarized in Table 1.1.

Table 1.1: Summary of principal components CMT microturbine

Component	New CMT config	Status
Gas generator turbine rotor	Si_3N_4 processed SN237 by Kyocera	Complete, w/ assembly and balance
Gas generator turbine housing/nozzle-less	Investment cast IN718	Cast, but not machined
Gas generator bearing core	Borg-Warner model S400	complete, and assembled
Gas generator compressor impeller	Titanium (machined for prototype, cast for production)	Complete, w/assembly and balance
Gas generator compressor cover		Drawing complete, no fab
Power turbine rotor	IN713 LC (new aero shape)	Complete, with shaft assembly and machining
Power turbine Housing	Sand cast Hastalloy-X (new aero)	Castings received, not machined
Combustor	Hastalloy std construction, 6 in dia.	complete
Recup bottom flange	Sand Cast 304 L	Complete
Recuperator	Standard	Same operating temps
Balance of plant	Standard	

Figure 2.1 also displays the locus of points that define recuperator gas inlet temperatures of 700°C and 800°C. Testing has established that the Ingersoll-Rand recuperator fabricated from an austenitic stainless steel should be operated below 700°C to achieve long life. The intention is to operate the CMT so as to maintain recuperator inlet temperatures in the vicinity of 650°C or below.

The cycle analysis and definition of thermodynamic state points leads to the specifications for the new gas generator turbine. The allowable operating temperature for the silicon nitride turbine material is dependent upon the stress level and oxidation ("recession") limits. Analysis to support the life goals will be presented later in this report. The general experience to date indicates that the material candidates are suitable for extended operation at temperatures up to at least 1100°C, however the final definition of turbine inlet temperature would be dictated by detailed probabilistic stress analysis (CARES) and recession life predictions.

2.2 Aerodynamic Analysis of Compressor and Turbine

The cycle analysis and gas generator specifications adequately frame the design requirements of the three aerodynamic components. The general design specifications for the three components are presented in Tables 2.1, 2.2, and 2.3.

Table 2.1: Gas Generator Compressor Specifications

Design Point ISO

Inlet Temp	T01	C	15.15
Inlet pressure, total	P01	kPA	101.3
Mass flow rate	Ma	kg/s	0.444
Compressor exit pressure –total	P02	kPA	483.9
Physical Speed	RPM		98347.0

Estimated design outputs (for guidance)

Compressor exit temp	T02	°C	216.0
Pressure ratio t-t			4.8
Compressor work	Wt	kW-s	90.5
Specific speed			0.765
Target diameter	mm		105.8
Target adiabatic efficiency, t-t			0.802

The compressor and turbines were designed using the well-proven Concepts/NREC software packages:

- PREDIG, - for centrifugal compressors; a 1-D preliminary design tool designed to predict the stage losses and optimize the selection of first order design parameters such as speed, blade dimensions, and state points
- COMIG® - for centrifugal compressors and radial turbines; a 2-D streamline coordinate analysis tool optimize blade loading and finalize blade geometry
- MAX-5 – a 5-axis milling program design to optimize the COMIG coordinates for machining
- VANGO – for centrifugal compressors; an aerodynamic design tool for the design of vaned diffusers. The tool predicts performance and defined the machining geometry
- RITDAP – for radial inflow turbines; the tool performs a 1-D "jet-wake' analysis on the specified geometry, predicting performance and optimal 2-D geometry parameters

Over the course of designing the silicon nitride turbine, several novel geometry features were explored to maximize the turbine efficiency, given the unusual properties of the ceramic. Also, the Kyocera forming procedure for the SN237 material placed unusual demands on the blade geometry. Thirdly, the CMT gas generator turbine geometry was modified aerodynamically to be tolerant to foreign object impact damage at the tip. The performance prediction for the silicon nitride gas generator turbine is summarized in Table 2.4.

Table 2.4: Final Gas Generator Turbine Performance Prediction (based on RITDAP)

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

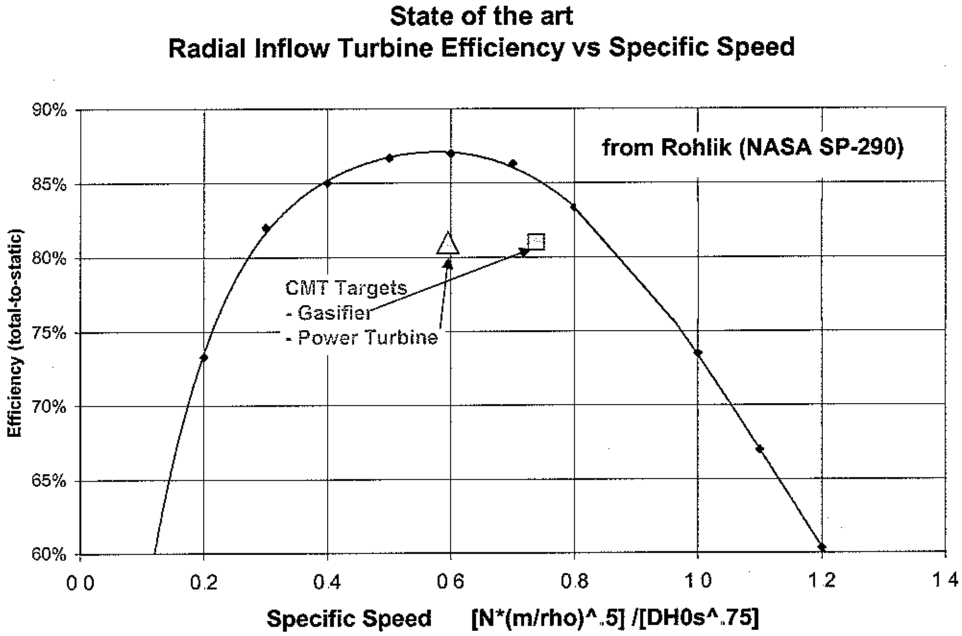


Figure 2.3 – Comparison of CMT turbine adiabatic total-static target against the NASA RIT reference stage

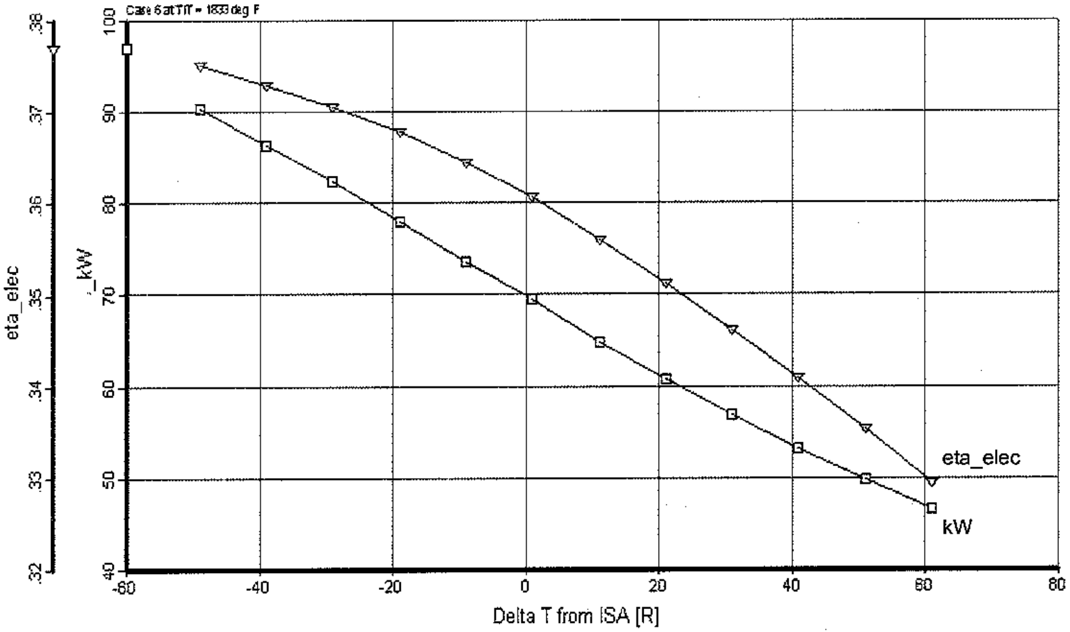


Figure 2.4 – Ambient de-rate performance (power and efficiency) of the CMT. Target flow point is a net 70kW at ISO conditions

The baseline rotor geometry was derived for the nominal cycle conditions (see Table 2.5). The preliminary physical geometry is used to normalize the recession rate against the nominal and minimum blade thickness.

Table 2.5: Nominal Rotor Geometry for the Frame 3 CMT

	Frame 3 CMT (72kW)
Tip diameter, mm	95
Exducer diameter, mm	70
Tip blade thickness, mm	2.0
Min blade thickness, mm	1.0
Root blade thickness, mm	4.0
Nominal blade thickness, mm	2.5

The kinetic model indicates that the water vapor partial pressure is a relatively significant factor in the recession rate. Water vapor is naturally present in the ambient air and is created a product of combustion. Figure 2.6 shows the blade *recession rate (absolute and normalized) for both the CMT as a function of three* ambient temperatures and a range of relative humidity. The combustion water

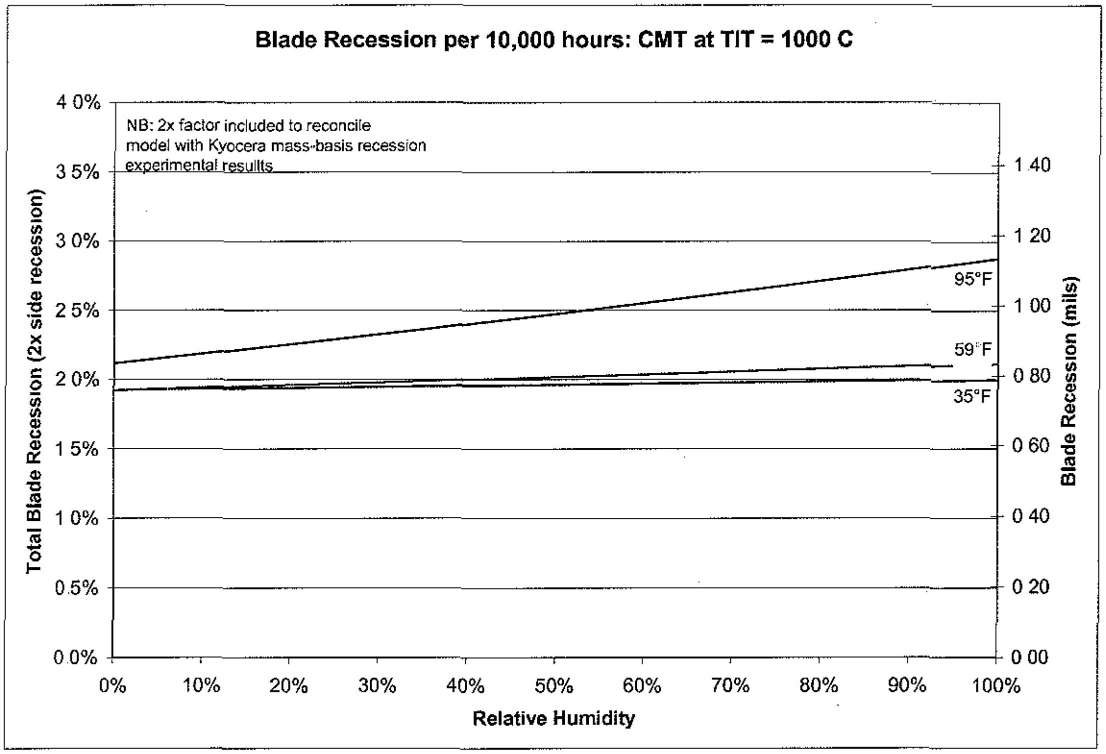


Figure 2.6 – Recession Rate of CMT Silicon Nitride Rotor at TIT=1000°C

Table 2.6: Blade Recession Assumptions and Sample Parameters

Parameter	Value
Ambient Temp, F	95.0
Ambient Humidity	60%
Inlet flow angle, degrees	72.97
Blade thickness, mm	2.00
Recovery factor	0.90
U/Co	0.69
ER	2.10
Sat. pressure, psia	0.4899
Operating pressure, atm	4.8
Sat. mole fraction, inlet	0.05556
Mass flow, lbm/s	0.979
fuel flow, lbm/s	0.00895
AFR	110.0
Mole fraction, O2	0.20346
H2O Mole fraction at compressor outlet, from ambient	0.03155
MW mix	28.498
Mole fraction H2O, from combustion	0.0342
Velocity, m/s	147.4
H2O pressure, atm	0.1636
TIT, C	1000.0
Mach number, relative	0.230
Adiabatic wall temp, C	897.0
Blade recession, um/hr	0.00230
Blade recession, mills/10,000 hrs	0.906
Blade loss fraction	2.301%

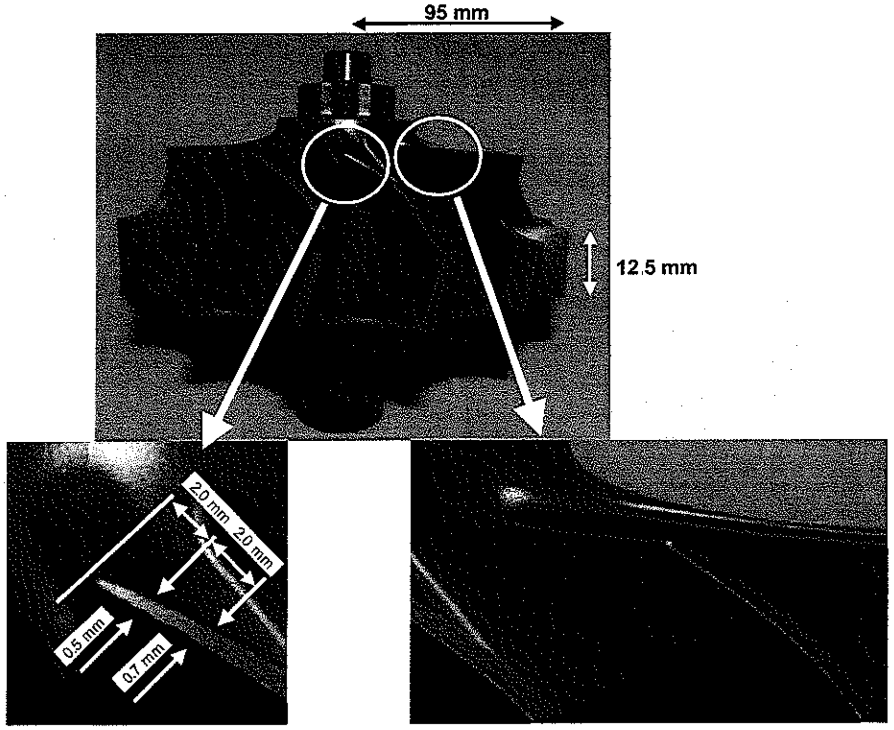


Figure 3.1 – First SN237 CMT Gas Generator Rotors Cast By Kyocera

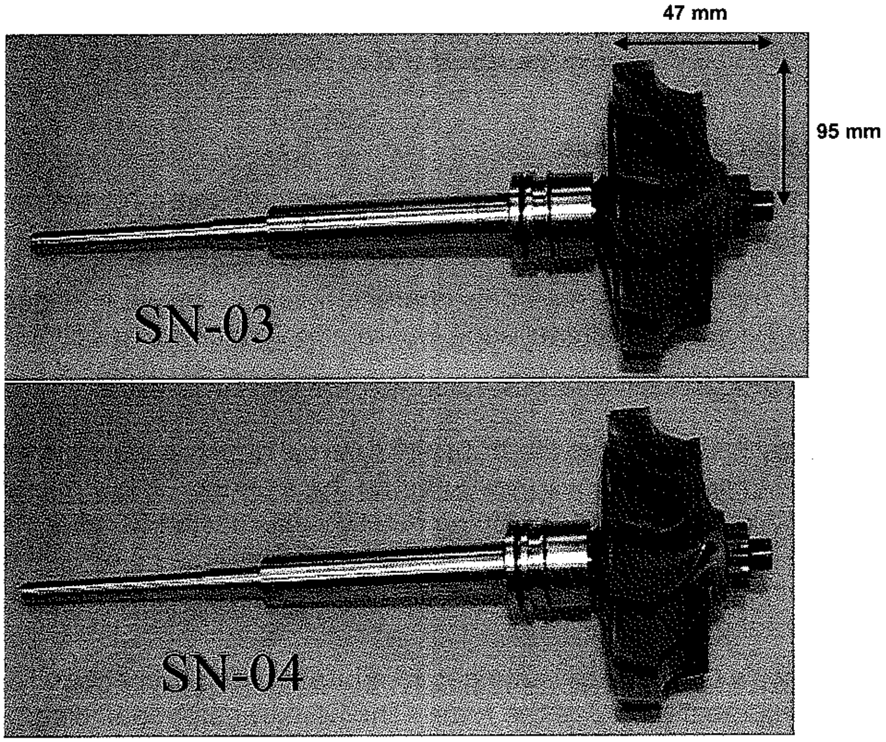
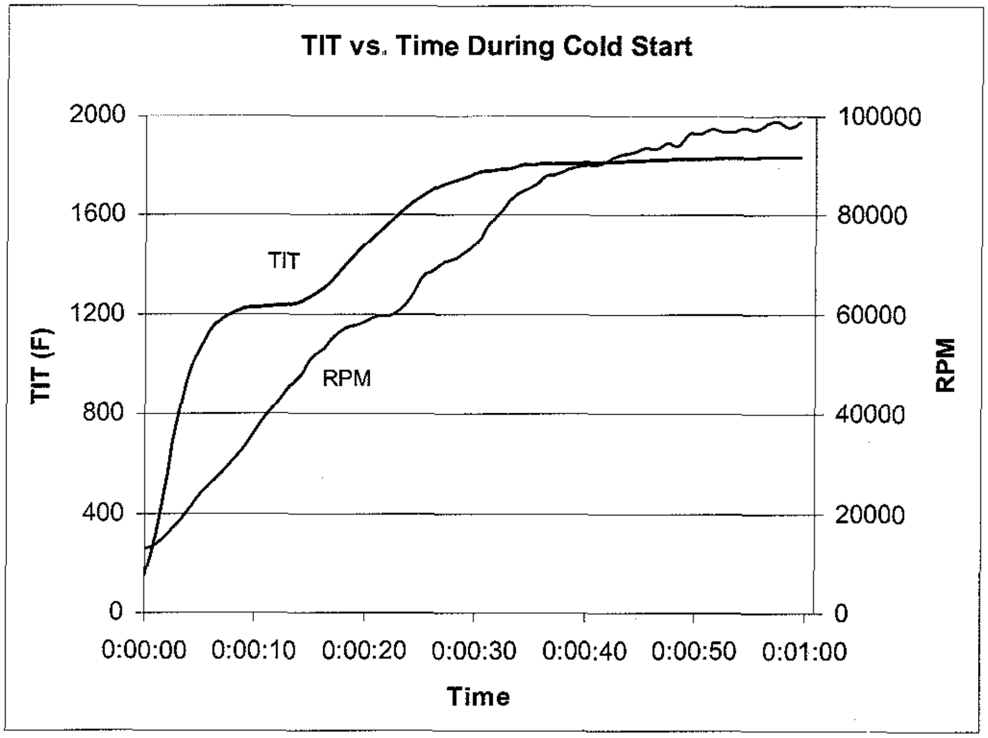


Figure 3.2 – Finished CMT Gas Generator Rotors and Shaft



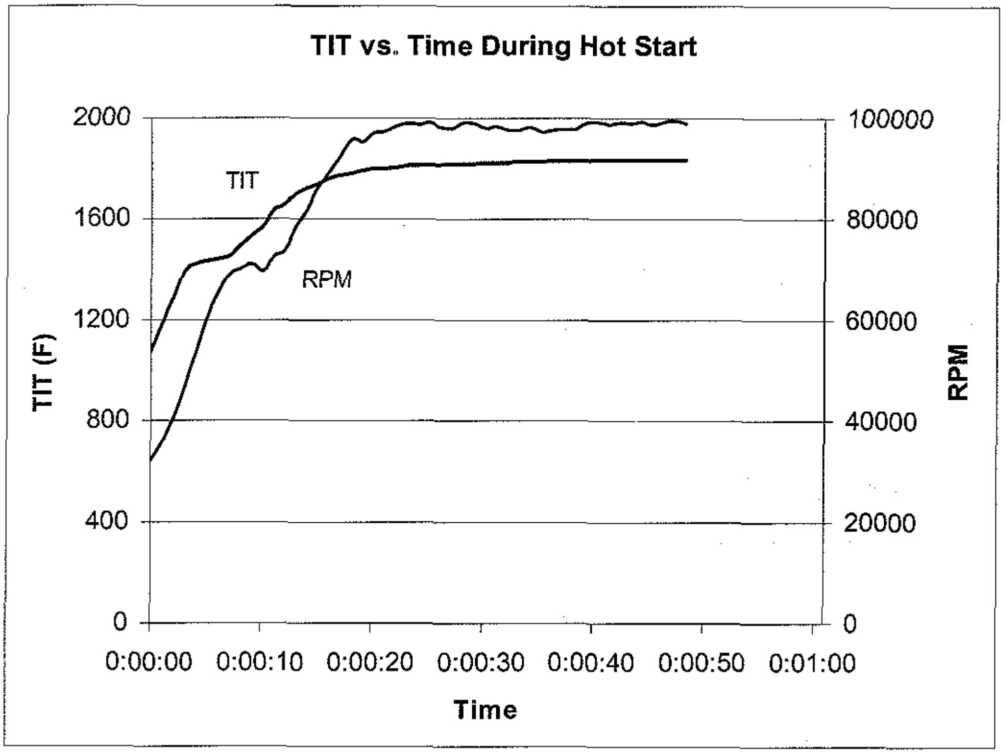
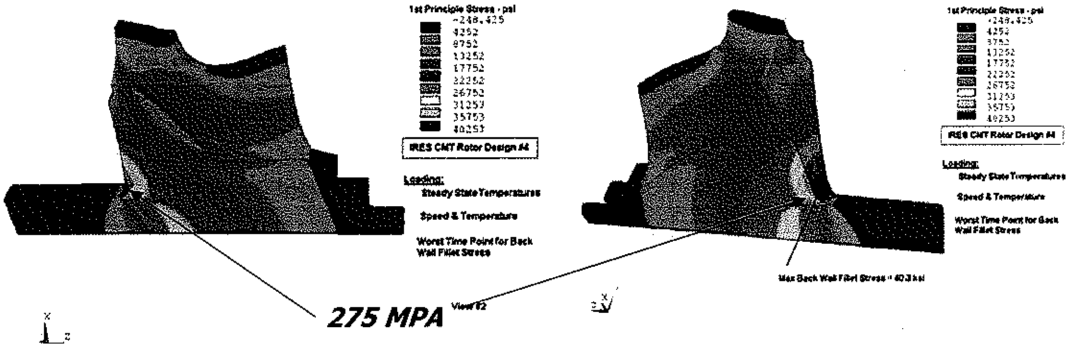


Figure 3.4 – Hot Restart and Cold Start Transient Boundary Conditions Assumed For CMT Rotor Analysis

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



275 MPA

All blade and root is below 200 MPa

Figure 3.7 – Steady State Stresses Within CMT Rotor

The rotor transient thermal and mechanical strain analysis was performed at one-second time steps, observing the empirical turbine inlet flow and temperature profiles for both "hot" and "cold" start. The transient stresses under both starting conditions are shown in Figure 3.8 for three critical zones.

Initial estimates of the component reliability were determined using the FEA results presented above and strength data generated from machined specimens. As the input file for the first CARES analysis, the life prediction results indicated a failure probability of $1/10^5$.

After receiving the first finished rotor samples from Kyocera, detailed material testing was initiated at ORNL. Over thirty miniature biaxial disk samples were prepared to characterize the three critical processing regions.

- As-cast surfaces of the air foil and hub
- The interior volume, throughout the rotor hub and blades
- The machined backface and vicinity of the shaft attachment.

The airfoil specimens had an as-processed tensile surface while the specimens removed from the hub were machined on both the tensile and compressive surfaces. Scanning electron microscopy and x-ray diffraction were used to supplement the mechanical testing.

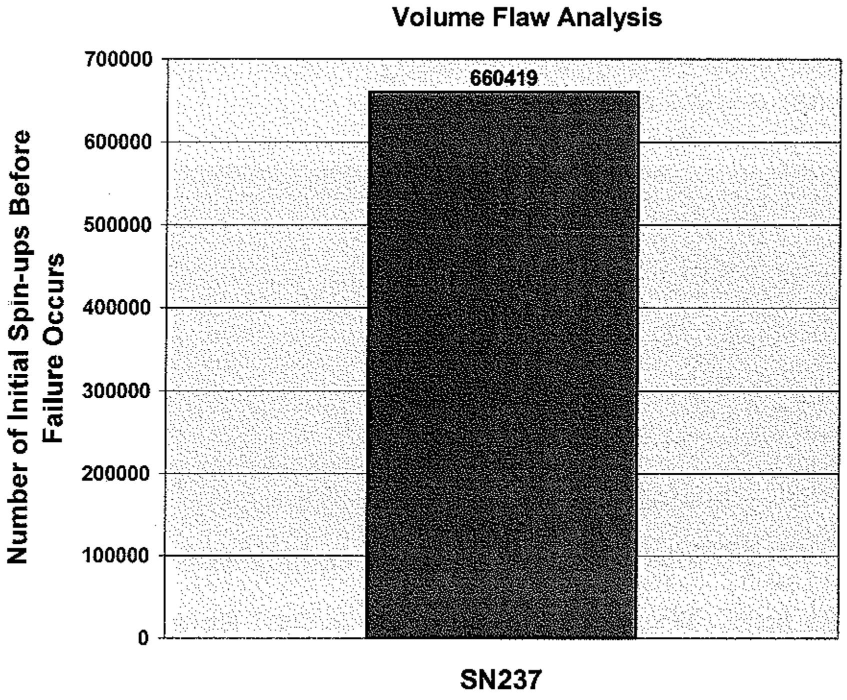


Figure 3.9 – Survival Rate at 38 Seconds

Table 3.2: CARES Results

Model 38 seconds -- Parameters @ 21C				Failure
m	sig_not	Pf	Rel	Rate
5.00	243,560	2.00E-06	0.9999980	500,088
7.50	97,019	2.00E-06	0.9999980	500,108
10.00	62,100	1.99E-06	0.9999980	501,482
15.00	40,365	2.00E-06	0.9999980	500,884
20.00	32,926	2.00E-06	0.9999980	500,110
25.00	29,420	1.99E-06	0.9999980	501,404

Table 3.3: Burst Conditions Tested At Kyocera (Jan 2003)

Material	Kyocera SN237
Sample configuration	95 mm CMT rotor
Burst speed, RPM	**167,197**
Design Speed, RPM	97,500
Burst speed ratio N_{burst}/N_{design}	1.71
Burst Stress ratio $(N_{burst}/N_{design})^2$	2.92
Design root stress for spin test at Design Speed (fig 3.10)	225 Mpa
Approximate burst stress	658 Mpa

3.2 Gas Generator Turbine Housing Analysis

The gas generator turbine housing has been designed with the requirement to employ conventional metallic turbine alloys. Operating at a gas temperature of 1000°C (1832°F), a limited number of practical candidates were evaluated. Unlike the turbine rotor, the housing operates at relatively low stress and has far fewer geometric constraints, thus ceramic materials were not required.

The finite element analysis for the turbine housing is a nozzle-less design. That is, the rotor incidence is established by a free vortex between the housing entrance and the turbine blade tip. An advantage of this aerodynamic design is its simplicity as well as the elimination of a component that would otherwise be required to operate at the turbine inlet temperature. The disadvantage of not having a vaned nozzle is a wide circumferential variation in flow angle, and consequentially lower efficiency. As an aside, a nozzle type radial inflow turbine might surpass our quoted efficiency by 2 to 3 percentage points.

The approach to the housing was to induce a moderate percentage of film cooling (recuperator exit air) at the entrance flange, totally insulating the external surface of the housing. This film cooling dissipates prior to entering the throat of the housing hence the circumferential area contraction within the volute must tolerate the total turbine inlet temperature. The volute must also manage the internal pressure loading. The principal remaining design challenge will be the oxidation resistance of the housing. The selection of a suitable coating may be required.

The FEA solution to the low cycle fatigue and creep design trades was to optimally thin the housing section, while incorporating a series of radial ribs. The ribs provide the stiffening to the cross section to meet the creep life, while the freely supported, thin section modulus of the housing develops minimum thermal stress. The transient stress levels were analyzed for the "hot and cold" start temperature profiles described in Figure 3.4. An example of the FEA model is shown in Figure 3.12.

The gas generator turbine housing was manufactured by conventional investment casting methods, employing an SLA form for prototyping. The

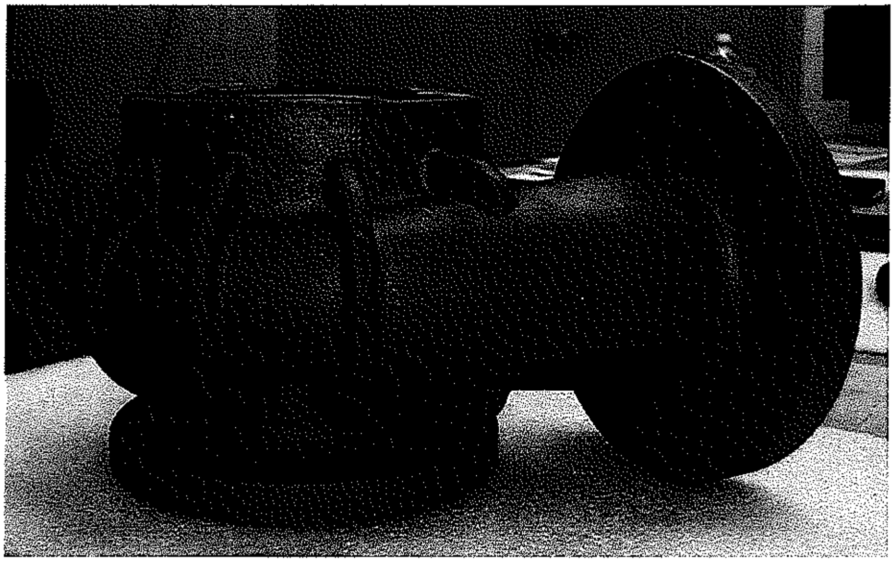


Figure 3.13 – Gas Generator Turbine Housing Cast From IN718

3.3 Gas Generator Bearing Core

The bearing core selected for the gas generator follows the design philosophy of the standard microturbine. The bearing core is an industrial truck turbocharger component, sold for 11 to 16 liter Diesel engines. Figure 3.14 shows the CMT rotor system (turbine, shaft, compressor) installed in the turbocharger bearing core. The system uses common oil-lubricated journal bearings

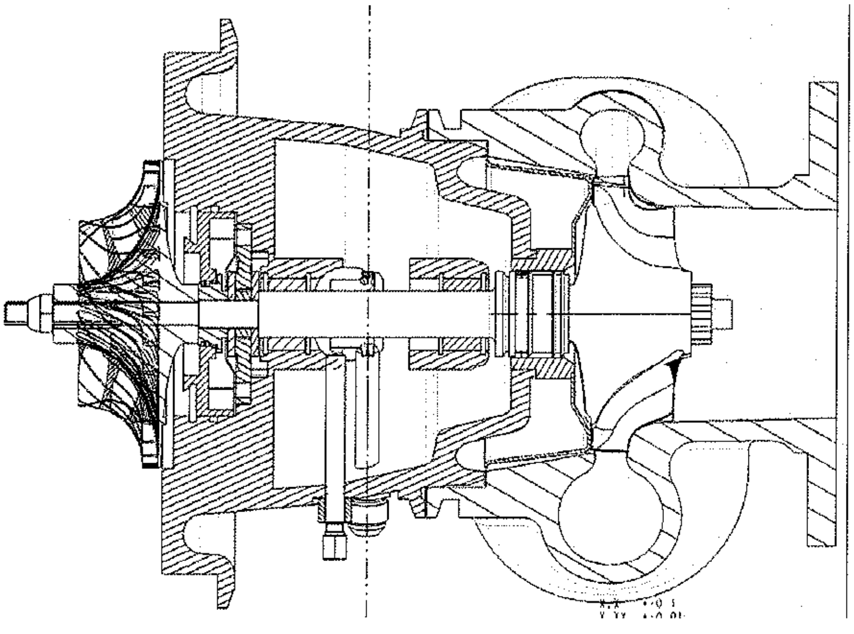


Figure 3.14 – Compressor / Bearing Core / Turbine Assembly

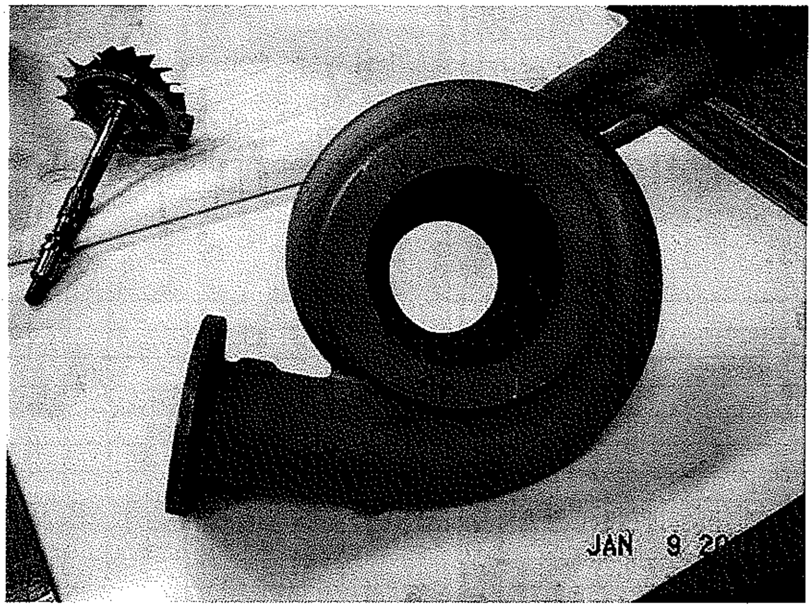


Figure 3.17 – Power Turbine Housing Cast From Hastalloy-X

3.5 CMT Combustor

The CMT combustor design employs the patented Ingersoll-Rand design, well proven on the standard 70kW engine. The CMT design is about half the volume of the standard 70kW design, owing to the elevated pressure and reduced mass flow of the CMT engine. Though the exit temperature has been raised to 1000°C (1832°F) for the CMT engine, the inlet air and reaction zone operate at essentially the same temperature as the progenitor currently in production on standard engines. Consequently the emission levels for NOx and CO as well as the life and reliability are expected to be comparable to our standard product. Figure 3.18 shows the finished CMT combustor.

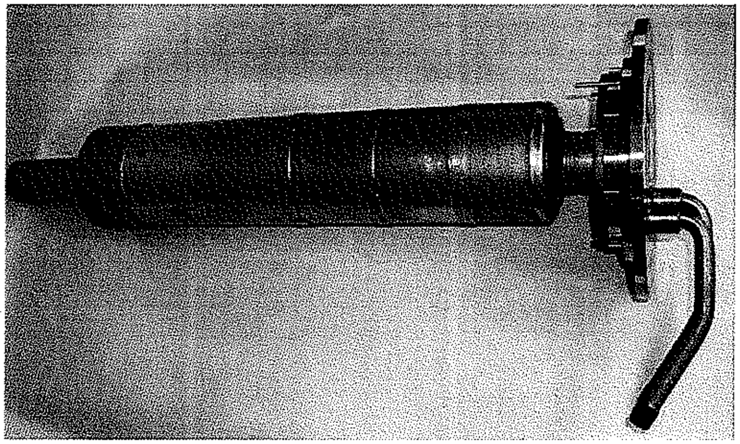


Figure 3.18 – CMT Combustor

Table 4.2: CMT Program Milestones Completed

Milestone	Task	Title	Original date	Revised date
	1	*Concept R&D define most suitable microturbine platform*		
1		**Down-select micro-turbine platform for ceramic rotor**	1-May-01	1-May 01
	2	*Detailed design of ceramic turbine and hot section*		
2		**Complete rotor detailed design**	1-Nov-01	1-April 02*
3		**Select ceramic rotor supplier**	1-Dec-01	1-Dec-01
	3	*Final design of Microturbine system*		
4		**Detailed Design Review**	1-Feb-02	4-Sept-02
	4	*Fabricate principle Ceramic Microturbine components*		
5		**Release for manufacturing**	1-Apr-02	30-Sept-02
6		**Factory acceptance**	1-May-03	15-Nov-2003

*M2 – The detailed design of the rotor was completed April 4 2002, and sent to Kyocera for manufacturing review.

*M4 – The redirection of the project from the originally proposed Frame 3 air compressor to the Frame 3 microturbine generator resulted in a 5-month delay. Travel restrictions by the DoE resulted in a 2-month delay