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The use of Micro turbine generators in hybrid electric vehicles

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Introduction

This document briefly describes some ideas for ultra-low emission power trains using a micro turbine in a series hybrid configuration. Over the last decade or so, there has been considerable debate in the technical press describing the relative merits and drawbacks of parallel, series and more complex drive lines. However, most of this debate has been based on the implication of using diesel or petrol engines as the thermal engine source.

HILTech's activities in hybrid systems are focused on three prime sources of power for series hybrid vehicles they are: *fuel cells* - *rotary engine* and *micro turbines*. The actual power train design is dependent on a wide number of factors and can result in complex systems. For example; under certain commercial circumstances, we can include both a small PEM fuel cell and a thermal engine system in one vehicle.

This document however, is mainly focused on the use of micro turbines.

Generally, HILTech considers a series hybrid solution is a preferred solution to current power train design for the following reasons:

a it overcomes the major draw back of micro turbines namely, the limit to the number of times that they can be started up and shutdown

b it allows us to offer a modular power train solution

c it enables the micro turbine to run at constant speed and maximum efficiency whereby the micro turbine is rated to provide the average load and the batteries / super capacitors provide instant peak power for acceleration gradients etc.

d it allows for "black box" fast interchange serviceability

The design algorithm is rated to allow for the constant recharging of the batteries providing the best overall economic solution

What is a Micro turbine?

Micro turbines are small combustion turbines approximately one third the size of its equivalent diesel engine with outputs of 25 kW to 500 kW. They evolved from automotive and truck turbo-chargers, auxiliary power units for air planes, and small jet engines and comprise a compressor, combustor, turbine, and recuperator.

Micro turbines can run on a number of fuels which include; hydrogen, CNG / LPG, alcohol, Kerosene, recycled oil, possibly vegetable oil all which reduces dependence on diesel or petrol. Indeed using CNG / LPG the micro turbine is a micro gas turbine. It is the replacement of a conventional thermal engine by a micro turbine which is the significant technical innovation described in this document.

Micro turbines offer a number of potential advantages compared to other technologies for mobile power generation. These advantages include:

a a small number of moving parts,

b compact size with the potential to be located with strict space limitations

c light-weight

d lower energy costs

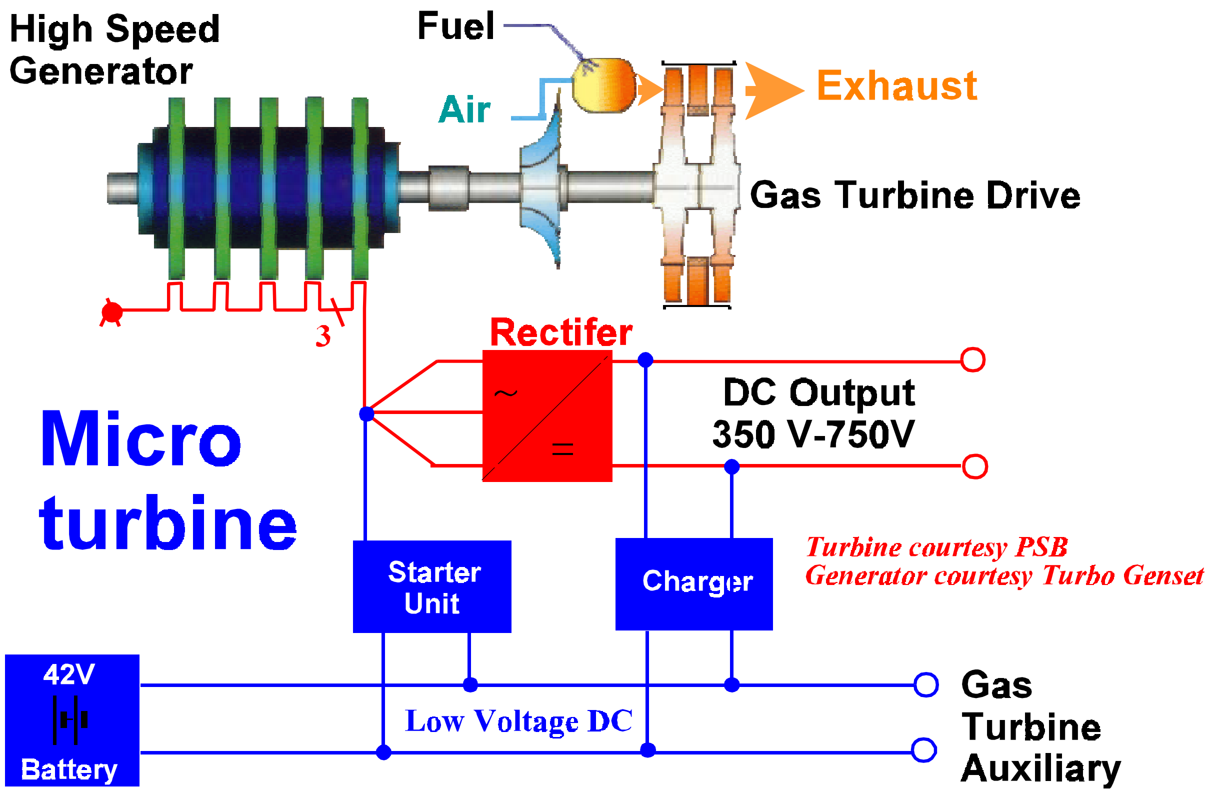
e lower emissions with multi-fuel capability

f improved overall vehicle design due to weight and size savings

g the opportunities to utilize otherwise waste fuels

Turbines are classified by the physical arrangement of the component parts: single shaft or two-shaft, simple cycle or recuperated, inter-cooled, and reheat. They generally rotate at over 60,000 rpm.

The schematic below shows a typical overall system.



Bearings can be oil but HILTech uses manufacturer which fit air bearings only. A single shaft is the more common design as it is simpler and less expensive to build. Conversely, the split shaft is necessary for machine drive applications, which does not require an inverter to change the frequency of the AC power.

Micro turbines can also be classified as simple cycle or recuperated. In a simple cycle, or unrecuperated, turbine, compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is allowed to expand through a turbine to perform work. Simple cycle micro turbines have a lower cost, higher reliability, recuperated units use a sheet-metal heat exchanger that recovers some of the heat from an exhaust stream and transfer it to the incoming air stream. The preheated air is then used in the combustion process. If the air is preheated, less fuel is necessary to raise its temperature to the required level at the turbine inlet. Recuperated units have a higher thermal to electric ratio than unrecuperated units and, in addition, can produce 30-40 percent fuel savings from preheating.

Advanced materials, such as ceramics and thermal barrier coatings, are some of the key enabling technologies to further improve micro turbines. Efficiency gains can be achieved with materials like ceramics, which allow a significant increase in engine operating temperature.

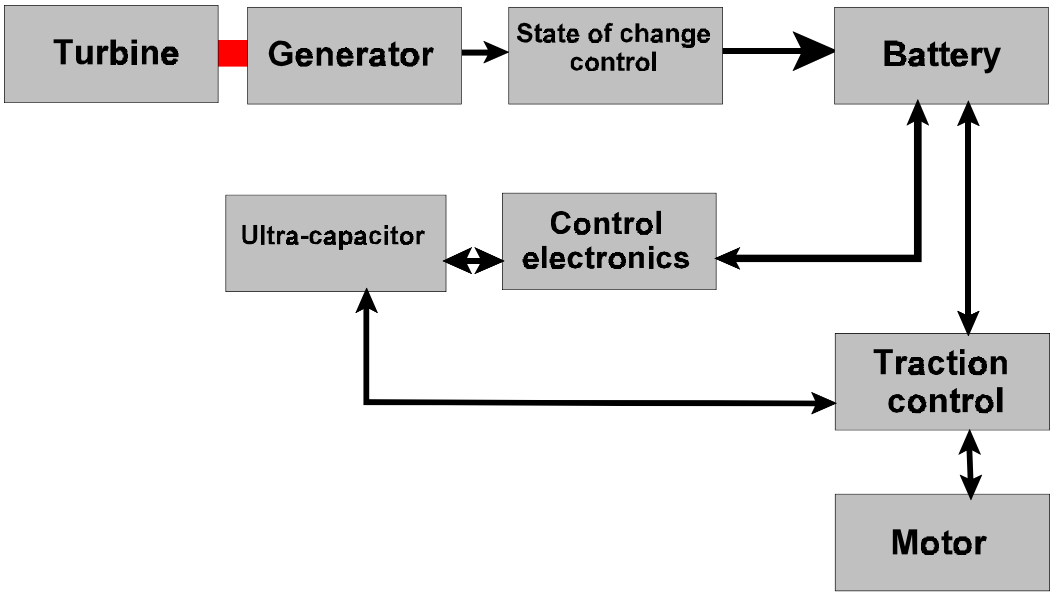
Because of their compact size, low operational and maintenance costs, automatic electronic control, micro turbines are ideal for hybrid vehicle applications however because of their relatively high capital cost their markets are considered to be:

a public service vehicles (buses)

b heavy commercial trucks of say >10Tonne payload

c light rail systems where public utility supply is unreliable

d shunting locos



The diagram above shows a typical series hybrid system configuration, its advantages are:

ultra low weight a typical 100kW (134HP) turbine system weighs about 640 kg

very small dimensional envelop

typically over 25% thermal efficiency

very low maintenance requirement and ease of maintenance

direct drive to generator eliminating the need for gearbox

back-box installation allowing for service exchange reducing vehicle off road maintenance delay

constant speed thus narrow noise hysteresis

multi fuel capability

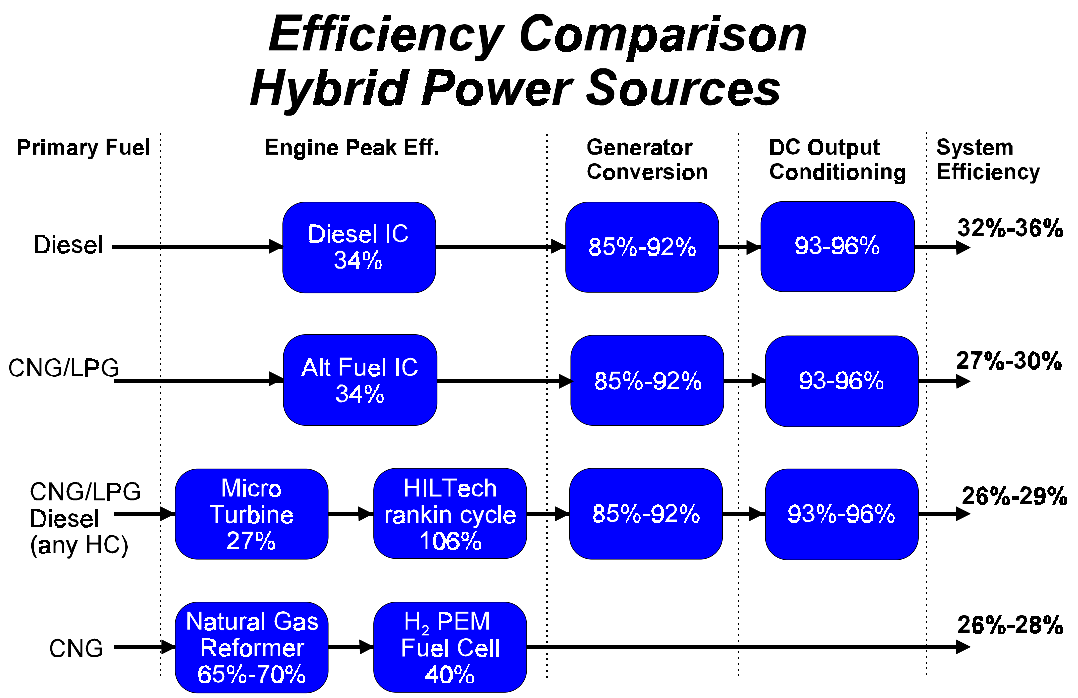
The efficiency of turbine systems

The micro turbine has a base twenty-six to twenty-eight percent (26 / 28%) thermal efficiency however, this is compensated by weight saving and overall hybrid system efficiency. The thermal efficiency can be increased to typically 31/32% by using waste heat absorption technology to power air conditioning or vehicle space heating or used to power a Rankine cycle to generate more electrical energy.

The following table (overleaf) illustrates the technology comparison between a micro turbine generator powertrain solution against the current PEM fuel cell state-of-the-art and a conventional CNG powered thermal engine.

Parameter	Micro turbine / generator	PEM Fuel cell	CNG engine /generator
Lifetime in operating hours	>20,000	>2,000	~13,000
Moving parts number of units	rotor only	blower / pump	>50
Thermal management	exhaust emissions	water cooled	water cooled
On-board fluid storage	none	water/antifreeze	water antifreeze and lubricating oil
Electrical generation	yes	yes	yes
Emission control / treatment	yes	no	yes
Freeze tolerant	yes	no	yes
>60^{O}C ambient operation	not proven	not proven	yes

There is on-going development by the micro turbine suppliers in the application of more advanced materials, e.g. ceramics and thermal barrier coatings. These are some of the key enabling technologies to further improve micro turbines. Efficiency gains can be achieved with ceramics which allow a significant increase in engine operating temperature.



Hybrid power train applications

Typical applications include:	cars, trucks and public service vehicles (buses) locos for use in mining, shunting (switching) and other areas certain industrial vehicles including materials handling trolleybus auxiliary power units military applications

In using an ultra-low weight, all-composite public service vehicle body technology, the following table illustrates the weight comparison of a micro turbine electric power train with a conventional diesel engined having the same payload capability.

The table also indicates the numbers for a current state-of-the-art conventional steel chassis bus for comparison:

		Kerb Weight kg	Passenger payload kg	Total Weight kg
Conventional diesel powered conventional steel chassis bus	a	7,500	3,500	11,000
All-composite body bus with diesel engine power train	b	5,900	3,500	9,400
All-composite body bus with micro turbine and battery pack	c	5,100	3,500	8,600
WEIGHT REDUCTION b / a			Kerb weight 21% Total Weight 14.5%	
WEIGHT REDUCTION c / b			Kerb weight 13.5% Total Weight 8.5%	
WEIGHT REDUCTION c / a			Kerb weight 32% Total Weight 22%	

These weight savings represent direct saving savings in fuel costs and pollution over and above the energy efficiency savings by using a hybrid power train over a conventional diesel system. In the case above further analysis shows an overall fuel saving of some 58% over the current state-of-the-art diesel steel chassis counterpart under identical operational conditions.

The design procedure for developing a particular hybrid electric power train involves integrating and coordinating a number of operational variables with the best solution control strategies.

The ultimate system algorithm has to consider:	energy / fuel source payload and payload variance climb-ability acceleration and braking speed demand and duty cycle system efficiency auxiliary equipment energy storage systems (battery / super capacitor) traction drive algorithm mechanical design including FEA and anti-collision protection

All of which have to be considered in real time.

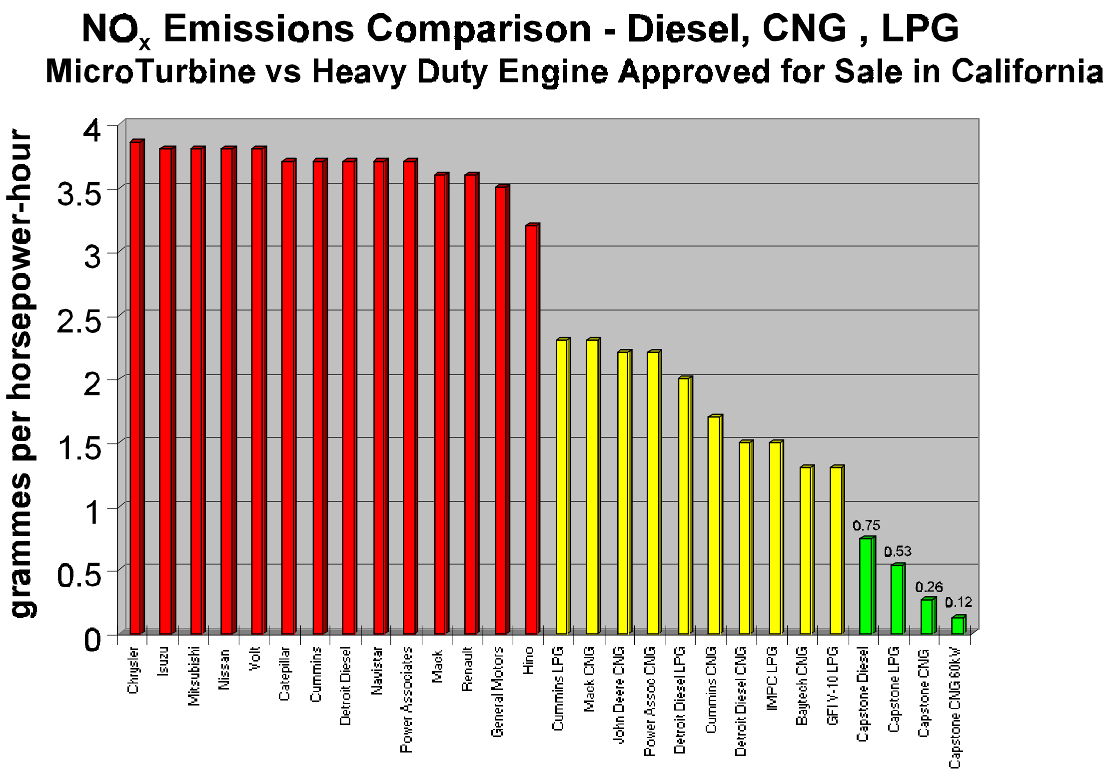
Sophisticated mathematical modelling of hybrid sub-systems and total system integration plays an importance precursor for the actuate prediction of the whole system followed by hardware packaging.

Integration and optimisation of systems provide the rationale for the choice of specific control choices.

Emissions and pollution

Road vehicle pollution causes at least 35% of all air pollution today, resulting in an ever growing concern by Government and the general public alike. Air pollution is now firmly on the international stage and is responsible for enormous costs. These are not generally accounted for because of the complexity of the issues involved from health related issues to city infrastructure damage.

The table, for which we thank Capstone Micro turbines, below gives a general overview of the overall pollutants of different vehicle power trains.



Source: Data obtained from CARB for all diesel, natural gas and LPG on-road heavy duty truck and bus engines under 400 bhp approved for Sale in California for model yea 2000. Data listed is cleanest emissions engine family available from each manufacturer meeting regulations. Capstone CNG and LP actual emissions results per CARB certifications. Diesel unit emissions per internal testing. CARB certification pending Q2 of 2001. Capstone emissions are per a modified Federal Test Procedure for Heavy I Diesel Engines, approved by CARB for use with microturbine engines.

The table below indicates the calculated emissions for a fifty passenger all-composite public service transit bus.

Oxides of nitrogen NO_x	Particulate Matter
Better than 1.3 based on 200kW drive	Better than 0.03 based on 200kW drive

The table, overleaf, courtesy of Capstone Turbines, which shows the comparison in emissions between Capstone micro turbines and current state-of-the-art diesel engines - for the same vehicle performance - payload.

Emissions Comparison

grammes per horsepower hours

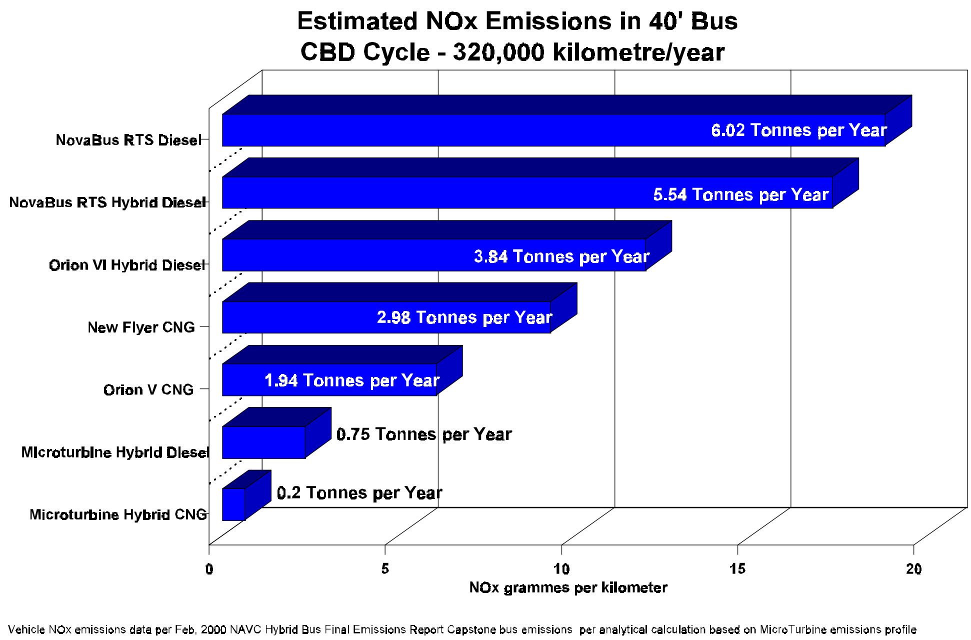
Engine	NO_x	HC	CO	PM
Typical Current Diesel “Euro 3"	3.9	0.1	0.9	0.04
Cummins C8.3 CNG	1.7	0.2	0.6	0.01
Detroit Diesel S50 CNG	1.5	0.8	2.2	0.01
30kW Capstone Turbine Diesel	0.8	0.3	0.4	0.01
30kW Capstone Turbine LPG	0.5	0.4	0.2	0.004
30kW Capstone Turbine CNG	0.3	0.4	0.4	0.004
60kW Capstone Turbine CNG	0.1	0.0	0.2	Pending

Clean diesel info per California Transit Association report

Cummins and DDC engines listed are cleanest urban bus engine available from each manufacturer, per CARB heavy duty engine database. Data is actual emissions achieved.

Capstone LPG, CNG and Diesel data are actual engine emissions achieved per CARB certification using a CARB approved modified engine test cycle for use with Micro Turbines. Capstone CNG 60kW emissions are preliminary laboratory results, CARB certification and PM testing pending.

The bar chart below shows the annual reduction in emissions for a typical forty-five passenger public service vehicle being run for 320,000kilometres per year.



Operating Environment

Generally, HILTech design their power trains to operate normally under all environmental conditions prevailing in the client's service area. Speed, grade-ability, and acceleration performance requirements shall be met at 50^{O}C. with all accessories on including air conditioning.

A typical environmental requirement is given below:

Maximum continuous ambient temperature	65^{O}C
Maximum ambient operating temperature one hour rating	85^{O}C
Minimum continuous operating temperature	-15^{O}C
Maximum barometric reading for continuous operation	1,200 mb
Minimum barometric reading for continuous operation	98 mb
Relative humidity	5 to 100% at altitudes up to 1,500 metres above sea level
Performance degradation at conditions other than the test standard	shall not exceed 1 percent for each 1^{O}C and 4 percent for each 400metres of altitude above the standard
Internal noise	74 dB
Eternal noise	76 dB

Maintenance and service

HILTech's power train design philosophy is to design in minimum maintenance requirements. It is our policy to minimise routine maintenance This involves using low maintenance components, service diagnostic capability and fast "black-box service replacement" of on-board vehicle components and sub-systems.

For example: a micro turbine power train will normally have a planned life of 50,000 miles between <u>major</u> services and 25,000 miles between <u>minor</u> intermediate services. Every fifty thousand miles the gas turbine may require new combustion chambers which would be effected by engine change and works refurbishment. Micro turbines have a far lower maintenance profile than their conventional thermal engine counterparts (no oil, air filters etc.).

On-board diagnostic checks will be used for: fluid levels, state of traction and auxiliary batteries, insulation resistance, brake condition, and wherever possible as many other sub-systems it is practical or desirable to do so. The use of wireless LAN technology for the daily automatic transfer of diagnostic information giving the fleet operator a review of vehicle status can further reduce time and operational costs.

The traction battery may need replacing every 10 to 15,000 miles on a service exchange basis depending on battery chemistry. Super capacitors are expected to have a circa fifteen year life, though one or two cell failures might be expected with such large number. Protection will ensure no single cell failure causes total system failure.

We anticipate HILTech designed all-composite bus bodies (other than collision damage) to have an operational life of not less than fifteen years and probably twenty years.

HILTech designed vehicles are offered with specific maintenance requirement. The table below gives a design target in terms of "***mean time to fix***" (MTTF). Such a table represent the total elapsed labour time (hours / minutes) required to complete the maintenance task by one mechanic but do not include time required to prepare the bus such as bringing the bus to the hoist, raising it, etc because this is client workshop dependent.

We normally expect to demonstrate these maintenance tasks using the information as contained in the service manual. Using a pilot bus, the clients facilities and the clients personnel (after training). The purpose of these demonstrations is to validate the maintenance manual, special tool requirements and MTTF.

	SERVICE TASK	MTTF Prediction
INSPECTION	20,000 Mile Inspection	2 hours
	Daily Inspections	10 minutes
	Brake Inspection	15 minutes
REMOVE AND REPLACE	Alternator	1 hour
	Access for Door Motor Adjustment	< 2 minutes
	Batteries Set	45 minutes
	Brake Application Valve	1 hour
	Engine/Transmission PPA (2 mechanics)	2hour (a)

Micro Turbine Suppliers

HILTech generally recommends micro turbines from circa 25kW through to 500kW from the following suppliers:

PBS	Czech Republic	25kW units
Capstone	US	30 and 60kW units
Honeywell	US	100 kW units
Pratt and Whitney	Canada	250 to 500 kW units