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ICR350 - A TURBINE SOLUTION FOR MEDIUM AND HEAVY DUTY VEHICLES

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ABSTRACT
This paper briefly reviews automotive gas turbine history, examines the factors that influence engine selection, and introduces the ICR350 intercooled-recuperated gas turbine, an engine designed for Medium and Heavy Duty Vehicles, (MHDV).

After turbines successfully displaced reciprocating engines from aircraft in the 1950's, it was widely believed that they would rapidly penetrate the vehicular market. With the promise of low cost and simplicity all major automotive companies had aggressive turbine programs. But what began as a sprint became a marathon. Of the many that started, just a few managed to reach the finish line, only to be defeated by revised emissions legislation and the unforeseen energy crisis.

The DOE continued funding automotive turbine development and transitioned from mechanical to hybrid drivetrain solutions. Ultimately, and somewhat serendipitously, microturbines were developed from range extender engines conceived as battery chargers in the Hybrid Vehicle program. Most recently, the Advanced Microturbine Systems program, AMTS, is responsible for technologies leveraged in ICRTec's next generation vehicular turbine.

Today battery technology has advanced sufficiently for low daily use vehicles and collection or delivery vehicles with regenerative braking. With its low power density, this same technology does not work for MHDV's, a sector dominated by diesel engines. Emissions compliance is placing heavy cost and performance penalties on incumbent diesel engines, and the recently proposed MHDV efficiency legislation will only exacerbate the situation.

After 40 years it appears that externalities, coupled with advances in turbomachinery, now favor a gas turbine solution.

1.0 INTRODUCTION
Automotive gas turbines have enjoyed a rather turbulent history. In the 1950's through to the 1980's they were the focus of significant R&D by the world's leading automotive and gas turbine companies. However, reciprocating engines dominated and the promise of gas turbine powered automobiles was largely forgotten with one notable exception; the Lycoming AGT-1500, shown in Figure 1, the power plant for the M1 tank.

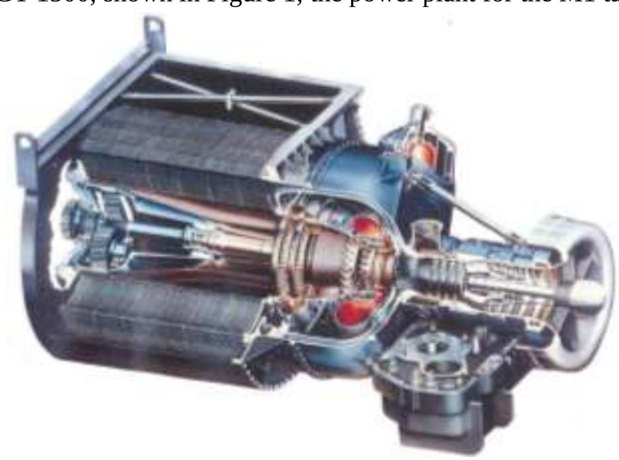

Figure 1. AGT-1500 Cut Away
Source: Honeywell International

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Small turbines for automotive applications saw renewed opportunities in the mid 1990's with the DOE's Hybrid Vehicle program. In Europe Volvo continued its fascination with automotive turbines and was involved in car, bus, and truck programs. This time success was enjoyed on both sides of the Atlantic: Volvo's high speed generator program launched Turbec in Europe, and the Hybrid Vehicle program stimulated US microturbine development.

Enthusiastic revenue forecasts encouraged many companies to participate in microturbine development, but with sales reaching only a fraction of projections, most companies withdrew. Of the original companies, only Capstone, Ingersoll Rand and Turbec remain. While microturbines have benefited from significant technology maturation they have failed to topple their nemesis, the ubiquitous diesel genset.

In addition to the prevailing externalities that prevented automotive turbine solutions and compromised microturbine success, cost was also a factor. However, in the same way that revised emissions legislation placed cost penalties on the first automotive turbines, it now penalizes the diesel engine. Recognizing cost as the main issue of microturbines, the ICR350, with its intrinsic emissions, weight, fuel flexibility, and performance advantages, is designed to be cost competitive with EPA compliant diesel engines.

We are now in a legislative era that will influence several decades to come - one in which emissions, energy security, and efficiency dominate. Turbines are clean, fuel agnostic, and efficient, perfectly aligned with all current and foreseeable legislation activity. With diesel engines hampered by increased legislation, and turbines competing favorably with diesels on all customer metrics, the table has been turned, and the probability of automotive turbine success is now higher than ever before.

2.0 AUTOMOTIVE GAS TURBINES

With the rapid and successful displacement of reciprocating engines from aircraft after World War II, the turbine was expected to quickly revolutionize the automotive industry. In the early 1950's most major auto manufacturers were heavily involved in gas turbine development. In the US, Ford, GM, and Chrysler had programs covering a broad range of power ratings. Europe and Japan were engaged in their own activities. Rover gained the most visibility with the release of the JET1 car in 1950, and then again in 1963, teamed with BRM, completing the LeMans 24 hour race.

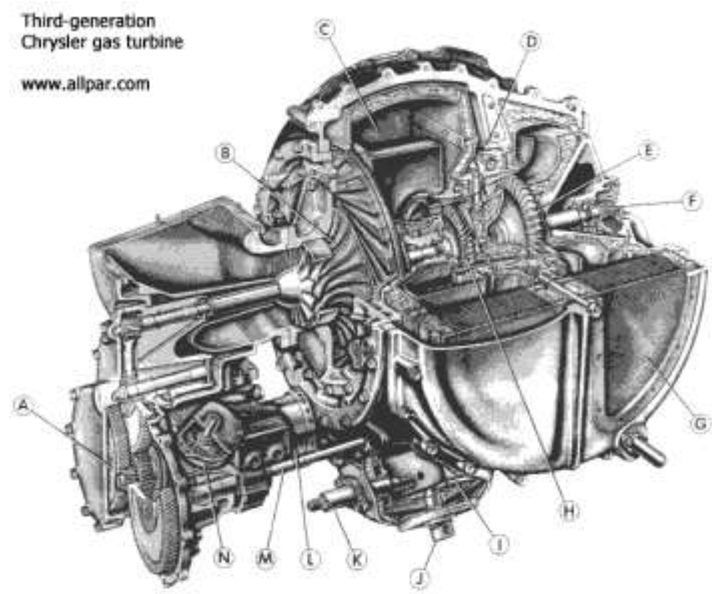

Figure 2. Chrysler Automotive Gas Turbine
Source: www.allpar.com

In the US Chrysler distributed a fleet of 50 turbine-powered cars for field trials. The cars performed well but needed refinement to resolve regenerator reliability, oil coking, and performance issues. After the trials Chrysler continued improving their regenerative gas turbine and by the mid 1970's had a production-ready engine. However, their launch plans for the 1977 LeBaron were ultimately prevented by severe financial conditions. With the introduction of catalytic converters, enabled by unleaded fuel legislation, turbines lost their main advantage and Chrysler, after coming so close, finally conceded. A version of the Chrysler turbine, with its characteristic twin regenerators, is shown in Figure 2.

While Chrysler had concentrated on a small turbine, GM and Ford decided competing with the larger more costly diesel engines was a better strategy. Using recuperators in place of problematic regenerators both companies completed successful demonstration programs. GM, through their Allison division developed a turbine for buses and although Greyhound reported favorably, GM never committed to production. Ford came closer to full production and even built an automotive turbine plant, only to close it three years later when it was flooded. All three came close, none succeeded. Some vindication for these larger recuperated engines came when the AGT 1500 won a military down select program to power the M1 Abrams battle tank. Production started in 1979 and continues today.

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Somewhat ironically the tank was initially manufactured by the Chrysler Corporation.

The demise of commercial automotive turbines cannot be attributed to one single event. While the Clean Air Act of 1970 regulated passenger cars and clearly hurt Chrysler's turbine plans, it had no immediate impact on buses or trucks. These heavier vehicles however, were affected by later efficiency legislation precipitated by the Arab oil embargo of 1973. The changed emphasis for engine selection criteria resulting from these events minimized turbine advantages and rebalanced the equation in favor of the diesel. This outcome could have been different had any one of these events been delayed.

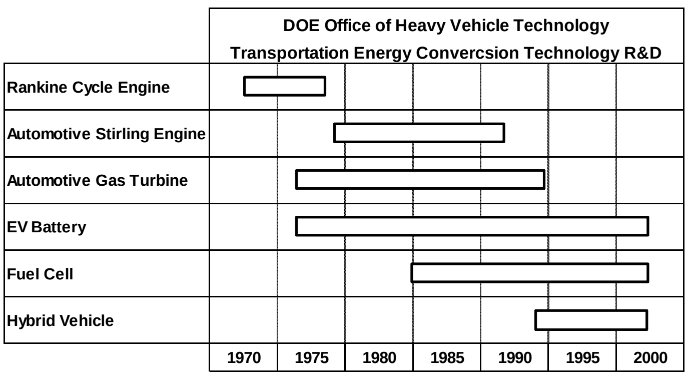

Figure 3. DOE Transportation Program 1970-2000
Source: DOE

The DOE, recognizing the critical importance of fuel flexibility to energy security, sustained automotive turbine development and provided uninterrupted support through the AGT and Hybrid programs shown in Figure 3. The AGT program yielded robust technology demonstrators that became the vehicles for advancing ceramic materials. Later with increased focus on electric drivetrain solutions, the Hybrid program developed a turbine range extender, a configuration that stimulated microturbine development in the US.

In Europe Volvo maintained a leadership position in automotive turbine applications and established a highly integrated approach. Figure 4 provides a timeline of Volvo's automotive gas turbine programs all of which had some degree of success. The VT300 mechanical drive truck engine concluded with successful road trials, and the electric hybrid program provided the microturbine technology for Turbec, a JV with ABB, (1).

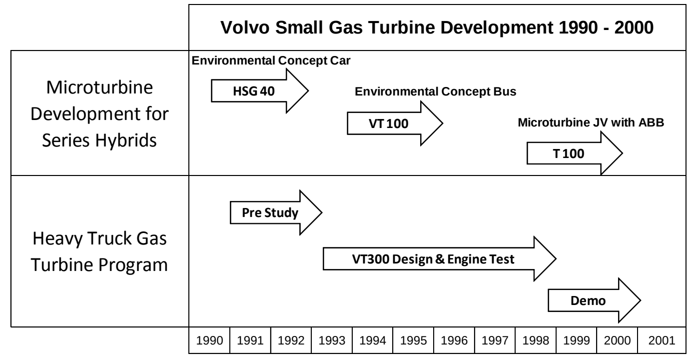

Figure 4. Small gas turbine development at Volvo
Source: SAE2005-01-3504

While history indicates that automotive turbine programs have enjoyed success in field trials, none have succeeded in displacing the diesel engine. One might imagine the reasons are complex but in reality they are not. The simple fact is that historically the diesel engine, though sometimes helped by fate, has always managed to represent the financially favorable solution. However, the current landscape is different. This time the benefits are significant and the prospects for a commercial automotive turbine are very real.

3.0 MICROTURBINES

Emerging from the Hybrid vehicles program microturbines were further enhanced through the AMTS program that targeted increased penetration through improved energy utilization, (2). The AMTS objectives, listed in Table 1, were not achieved but the resulting improvements to efficiency, reliability, and cost, did much to validate and strengthen the enabling technologies.

System Parameter	Units	Interim Development	ATMS Goals
Power	kW	200	270
Electric Efficiency (LHV)	%	34	40
Electric Efficiency (HHV)	%	30.6	36
List Package Price	$/kW	650	500
Maintenance Cost	$/kWh	0.016	0.011
Exhaust Temp (Deg F)	Deg F	~500	~500
Recovered heat for 135 F Water (165 F exhaust temp)	BTU/kW	4,200	3,100
Hot Water CHP Efficiency (HHV)	%	68.1	68.7
Recovered Heat (Rel to ambient)	Btu/kW	5,510	4,100
Direct CHP Efficiency (HHV)	%	80	79.1

Table 1. AMTS Cost and Performance Objectives
Source: AMTS market assessment, May 2003

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Microturbines, unlike their earlier automotive counterparts, are significantly less complex, use metallic recuperators, and employ direct drive high speed generators. Benefiting from modern design tools, and enhanced manufacturing methods, microturbines achieve respectable efficiencies around 30% and burn a variety of fuels with near zero emissions. With maturation they also exhibit the reliability attributes characteristic of conventional gas turbines.

Despite their inherent simplicity microturbines suffer from significantly higher specific cost than their gas turbine cousins. A significant proportion of this cost anomaly with respect to vehicle applications can be attributed to the low system pressure ratio of 4:1, and added recuperation. Unfortunately, without the recuperator efficiencies would be unacceptable at around 15%, and higher pressure ratios are inconsistent with their design criteria.

A simple way to reduce cost is by increasing pressure ratio. For the same fluid temperature, doubling pressure maintains constant velocity with 50% less area and requires only 25% of the volume to contain an equal mass of air. While a pressure ratio of 4:1 provides near optimal efficiency for recuperated microturbines, it naturally leads to cost inequalities when compared to higher-pressure ratio turbines.

The cost impact of pressure ratio can be readily appreciated when you consider the simplified representation in Figure 5, where both cubes represent turbines of the same power. The smaller cube has a pressure ratio 4 times greater and a mass only 12.5% of the larger.

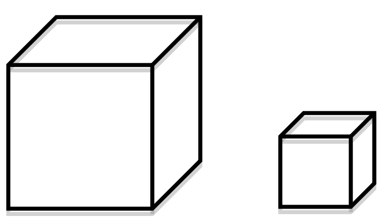

Figure 5. Volumetric impact of a four-fold increase in pressure.

At 15:1 pressure ratio the ICR350 represents a new breed of microturbine. Employing an independent multi-spool approach it is able to leverage microturbine technology while benefiting from a pressure ratio associated with MW size machines. The smaller turbocharger-like components, readily identified in Figure 6, not only result in a cost effective solution, but one that is easily accommodated within the existing automotive manufacturing infrastructure. Overcoming the critical cost flaw and reducing price of adoption are vital elements for the success of any automotive turbine solution.

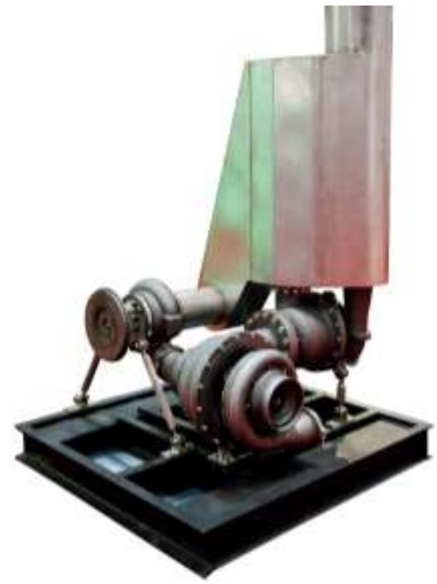

Figure 6. ICR350 Horizontal Generator Configuration.

4.0 DIESEL ENGINES

Diesel engine dominance of MHDV's has been achieved by maintaining cost & efficiency superiority. With continuous improvement and timely technology injection, diesel engines have always risen to the challenge, a trend interrupted by recent EPA mandates.

	2004	2005	2006	2007	2008
Caterpillar	Advanced combustion emissions reduction technology	Advanced combustion emissions reduction technology	Advanced combustion emissions reduction technology	Diesel particulate filter & clean gas induction	Diesel particulate filter & exhaust gas recirculation
Cummins	Exhaust gas recirculation	Exhaust gas recirculation	Exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation
Detroit Diesel	Exhaust gas recirculation	Exhaust gas recirculation	Exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation
Navistar	Exhaust gas recirculation	Exhaust gas recirculation	Exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation
Mack/Volvo	Exhaust gas recirculation	Exhaust gas recirculation	Exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation	Diesel particulate filter & exhaust gas recirculation

Table 2. Diesel Emissions Technologies
Source: 21st Century Truck program

To comply, diesel engines have significantly increased in complexity, requiring in-cylinder refinements and exhaust after

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treatment systems, (3). Emission compliance technologies, such as those identified in Table 2, are now causing efficiency to fall and cost to rise. The precipitous drop in efficiency that occurred in 2002 and a current efficiency reflective of mid-1990 levels is illustrated in Figure 7. While technology development has successfully mitigated further efficiency erosion, the uncharacteristic accelerated deployment has greatly impacted reliability.

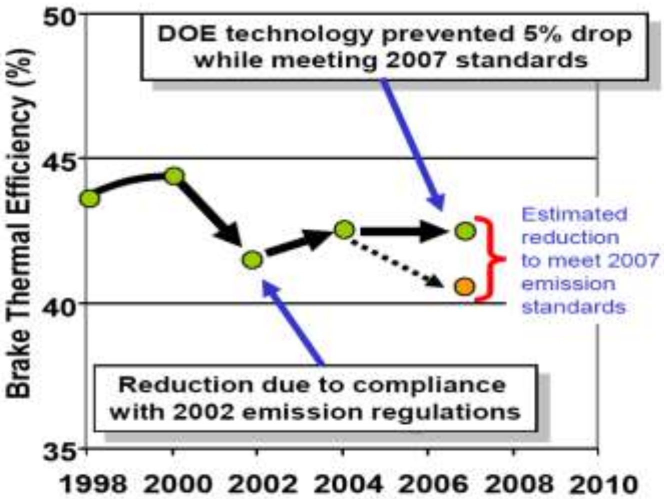

Figure 7. Impact of Emissions legislation on diesel efficiency
Source: D. Ronneberg, Vehicles Technologies Program, 2009.

Diesel engines are now caught in the perfect storm. Not only have the added emissions technologies caused a reduction in performance, increased engine costs, and reduced reliability, but recently proposed efficiency measures introduce the conundrum of reducing weight and improving efficiency without impacting emissions: A task made more daunting by the added constraint of reducing costs. Some of the solutions in consideration for efficiency improvements even include additional turbomachinery in the form of organic Rankine cycle machines and turbo-expanders. When simplification is required, it seems the only solutions drive diesel engines towards increased complexity, a characteristic not typically associated with cost reduction and reliability improvement.

5.0 INFLUENCE OF EXTERNALITIES

Besides economic and functionality benefits, new technology deployment and rate of penetration is also influenced by legislation and uncontrolled events, (4). It was a combination of emissions legislation and the fuel crisis that sealed the fate of early automotive turbines. Today, those same forces, in the form of combined EPA mandates, depicted in Figure 8, and pending efficiency and alternative fuel legislation today enhance the prospects for automotive turbines at the expense of the incumbent diesel engine.

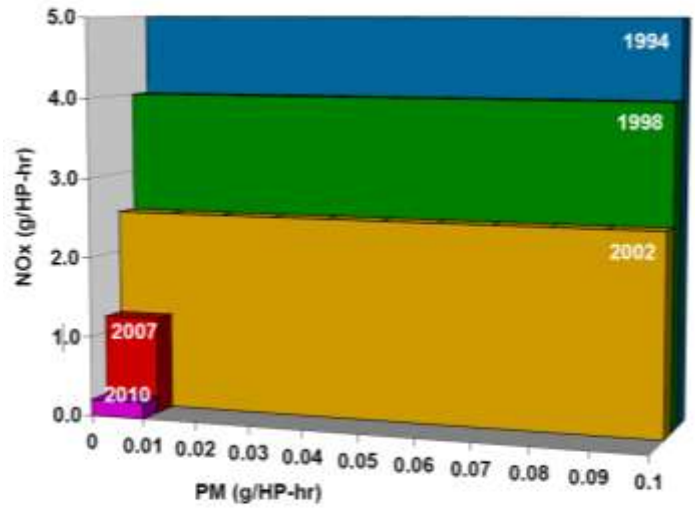

Figure 8. Diesel Emissions Regulations
Source: EPA

Hybrid Electric Vehicles, (HEV's), are the auto industry's latest solution for lowering emissions and reducing petroleum dependency. While offering a solution for smaller vehicles, routinely used for commuting short distances in heavy traffic, it is not a solution for long haul vehicles which, as shown in Figure 9, are typically heavily utilized.

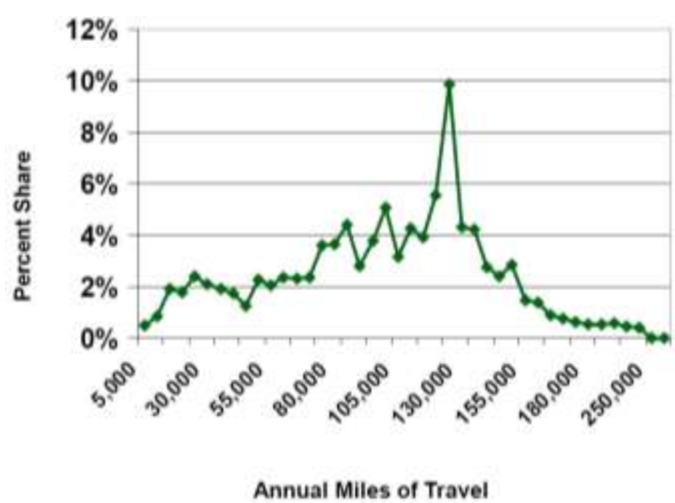

Figure 9. Long Haul Truck Use.
Source: 2002 Vehicle Inventory and Use Survey, EC97TV-US

These vehicles with high annual miles cannot be satisfied by the relatively low energy densities of current battery technology, see Figure 10. Indeed, the added weight of hybrid

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and emissions technology to vehicles not only limits payload capability but also impacts the key efficiency metric Load Specific Fuel Consumption, (LSFC). For long haul MHDV's, the replacement of energy dense hydrocarbon fuel, which has an equivalent energy density over ten-times that of the best battery technology, is a difficult proposition.

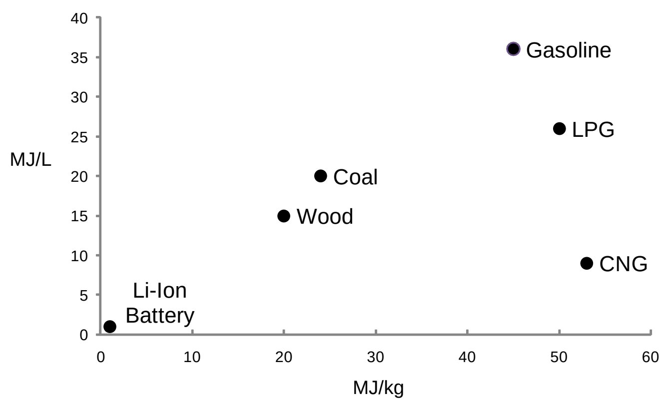

Figure 10. Energy Density comparison.

For high mileage vehicles O&M represent the predominant cost impact to ROI. It is in this category where the superior efficiency and maintenance characteristics of gas turbines are most valued. Fuel costs on average represents 37% of carrier expenses and are the largest single cost element. As indicated in Figure 11, the Class 8 vehicle group consumes 78% of all MHDV fuel, and has been hardest hit by EPA mandates. More than any other vehicle classification, the Class 8 long haul vehicle needs an efficient and cost effective, low weight solution.

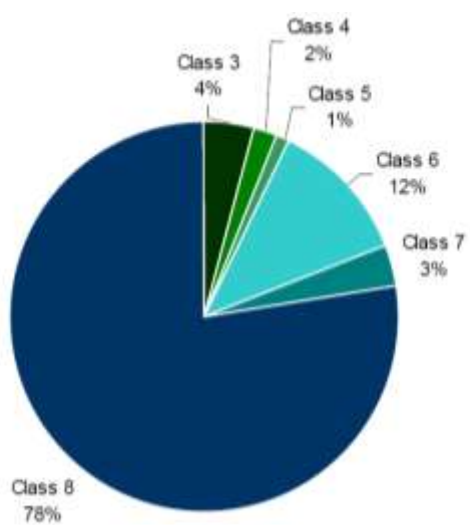

Figure 11. MHDV energy Use:
Source, ORNL Energy Data Book

The current EPA regulations are responsible not only for reducing diesel engine efficiency, increasing weight and complexity, but for raising engine costs by as much as 50%. The consensus of OEM's at the 2010 Diesel Engine Efficiency Research Conference was that having achieved emissions mandates, they now have to apply a similar level of effort to reduce both cost and weight. The newly announced MHDV efficiency standards and the pressure for alternative fuels, deliver further challenges for diesel OEM's and carriers alike. This confluence of externalities, both regulatory and economic, would now appear to favor a turbine solution.

6.0 MHDV ENGINE REQUIREMENTS

Value added solutions address customer requirements that are prioritized to allow for optimization. These requirements are influenced by technical advances, customer perception, legislation, and other external pressures. While product improvements are reasonably predictable externalities are not. It was such unforeseen events that contributed to failed turbine efforts of Chrysler, GM, and Ford.

With the recent legislative changes in the trucking industry a new list of MHDV engine critical characteristics has been developed. The following list was compiled with the assistance of individuals well respected in the industry. These characteristics are prioritized in order of importance.

1. Emissions
2. Reliability/durability
3. Fuel Consumption
4. Low First Cost
5. Ease of Maintenance
6. High Power to Weight ratio
7. Low Weight
8. Small Bulk

The list represents current reality with respect to incumbent diesel engines. Emissions top the list because they are the price of entry, a must have. Reliability and durability rank second because of problems caused by recent introduction of complex new technology. The impact of emissions compliance is punctuated by the low emphasis given to fuel consumption, historically responsible for over 60% of operational costs (5).

With emissions compliance diesel engines have recently incurred cost increases approaching $16,000. These will reduce

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with time because of learning curve effect, but gas turbines, benefiting from new production technologies, stand to be the greater beneficiary. The inherent simplicity and low part count of gas turbines compared to reciprocating engines has long been associated with the promise of low cost. Internal cost analysis indicates the potential for a significant cost advantage when comparing an ICR350 to today's heavy and complex diesel engines.

The remainder of the list also heavily favors gas turbines over diesel engines. Gas turbines do not consume oil or emission reducing fluids, require catalyst replacement or regeneration, or any general maintenance beside air filters. The ICR350's modularity is maintenance friendly with down time considerably reduced by module replacement rather than in-frame repair. Turbines excel in power density and enjoy a significant weigh advantage over diesel engines. With the added penalty of emissions systems the weight advantage is well over 50%, a characteristic that will grow in importance with the introduction of load specific fuel consumption, (LSFC), targets.

Figure 12, Size differential between a Diesel Engine and Class 8 configured ICR350.

Turbines have a high specific power, (power/weight), and therefore occupy a smaller volume than an equivalent power diesel engine. A characteristic amplified by the favorable torque speed characteristics of turbines that allow lower powered turbines to match larger diesel engine performance. The size advantage of the ICR350 compared to an equivalent diesel engine is illustrated in Figure 12. With a favorable aspect ratio, small bulk, and no radiator to consider, one can easily see how the ICR350 could improve vehicle aerodynamic possibilities. Unencumbered by the traditional radiator, creative body styling has the potential to dramatically reduce drag that, as indicated in Figure 13, can account for almost 25% of total losses during interstate driving.

Today, the regulatory framework for the next several decades is in place, EPA and EU emissions rules are harmonized, and gas turbines have significant advantages for transitioning to alternative fuels. With the legislation understood and design criteria known, the ICR350 represents an attractive alternative to the diesel engine, and unlike past turbine solutions is producible and financially viable.

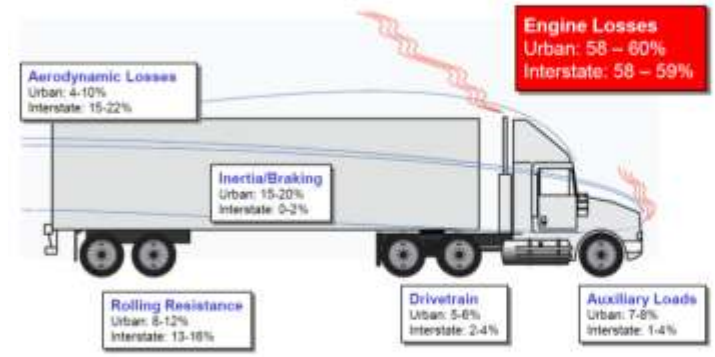

Figure 13, Typical Level Road Energy Losses
Source: 21st Century Truck program

7.0 ALTERNATIVE FUELS

Fuel diversity may be the most important and undervalued attribute not included in the list of MHDV critical characteristics. The inherent flexibility of a turbine to run on liquid or gaseous fuel offers both operational and logistical advantages. Today, with the US having an estimated 200-year supply of clean natural gas and the renewed emphasis on energy security and alternative fuels, the turbines multi-fuel capability could play a pivotal role during early fuel infrastructure development.

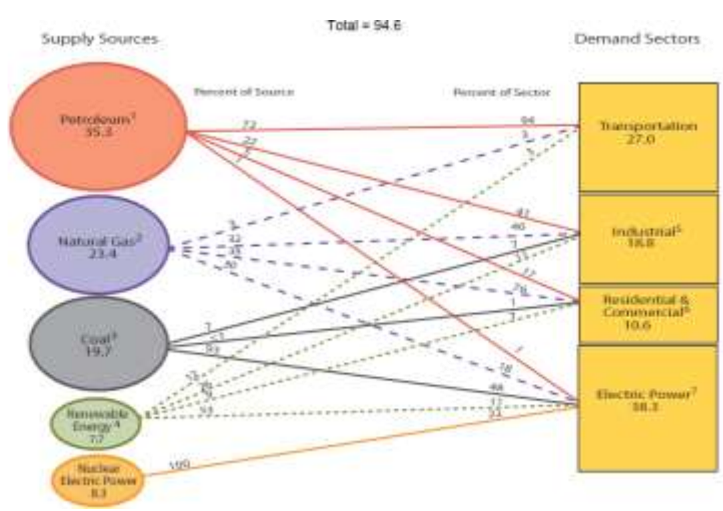

Figure 14. 2009 Estimated Energy Use.
Source: 2009 Annual Energy Review. EIA-0384

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Figure 14, shows the distribution of energy between the different end use segments. Petroleum is the largest fuel component and represents 35.3% of total 2009 US energy use. While other sectors have transitioned from petroleum, transportation, with its dependency on fueling infrastructure, has not. Despite incentive programs, alternative fuels have had little impact, a fact clearly indicated by Figure 15. Transportation is now responsible for 72% of total US petroleum consumption, (6). Adoption of alternative fuels for transportation would go a long way towards both creating a secure energy infrastructure and restoring our balance of trade.

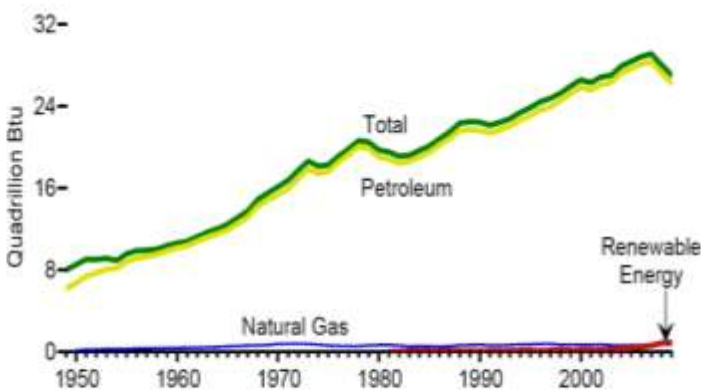

Figure 15. Transportation Total Energy Consumption
Source: 2009 Annual Energy Review. EIA-0384

Our dependence on petroleum, 65% of which is imported, and the need to encourage change is addressed by two recent pieces of major legislation: EISA, Energy Independence and Securities Act of 2007, and ARRA, American Recovery and Reinvestment Act of 2009. At the time of writing there is also focused Natural Gas Vehicle, (NGV), legislation tabled in the Senate, S.3815, titled "Promoting Natural Gas and Electric Vehicle Act of 2010". This latter bill, supports and incentivizes NGV's, with a particular emphasis on MHDV's. This bill, as any natural gas favored legislation, increases the value of an infrastructure flexible solution.

Replacing petroleum with natural gas not only reduces our reliance on imported oil but also significantly reduces GHG emissions. Transportation represents the single largest CO2 source both in the US and worldwide, and is responsible for 85% of total GHG emissions. While Figure 16 shows that the industrial sector has seen a reduction in CO2 emissions over recent years, it is evident that transportation has continued to climb, hardly influenced by legislative efforts.

EPA studies suggest that simply replacing diesel fuel with Natural Gas would reduce CO2 emissions by 25%, (7), and is the most viable alternative for the reduction of GHG's. Natural gas, which is both local and cheap, would therefore seem an obvious choice but despite subsidies the results have been poor typically only resulting in localized solutions. While natural gas has displaced carbon richer fuels in the industrial segment, transportation remains hostage to the established petroleum infrastructure.

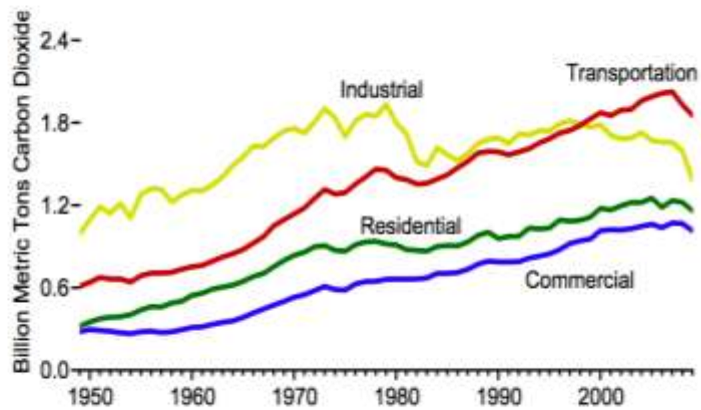

Figure 16. Carbon Dioxide Emissions from Energy Use
Source: 2009 Annual Energy Review. EIA-0384

Gas turbines can be considered fuel agnostic, with the ability to burn a wide range of fuels both liquid and gaseous, and within reason turbines are also insensitive to calorific value. In power generation it is not uncommon for turbines to have dual fuel capability, including on-the-fly fuel switching. This ability provides energy security for interruptible fuel supplies and the economic advantages of fuel scheduling based on spot price.

These advantages equally apply to long haul MHDV's, permitting the choice of the most economic fuel while affording the flexibility to accommodate routes independent of infrastructure limitations. With its plentiful local supply and reduced GHG footprint, natural gas will ultimately grow from its current niche application to widespread use. When it does the fuel flexible automotive turbine affords the ideal transitional solution.

8.0 ICR350 TURBINE ENGINE

The 350kW/470hp rated ICR350 is a three-shaft, intercooled-recuperated gas turbine comprising HP and LP turbocharger modules for the gasifier section, and an expander module for power take off. At 15:1 it has a higher pressure ratio than typical microturbines but because of its multi-shaft

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arrangement uses a similar class of turbomachinery. At this higher-pressure ratio, size and cost of expensive hot-section components are reduced dramatically, especially for the high temperature turbine, recuperator, and combustor, (7).

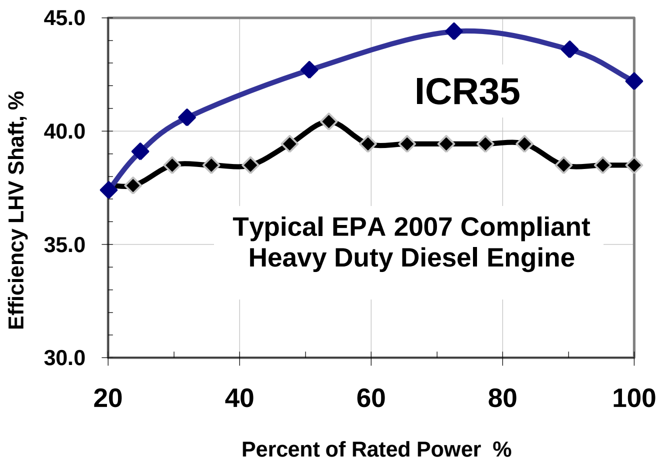

Figure 17. Part Load Efficiency of the ICR350 vs. 15L Diesel

Constructed from robust commercial turbocharger-like modules, the three spools of the ICR350 operate in a low-stress regime for improved reliability. The small HP turbine stage operates at very low tip speed, enabling the use of production ceramics well proven in the turbocharger industry. Figure 17 illustrates the superior efficiency of the ICR350 compared to an EPA compliant diesel engine. The wide high efficiency operating range is achieved by using a variable geometry nozzle on the free power turbine, an architecture that has proven part-load performance advantages.

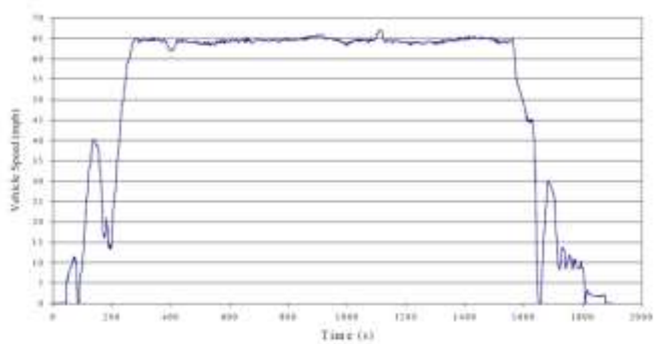

Figure 18. HHDDT Cycle

Mission analyses and simulations have led to an optimized engine design for the ICR350. The cycle was selected after several iterations to emphasize mid-to-low-range efficiency and thereby maximize fuel savings. Using the standard long haul industry cycle, HHDDT, Figure 18, simulations indicate a 14% better fuel consumption compared to an EPA compliant diesel engine. The study included engine performance improvements only. Reduced weight and lower aerodynamic losses will give rise to increased savings.

The ICR350 combustor, illustrated in Figure 19, is a silo combustor, designed using established formulae and practices employed in modern microturbines. These designs are characterized by high temperature recuperated inlet air, which enables lean reaction conditions. Despite relatively high turbine inlet temperature the reaction zone of the ICR350 is cooler than typical microturbines currently meeting CARB2007 emission standards. The moderate reaction zone temperature is the key to achieving ultra-low NOx levels.

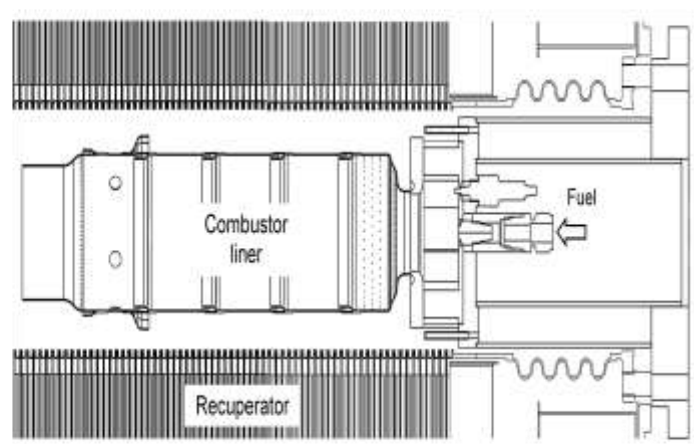

Figure 19. ICR350 Combustor located within recuperator.

A unique and advantageous feature of the ICRTec technology is that during power excursions volumetric flow remains nearly constant and thus does not impact reaction zone kinetics. This achieves similar results to a variable geometry combustor, maintaining low emissions throughout useful part load operation, without the mechanical complexities.

The main attributes of the ICR350 can be summarized as follows:

- *Design-Point Efficiency.* Net shaft efficiency exceeds 44% LHV over the majority of the driving cycle. This stems from the superior thermodynamics of the intercooled cycle and the elevated turbine inlet temperature.

- *Partload Performance.* Turndown net electrical efficiency exceeds 40% LHV from max power down to 30% load.

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- *Low emissions with multi-fuel capability.* As proven in today's microturbines, the ICR350 operates with a low reaction zone temperature for NOx control, and long residence times to achieve CO burnout.

- *Specific Power.* Increased specific power drives down the size of all components. The recuperator weight is 11% that of competing microturbines at comparable power and thermal effectiveness.

- *APU Mode Operation*. With a PMG integrated into the high-pressure spool the ICR350 can operate in low power APU mode as a single shaft recuperated turbine.

The ICR350 embodies the intrinsic values of an intercooled-recuperated turbine and with its unique integration of turbocharger-like modules benefits from existing high volume manufacturing, well understood by the automotive industry. At a time when the diesel engine looks to aerospace technologies for efficiency improvements, the ICR350 has incorporated automotive solutions to address cost. Even without the tremendous advantage of fuel flexibility the ICR350 presents a viable alternative to the modern diesel engine and a significant improvement over other microturbine solutions.

9.0 CONCLUDING REMARKS

Diesel engines have long been the prime mover of choice for MHDV's and have benefited from tremendous technological advancements over recent years. However, EPA 2010 mandated NOx and PM reductions place unprecedented strain on the incumbent technology. To comply, diesel engines have become less efficient, occupy more space, require emissions lowering sub-systems, have lower reliability, require specialized maintenance, and are significantly more expensive.

Engine OEM's, having just completed the engineering and production introduction of emissions compliance technologies, now face significant weight and cost challenges. With pending MHDV efficiency mandates in 2014 and in cylinder engine efficiency at its limit there is even consideration now being given to additional turbomachinery solutions to make use of waste heat recycling. That non-engine related improvements are being given serious consideration is indicative of impending technology stall.

Automotive gas turbines came close to reality once, only to be frustrated by emissions legislation and a poorly timed fuel crisis that placed increased importance on efficiency. Today benefiting from accelerated improvements, characteristic of a newer technology, and favorable legislation, gas turbines have at last caught up and surpassed diesel engines. The ICR350 offers a simpler, cleaner and more efficient solution that greatly exceeds EPA 2010 mandates without after treatment.
Looking to the future it is the turbines fuel flexibility that could provide the technology tipping point. With an increased sensitivity towards energy independence alternative fuels are again the focus of much attention. There is both a heightened level of legislation and technology development surrounding alternative fuels, particularly natural gas. If energy independence were pursued in earnest a turbine's inherent insensitivity to fuel type would greatly simplify the complex logistics of infrastructure transition.

In simulations verified against prior designs, the ICR350 performs substantially better than diesel engines and in addition affords aerodynamic and payload advantages. The ICR350 with its high-pressure ratio and turbocharger-like construction not only exceeds diesel engine performance but in volume production will enjoy cost benefits. At a time when diesel engines are resorting to aerospace solutions it is only fitting that a key ICR350 differentiator is its use of automotive technology.

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