PHASE III TRANSIT-BASED LPG MICROTURBINE RAPID-INTERVENTION PROJECT (DOCKET #10741)

FINAL REPORT

LESSONS LEARNED:
LPG MICROTURBINE FUEL SYSTEM

Prepared For:

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I. EXECUTIVE SUMMARY

From August 2001 to March 2003, The ADEPT Group, Inc. (ADEPT), with partial support of three (3) separate grants from the Propane Education and Research Council (PERC), actively assisted several LPG microturbine hybrid electric vehicle (HEV) integration sites (in Downey, CA, Galveston, TX, Los Angeles, CA, and Santa Clara, CA).[1] In conducting extensive site investigations that included, but were not limited to: safety inspections, fuel quality tests, fuel system parts selection, fuel system design, performance monitoring and troubleshooting of key components, conciliatory functions, and general problem solving, ADEPT worked closely with the: microturbine manufacturer, bus/shuttle integrators, bus/shuttle owners and staff, LPG fuel testing laboratory, LPG industry safety and fuel system experts, and LPG suppliers.

Over the course of the three projects, ADEPT acquired a considerable database on diagnostic and preventative measures to address various LPG fuel system-related issues. This report is to assemble and disseminate this information, while respecting the confidentiality of site-specific proprietary information.[2] This report is to be made available to HEV industry leaders, to known current and near-term HEV end-users, and to other interested parties.

The LPG HEVs investigated during this project utilize one (1) or two (2) 30kW Capstone LPG microturbines as "range extenders" (see Appendix 1 for Capstone's datasheet). In every case, the HEVs were of "in-series" hybrid design. The battery-powered electric motors were the prime movers. The microturbine/s generated electricity to recharge on-board batteries. This on-board power generator allows the vehicle to remain in service longer than would an equivalent all-electric vehicle.

Capstone microturbines demand specific conditions of the LPG fuel delivered to its fuel system entry point. The notable characteristics of LPG (discussed in detail below) increase the complexity needed in the fuel system design. Figure 1 is a diagram of a simplified fuel system provided as reference for the "menu" of fuel system options outlined in this report.

[1] ADEPT conducted a private inspection of a LPG microturbine HEV site in Christchurch, New Zealand. Lessons learned from this investigation are incorporated in this report.
[2] Thorough confidential site investigation reports were previously submitted to PERC.

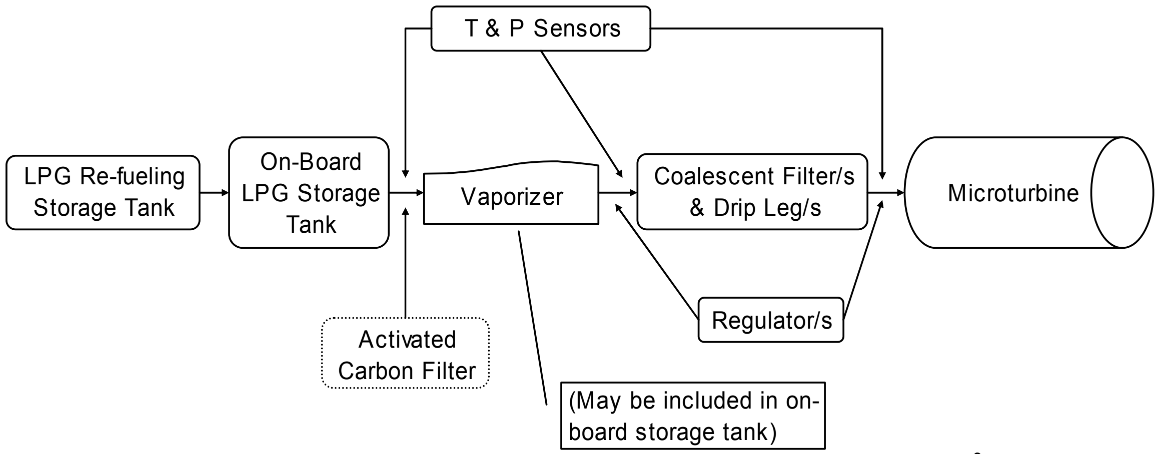

Figure 1: Generic LPG Microturbine HEV Fuel System Diagram[3]

Fuel quality was a concern throughout the projects. ADEPT conducted a total of 16 fuel quality and residue analysis tests. These tests proved to be a valuable tool to diagnose and identify sources of problems as well as to identify preventative measures. By and large, the sampled LPG was within HD-5 specification. At the close of the project, LPG was upheld as a viable HEV fuel.

The two primary concerns taken into consideration were the presence of heavy-end contaminants (heavy-ends) in the fuel and the possibility of partial condensation of butanes and heavier compounds in the LPG fueling system. The most desirable approach is to filter out the heavy-ends and to keep the fuel vapor temperature consistently throughout the fueling system and above its dew point, while at the proper delivery pressure required by the microturbine's own vaporized fuel control system. This report is to broadcast techniques (and to establish another documented reason for follow-on request for industry-wide support to validate yet-to-be-proven techniques) that will accomplish this task while maintaining the integrity of the fuel system.

II. VAPOR PHASE LPG

The particular microturbine used by the integrators in the PERC co-funded projects required gaseous phase LPG to be delivered to the microturbine's fuel system at below 120°F and between 60 and 66 psia.[4] This is not a small order when dealing with commonly sold HD-5 grade LPG. Yet, there are ways to design a fuel system to achieve the desired end result.

A. LPG: The Basics

To understand the behavior of LPG in the HEV fuel system, it is important to first review the properties of LPG and of the hydrocarbon compounds that account for the bulk of HD-5 fuel. Table 1 shows the compounds that are known to account for the large majority (>99.9%) of commercial LPG.

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[3] Not representative of a specific fuel system investigated during the projects.

[4] psia = absolute pressure in lbs./in.^{2} $P_{absolute} = P_{gage} + P_{atmosphere}$, where $P_{atmosphere}$ = 14.7psi.

Compounds shown in bold font typically account for most of the volume of commercial HD-5 or HD-10 LPG. Figure 2 is a plot of the condensation curves of these key LPG components along with the dew point curves of HD-5 and HD-10.

LPG COMPOUNDS

COMPOUND	DENSITY (lbs/gal @ 60°F)	VAPOR PRESSURE (psig @100°F)	TYPE
(1) Methane, CH_4	2.5	-	– *(paraffin)*
(2) Ethene, C_2H_4	3.3	-	– *(olefin)*
(3) Ethane, C_2H_6	**3.11**	**700**	**– *(paraffin)***
(4) Propene, C_3H_6	**4.35**	**212.5**	**– *(olefin)***
(5) Propane, C_3H_8	**4.23**	**175.8**	**– *(paraffin)***
(6) Butadiene-1,2, C_4H_6	-	-	– *(olefin)*
(7) Butadiene-1,3, C_4H_6	-	-	– *(olefin)*
(8) trans-Butene-2, C_4H_8	-	-	– *(olefin)*
(9) cis-Butene-2, C_4H_8	-	-	– *(olefin)*
(10) Butene-1, C_4H_8	5.011	47.6	– *(olefin)*
(11) iso-Butene, C_4H_8	5.004	48.9	– *(olefin)*
(12) iso-Butane, C_4H_{10}	**4.69**	**57.5**	**– *(paraffin)***
(13) n-Butane, C_4H_{10}	**4.86**	**36.9**	**– *(paraffin)***
(14) Pentene-1, C_5H_{10}	5.2	-	– *(olefin)*
(15) iso-Pentane, C_5H_{12}	5.387	5.7	– *(paraffin)*
(16) n-Pentane, C_5H_{12}	5.25	0.9	– *(paraffin)*
(17) n-Hexane, C_6H_{14}	5.49	-	– *(paraffin)*

Table 1: Typical LPG Compounds

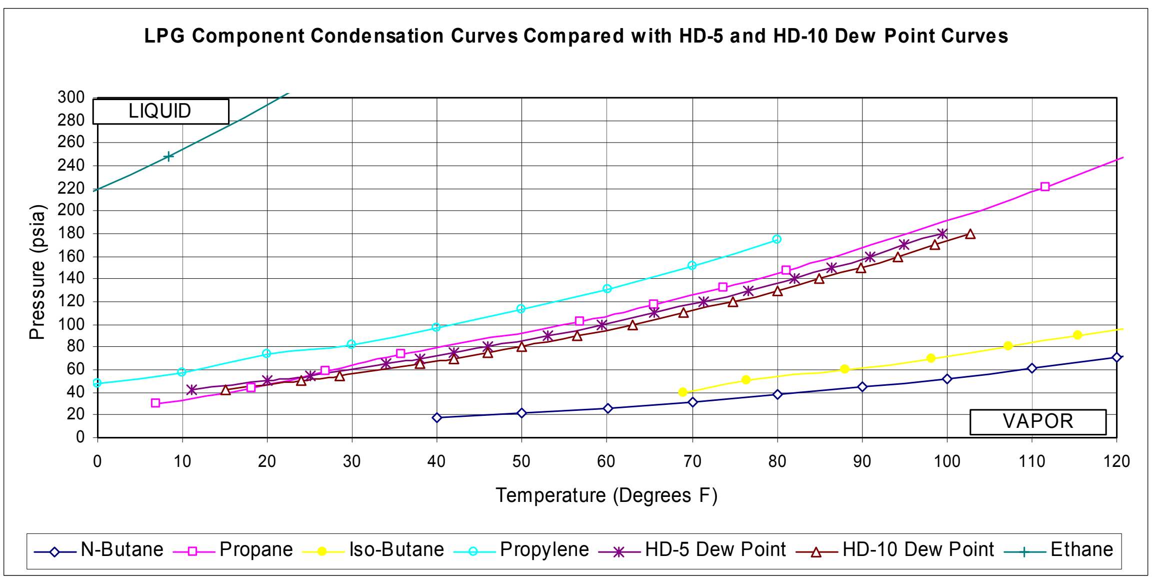

Figure 2: LPG Dew Point Curves Compared with Component Condensation Curves

A comparison of the empirical data of the hydrocarbon compounds that comprise LPG with likely operating condition parameters of the HEV LPG fuel system indicate the need to continuously monitor temperature and pressure conditions throughout the on-board fuel system. LPG is very sensitive to changes in temperature and pressure. Under normal conditions, LPG is close to the edge of transition between liquid and vapor.

LPG fuel systems should be designed with a keen awareness of bubble and dew point curves applicable to the LPG to be used at a particular site. Figures 3 and 4 are the bubble and dew point curves of HD-5 and HD-10 respectively.

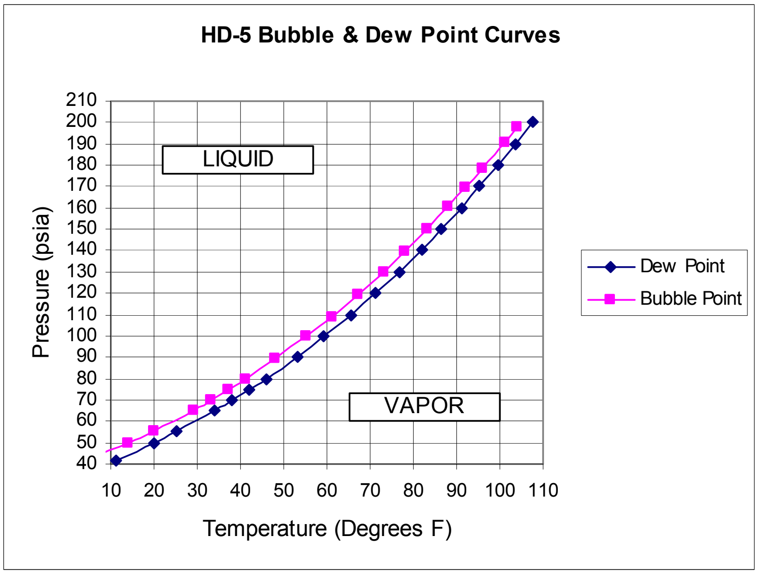

Figure 3: Bubble Point and Dew Point Curves for HD-5

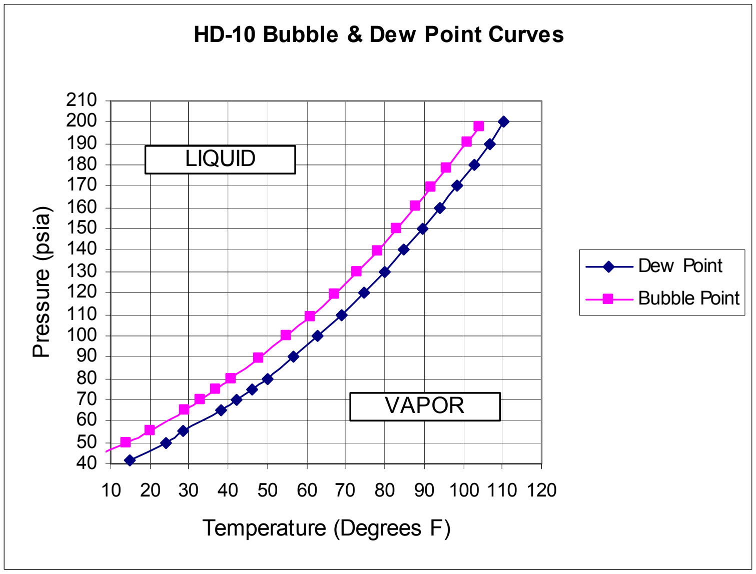

Figure 4: Bubble Point and Dew Point Curves for HD-10

Lower pressures and higher temperatures increase the probability of keeping LPG in vapor state. Given that the on-board pressure regulation system works as it is supposed to, the vapor pressure of gas phase LPG in HEV fuel systems is not supposed to fluctuate.

When LPG flows through a pressure regulator and its pressure is reduced, there is an associated temperature drop due to the expansion of the gas. This is called adiabatic expansion (i.e. temperature loss due to pressure drop). Depending on the pressure and temperature at origin (e.g. from the vaporizer), empirical analysis of actual recorded field data indicated that such temperature loss from adiabatic expansion can be as much as 10°F. One must take into account such adiabatic expansion when designing an HEV on-board fuel system.

B. Vaporizing LPG

There are several industry-accepted methods to vaporize LPG. Most require heating the LPG in one way or another. The most important concern to keep in mind is that any method used to heat an LPG tank or fuel system component should always be thermostatically controlled (with redundancy, when possible). Liquid LPG can expand up to 270 times when vaporized. ADEPT suggests not to heat LPG above 130°F.

1. Vapor Phase Draw

Vapor phase may be drawn directly from the on-board LPG storage tank via the vapor valve. The vapor valve draws vapor from the top of the tank. When operating at cooler ambient temperatures, the generated vapor pressure may be insufficient to meet the intake demand of the turbine to stay "at speed."

Also, when LPG vapor is drawn, some liquid LPG will evaporate to compensate, and this causes a cooling effect inside the tank. This cooling effect becomes increasingly significant with higher evaporation rates. As this cooling effect increases in importance, the supply of heat to compensate for it must be allowed for and properly controlled.

Vapor-draw type systems typically heat the tank to overcome the cooling effect due to the vaporization of LPG. Besides thermostatically controlling such a system, it is suggested to also incorporate a safety relief system to prevent the possible negative effects of overheating the tank.

Besides the above-described cooling phenomenon, using a tank as a vaporizer causes eventual "weathering" of the LPG in the storage tank. Vapor draw acts in effect as a slow partial distillation process. The lighter components boil off first, leaving the heavier components of behind. The heavier components (i.e. butanes, pentanes) gradually accumulate in the storage tank, increasing their overall volume percent in the tank versus the lighter ends. This will reduce the blend's vapor pressure and will change the fuel's overall characteristics.

The more "weathered" the fuel on-board becomes, the more likely it is for heavy-ends to be entrained into the fuel delivery system and to condense to liquid form (due to their lower vapor pressure, and higher boiling points). As previously mentioned, it is not acceptable to have liquid phase LPG forming at any point in a strictly vapor phase LPG fuel delivery system.

To avoid these problems, vapor drawn tanks must be drained and cleaned at appropriate time intervals. The replacement schedule of "weathered" fuel with new LPG requires further investigation (set up a protocol to draw periodic LPG samples and conduct fuel composition tests to asses the rate at which the tank is "weathering").

(a) Electric Heat Tape & Electric Heating Blankets

Utilizing heat tape and heating blankets to wrap fuel lines and/or storage tanks is an effective method for heating liquid LPG and keeping downstream components warm enough to ensure complete vaporization. However, there is not a lot of support from the LPG industry for this approach.

Thermal strains as well as corrosion due to electrolysis are concerns when heat tape or heating blankets are used on components under pressure (e.g. fuel manifold, fuel lines, on-board storage tank, etc.). Hot wires on metallic fuel system components raise the same issues as hot wires on neoprene hoses. Applying direct heat and possibly weakening areas that hold back pressure is not an accepted practice.

From what ADEPT has seen to date, it is not clear whether such thermal strain conditions exist in systems that incorporate these methods. However, this concern should not be ignored. It is strongly suggested that fuel systems incorporating electric heat tape and electric heating blankets be regularly and frequently inspected.

(b) Heat Exchangers

An external (to the LPG fuel system) heat exchanger can be used to transfer heat to a working fluid that can be circulated between the heat source and the on-board storage tank. When determining the technique to transfer heat to the tank, it is suggested to use a technique that will distribute heat over the tank surface area as evenly as possible.

Another method to heat LPG in a tank is to circulate liquid LPG through an external heat exchanger and return vapor to the storage tank. This technique was developed and made commercially available by an LPG tank manufacturer.

Jacketed or sleeved LPG tanks are also available. These allow the circulation of a working fluid to come in direct contact with the tank.

2. Liquid Phase Draw

Liquid phase LPG can be drawn from the liquid withdrawal port of an on-board LPG storage tank. Liquid draw systems avoid issues relating to tank pressure, tank heating, and weathering effects. These systems require an external vaporizer unit to convert the liquid LPG to a gas. Typical vaporizers cause a pressure drop to vaporize the LPG. This causes a cooling effect that could freeze the vaporizer. This can be countered by circulating a working fluid through and/or around the vaporizer. Microturbines do not use a coolant ("working fluid") so alternative means must be developed to transfer heat to a working fluid. A possible solution is to use the heat from the battery pack(s). Electricity available on a microturbine HEV can be used to operate an electrically powered vaporizer.

C. Performance Monitoring: Keeping LPG in Vapor State

The addition of appropriate sensing devices is crucial to: (i) allow for feedback/correction of fuel delivery rates and/or fuel/air ratio; (ii) detect any residue accumulation; and (iii) monitor fuel phase. Such electronic sensors can be connected with simple circuitry.

Using the HD-5 or HD-10 dew point curve as a boundary condition, pressure transducers and thermocouples can be installed in specific points throughout the fuel system to monitor operating conditions and fuel systems performance. For a Capstone turbine that requires 100% vapor phase LPG, it is critical to maintain temperatures and pressures that will keep all LPG components in gas phase throughout the fueling system leading to the microturbine's intake. The data from the fuel system monitors should be logged. ADEPT found this diagnostics approach to be a valuable troubleshooting tool.

III. FUEL QUALITY

ADEPT spent over $25,000 for fuel quality and residue analysis tests for the three projects (~$15,000 of which was PERC funded). Although a detailed analysis is outside the scope of this report, valuable data gained from these tests led to diagnostic techniques, near-crisis resolutions, and preventative measures.

The main fuel quality issue uncovered was the presence of heavy-end compounds (approximately 16 to 35 carbon atoms per hydrocarbon molecule) in LPG. Some of the LPG contaminants repeatedly identified include: rubber hose leachate compounds and lubricating oils from refinery sources. Heavy-ends accumulations were observed in LPG HEV on-board fuel system components (e.g. regulators, fuel metering valves, fuel manifolds, etc.). For instance, a build up of heavy-ends was reported to deteriorate a regulator's ability to maintain steady pressure. Ways to mediate heavy-ends caused problems are discussed in this report.

At one site, a fuel test result indicated unusually high propylene content (19.4%; 9.4% greater than HD-10 spec LPG required in California for automotive use). ADEPT arranged for HD-5 spec fuel to be delivered to this site.

IV. FILTERING LPG

A. Liquid Phase Filtration

1. "Rock Catcher"

A "rock catcher" is similar to a bar screen in wastewater treatment applications. Rock catchers pre-filter liquid phase LPG to remove large particles. ADEPT recommends that fuel quality-sensitive LPG fuel systems use a valve screen(s) to prevent debris from entering the fuel system. It is not a bad idea to use redundancy (e.g. one can be installed at the fill port, and another at on-board storage tank liquid withdrawal outlet).

2. Activated Carbon (AC) Filters

Research indicates that AC filters are a promising option to strip heavy-ends from liquid phase LPG.[5] This technique is not mutually exclusive to the use of coalescent filters mentioned below in "Vapor Phase Filtration."

From fuel tests conducted in Phases I through III of the Microturbine Rapid-Intervention Project, ADEPT concluded that:

(a) Upstream LPG suppliers have little, if any, financial motivation to change current production processes.
(b) LPG distributors and retailers must develop their own methods and processes to appropriately clean heavy-ends from LPG for applications other than naturally aspirated combustion (i.e. space heaters, cooking ranges, water heaters, barbeques, etc.). Such processes must be simple, relatively cheap, and readily implementable if LPG is to be a viable fuel for fuel cells or advanced internal combustion (IC) engines.
(c) There is good reason to believe that AC filters can do the job and at the same time reduce sulfur content (another desirable for fuel cells and/or advanced IC engines).

Chemically, AC is an imperfect form of graphite. This imperfect form leads to a very porous structure with a wide range of pore sizes (from visible cracks to molecular dimension pores). Porosity is what "activates" AC.[6]

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[5] This follows ADEPT's February 2002 report titled, "Preliminary Report on Activated Carbon Filtration of Liquid LPG" (Appendix #1).
[6] Source: Calgon Carbon Corp.

AC removes contaminants through adsorption. Contaminants attach to AC by a Van der Waals'-like force[7] that exists between molecules. The reaction is similar to precipitation, as adsorbates are removed from solution. AC can be used for the adsorption of mainly organic compounds. AC will attract carbon-based materials better than inorganic compounds ("like attracts like" principle of adsorption).

Critical parameters for AC are: (1) pore size distribution; (2) surface area; (3) chemical nature of carbon source; and (4) contact time between contaminant and AC. The longer the impurities are in contact with the AC the more likely the contaminants are to find a vacant bonding site on the AC.

"Generally, the higher the concentration and the larger the molecules, the greater the amount adsorbed."[8] AC will have a greater affinity for large contaminant molecules than it will have for smaller LPG fuel molecules (~3 carbon atoms).

Calculations were performed to provide an initial estimate on the amount (mass) of AC needed to effectively strip heavy-ends from liquid phase LPG at appropriate intervals. It is thought desirable to change the AC filter media about once a month. The findings of these calculations were the basis (among other specifications) of an AC filter prototype that ADEPT commissioned Southwest Research Institute (SwRI) to assemble. SwRI completed the construction of this prototype in September 2002.

Actual tests on the completed AC filter prototype are beyond the scope of this project. However, much work remains to be done to validate and eventually commercialize this technology. ADEPT, based on documented need and industry demand for such products, will apply to PERC to conduct a follow-on project to develop further empirical evidence to optimize AC filters to effectively clean heavy-ends from liquid phase LPG.

Since AC filters can strip out all or part of the required odorant (ethyl, tetrahydrothiophene, and/or ethyl methyl sulfide mercaptan), there are safety concerns that must be addressed to properly use an AC filter onboard an HEV. As the entire on-board fuel system or portions thereof will contain deodorized LPG, it is important for LPG to acquire a similar waiver as LNG for such applications (to install alarms in certain vehicle compartments).

[7] Van der Waals' equation of state allows for the volume occupied by the molecules and for the attractive force between molecules (Handbook of Chemistry and Physics, The Chemical Rubber Co., 1969).
[8] Source: Calgon Carbon Corp.

There is currently no off-the-shelf AC filter technology for automotive applications. The need for such a technology is critical as the LPG industry looks to broaden its market share as an on-road and off-road fuel, as well as to ensure its future in the fuel cell and HEV industries.

B. Vapor Phase Filtration: Coalescent Filters

Coalescent filters are commonly used to remove heavy oils and aerosol contaminants from vaporized gas streams (including vaporized LPG). Coalescent filters usually have replaceable filter media. Filter fibers can be made of several materials, including cellulose, polymers, and ceramics. Heavy oils suspended in the gas stream collect on the filter media by one or a combination of the following processes:

(i) Phase change;
(ii) Adhesion;
(iii) Surface tension;
(iv) Physical entrapment; and/or
(v) Gravity Separation.

If not already installed, ADEPT suggested that coalescent filters be installed in all vapor phase LPG fuel systems encountered during this project. In some cases, despite the inclusion of coalescent filters, some heavy-ends did collect downstream of the coalescent filter. Heavy-ends carried through the fuel delivery system can clog delicate fuel system components (i.e. regulators, solenoids, "smart proportioning valves," etc.).

ADEPT conducted a thorough investigation in the efficacy of coalescent filters. Several issues were raised in this investigation:

1. Efficiency

The question was raised of how efficient coalescent filters really are to trap and collect heavy-ends. An initial desktop analysis on the efficacy of coalescent filters was conducted. Calculations indicated that it may be beneficial to add a second coalescent filter. The downstream filter should be the same grade finite filter or higher (more efficient).

This suggestion brought up concerns of whether the filters could handle the gaseous flow rate requirements for the LPG fuel system. Forcing gas through the coalescent filter at an excessive rate could damage the media fibers. Such damage may contaminate the vaporized fuel line system downstream of the filter, potentially clogging the regulator and fuel mixing/injection system. To avoid such an undesirable development, ADEPT consulted with Capstone and the filter manufacturer to determine if a filter can be designed for the estimated LPG flow rate. Calculations illustrated that the fuel system's flow rate requirements were less than the maximum allowable for the selected off-the-shelf coalescent filters (within a comfortable margin, 20%).

Another concern was that the additional filter will cause additional pressure loss in the fuel line. The maximum additional pressure drop through the suggested second filter was calculated, but the decision to add such a filter was hinged on verifying that the LPG fuel system could allow for the additional pressure drop.

2. Additional Residue Formulation

It was also not known if the filter element could possibly contribute to the formation of heavy-ends. A used coalescent filter element was sent to an appropriate test lab to analyze the residue collected in the filter media. The analysis compared the gas chromatography-mass spectrometry results of the extracted residue with those residues collected from the drip leg downstream of the coalescent filter. The absence of any significant concentrations of new components in the residue extracted from the filter element eliminated the possibility that the filter element itself contributed to heavy-ends formation.

3. Coalescent Filter Performance

The coalescent filter is a natural collection point for residues in the LPG fuel system. However, if the filter bowl is not monitored and the residues are allowed to rise to a point where they might come in contact with the filter element, the function of the coalescent filter is impaired. Currently, there is no technology available to detect when the residues is at an unsafe overly high level. A non-intrusive, non-invasive point level sensor on the outer coalescent filter housing would help to optimize the maintenance process. If such technology is developed and implemented, coalescent filters would be drained on an as-needed basis. The coalescent filter point level gauge must be coupled a coalescent filter pressure drop sensor to properly inform operator/s of immediate necessary maintenance.

ADEPT suggested that HEV integrators place pressure sensors on either side of the coalescent filter to quantify the pressure drop and how it changes over time. The filter element is to be replaced when the pressure drop exceeds the manufacturer’s recommendations. Such a pressure drop sensing device is available from one of the coalescent filter makers.

It should be noted that such a device will not alert the operator of potentially dangerous levels of collected residues in the filter bowl.

4. Maintenance

There were no records to indicate if the coalescent filters were properly maintained (e.g. were they drained and monitored by the on-site personnel on a regular basis?; were the filters replaced as often as necessary?; etc.). Lack of coalescent filter maintenance might have been a possible cause of injector failures. Left unmonitored, spent filters could cause downstream pressure and fuel quality problems.

In some instances, ADEPT found that maintenance personnel discharged the entire contents of LPG in the fuel delivery system prior to being able to access the filter and replace the filter element. This unpleasant (and unhealthy) procedure was conducted without any indication that the filter bowl actually needed to be drained or the filter element needed to be changed. Discharge of explosive LPG laden with mercaptans was a fire hazard, health hazard, and a waste of good fuel. ADEPT suggested that valves be placed before and after the coalescent filter to isolate the coalescent filter without depressurizing the fuel lines.

V. LPG ADDITIVES

Contaminants can deposit within key fuel system components and interfere with proper operation. Additives may be a way to deal with deposits of heavy-ends in LPG fuel systems. Additives are reported to keep heavy-ends suspended in vapor phase from the LPG vaporizer's exit to the combustion chamber.

ADEPT has communicated its work under this project to several additive manufacturers. Two additive manufacturers expressed interest to participate and offer in-kind services to determine their products' efficacy to transport heavy-ends in vapor phase. The additives to be tested are reported to be specifically designed for LPG automotive use. ADEPT prepared a proposal to conduct such tests and this proposal was submitted to PERC on March 19, 2003.

This proposal outlines a protocol to quantify, via a scientific method, the efficacy of additives to maintain heavy-ends in vapor phase LPG. The proposed protocol compares the relative efficacy of additives to transport suspended heavy-ends in fuel systems with vapor phase LPG withdrawal (vs. liquid phase withdrawal). A test rig was designed to simulate what happens in LPG powered HEVs (as well as in other vapor drawn fuel systems) when the LPG storage tank is warmed with a heating blanket and where the fuel is drawn from the top of the tank (once vaporized). This funding application is still under review.

VI. RELATED SAFETY INSPECTION CONCERNS

The importance of thorough vehicle safety inspections directed at LPG components must be stressed. Several fuel system designs were checked for compliance with NFPA 58 (1998). Below lists several concerns uncovered during the three projects:

- Disconnected tank service valves must be capped;
- Proper tank orientation;

- Piping of outage valves to the fill port (not needed if the vehicle is equipped with UL approved stop fill devices);
- Hydrostatic relief valves must be installed in every place that LPG can be isolated between shutoff valves;
- Proper termination of tank relief valve/s;
- Fuel moving between multiple LPG storage tank [systems must be equipped with backflow check valves (and maybe even lock-off valves with solenoids) to prevent fuel transfer];
- Manual tank shut-off valves must be readily accessible;
- Double backflow check valves (spring-loaded) must be installed in the fill openings of on-board storage tanks;
- All container appurtenances must be suitable for working pressure of at least 250 psi;
- Ensure that all appropriate stickers and labels are in place (e.g. on the bumper, fill port, storage tanks, other fuel system-components, etc.);
- Design pressure of on-board LPG storage tanks for multipurpose passenger vehicles must be at least 312.5 psi;
- Pressure relief valves should not be located in an enclosed compartment;
- An approved automatic shutoff valve should be in the fuel system prior to the fuel entering the fuel components.

VII. MISCELLANEOUS DESIGN ISSUES

A. Regulator Seats

Some mechanical problems were attributed to the pressure regulator's inability to maintain steady pressure. One helpful move was to replace the regulator internal steel seats with Viton seats. The Viton seats acted as only a temporary solution as the pressure leakage recurred. Oily residue was thought to be the main cause for such regulator malfunction.

B. Plumbing

In the course of the project, ADEPT positively identified that rubber fuel hoses were a source of heavy-ends. On-board stainless steel fuel lines are recommended wherever possible to avoid such contamination. Also, the stainless steel and other thermally sensitive fuel system components are suggested to be insulated to moderate ambient temperature affects.

C. Air Filter

Although the scope of the projects was on LPG fueling systems, the importance of unimpeded and sufficient airflow to the microturbines became an issue that required ADEPT's involvement. In the absence of sufficient airflow, the microturbine's flame front becomes exceedingly unstable. Proper air intake directly affects combustion and how LPG is used. Also, if the air is dirty, the turbine internals may be damaged. ADEPT coordinated an air filter inspection and maintenance protocol to ensure that proper clean air flow was fed to the microturbine's combustion chamber.

D. "Drip Leg"

In some cases a "drip leg" was used in the LPG fuel system to protect the microturbine from a possible slug of liquid fuel that may condense (during operation or over night) in the fuel lines. A drip leg is a valve located at a low head position in the vaporized LPG fuel line. The drip leg can be installed before or after the coalescent filter.

ADEPT found that one integrator's maintenance procedure was to daily drain the drip leg to the environment before starting the HEV. This drops "heavy residues" and/or "contaminants" on the ground, and at the same time it depressurizes the LPG fuel system. Depressurizing the fuel system wastes LPG and creates environmentally and safety-wise undesirable conditions. ADEPT recommended to install pressure insulated drain trap/s under the drip leg (also applicable to drainable coalescent filter bowls). Such drain trap/s would allow for regular draining of the drip leg (and coalescent filter/s) as well as make it possible to drain the filters without depressurizing the vaporized LPG fuel system.

E. Turbine Shutdown

A permanent solution was needed to remove as much as possible of the fuel from the line on shut down to avoid a possible liquid LPG slug upon the subsequent startup. ADEPT assisted in coordinating a strategy to have the turbine starve the line all the way to flame-out (thereby drawing down pressure in fuel supply lines upon turbine shutdown).

VIII. CONCLUSIONS & RECOMMENDATIONS

Like with other alternative fueled HEVs, the success of an LPG dedicated HEV fleet integration depends on the fleet operator's commitment to periodic preventative maintenance. This periodic maintenance should be the result of collaborative efforts leading to a consensus of requirements among the "range extender" manufacturer, the HEV integrator, critical electrical and fuel system-related component manufacturers, and the site operator.

This project's findings are not limited to the arrangement of LPG fuel system components. Once again, we ran head-on into an issue that haunts the LPG industry: inconsistent fuel quality. As IC engines become more fine-tuned and performance optimized, tolerances for fuel quality fluctuations decrease. For LPG to be a viable fuel for modern IC technologies as well as to play a significant role in the fuel cell industry, fuel quality concerns must be addressed and dealt with. Reliable, industry-backed techniques to remove heavy-ends and to keep LPG from condensing out of vapor phase must be proven and made readily available for those integrators and engine manufacturers who wish to use commercially available LPG.

There are immediate steps available to PERC to rapidly advance applied know-how to deal with heavy-ends removal or suspension in LPG. It is recommended that PERC consider such aforementioned steps:

- AC filter study;
- Coalescent filter bowl point level sensor; and
- Additives study.

IX. APPENDICES

Appendix 1: Capstone's C30 HEV Datasheet

APPENDIX 1

Capstone MicroTurbine™

MODEL 330
HEV MicroTurbine
Multi Fuels

The Product

Features

- 30 kW net (ISO conditions)
- 250V-700V DC
- Patented air bearings
- Digital power controller
- Air cooled
- Fuel flexible, freeze-tolerant
- Permanent flash memory with full operating history

Benefits

- Near-zero emissions performance
- No fluid lubricants or coolants needed, ever
- Compact size & weight
- Reliable operation
- Fast in-field serviceability
- Minimal maintenance
- Full diagnostic capability
- Suited for a wide range of transport applications

Up to 70% lower emissions than EPA 2004 Truck & Bus Regulations ...available today!

HEV EMISSION CYCLE TESTING

Emissions	CNG*	Propane*	Diesel*
NO_x g/bhp-h	0.26	0.53	0.70
HC g/bhp-h	0.42	0.42	0.80
CO g/bhp-h	0.41	0.18	0.56
PM g/bhp-h	0.0041	0.0041	0.01

* Emissions are actual internal test results as per CARB-approved battery-dominant engine cycle protocol. Manufacturer emissions warranty limits are slightly higher.

Performance Specifications Under ISO Conditions (15° C / 59° F @ sea level)

MicroTurbine Performance	Fuel Type: Natural Gas (55 psig)	Propane (55 psig)	Diesel (5 psig)
Overhaul Life	20,000 hrs	20,000 hrs	20,000 hrs
Full-Load Power	30 kW net (+/- 1 kW)	30 kW net (+/- 1 kW)	29 kW net (+/- 1 kW)
Peak Efficiency (LHV)	27% (+/- 2%)	27% (+/- 2%)	26% (+/- 2%)
Fuel Flow*	18.7 lb/hr / 8.5 kg/hr	19.0 lb/hr / 8.6 kg/hr	21.9 lb/hr / 10.0 kg/hr
Fuel Flow, Equivalent	N/A	4.5 gal/hr / 17.2 l/hr	2.9 gal/hr / 11.0 l/hr
Exhaust Gas Temperature	261˚C / 500˚F	261˚C / 500˚F	261˚C / 500˚F
Output Voltage	250V - 700V DC	250V - 700V DC	250V - 700V DC

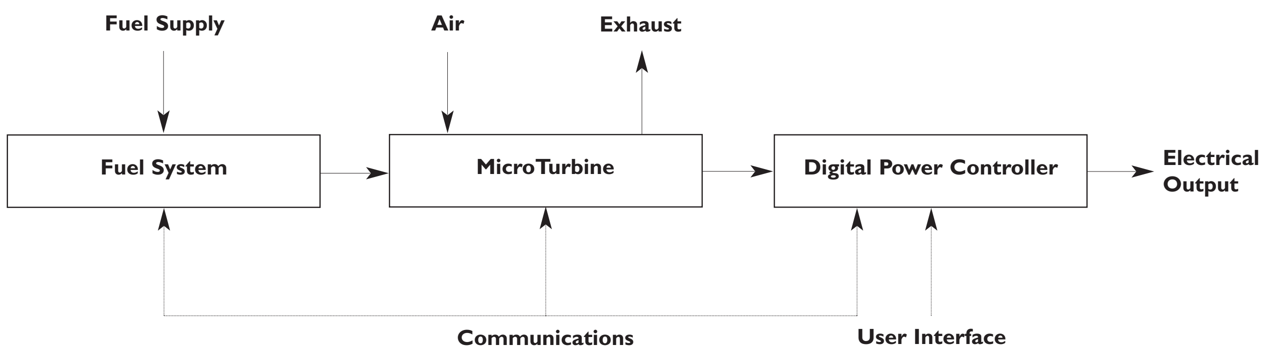
*Rated at LHV: 20,167 Btu/lbm (Natural gas); 19,916 Btu/lbm (Propane gas); 18,250 Btu/lbm (Diesel).

Engine Assembly
Dimensions
L: 836mm / 32.9"
W: 572mm / 22.5"
H: 729mm / 28.7"
Weight
102 kg / 225 lb

Digital Power Controller
Dimensions
L: 825mm / 32.50"
W: 311mm / 12.25"
H: 464mm / 18.25"
Weight
68.5 kg / 151 lb

All specifications rated at full-load power.
Note: The manufacturer reserves the right to change or modify without notice, the design or equipment specifications without incurring any obligation either with respect to equipment previously sold or in the process of construction.

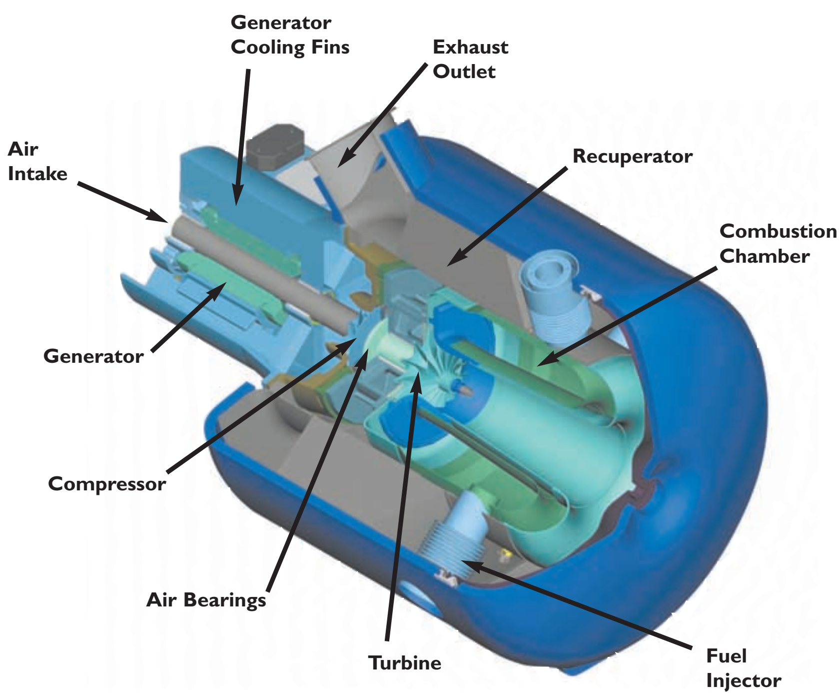
Capstone Model 330 MicroTurbine System



The Capstone Model 330 MicroTurbine system is a compact, low emission, power generator providing electrical power up to 30 kW. Solid-state power electronics allow grid-connect operation; stand-alone battery support and automatic grid/stand-alone switching are available options.

The system incorporates a compressor, recuperator, combustor, turbine and permanent magnet generator. The rotating components are mounted on a single shaft that rotates at up to 96,000 RPM (full load) and is supported by air bearings. The generator is cooled by intake air flow, thus eliminating the need for liquid cooling. Output of the system is variable voltage, variable frequency AC power. Integrated power electronics convert this to programmable DC power for HEV applications. A similar 60-kW engine will be available in 2002.

The Capstone Model 330 MicroTurbine Generator



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