DEVELOPMENT OF AUXILIARY POWER UNITS FOR ELECTRIC HYBRID VEHICLES

INTERIM REPORT
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13. ABSTRACT (Maximum 200 words)

Electric drive is being considered for a wide variety of urban vehicles. Larger urban commercial vehicles (such as shuttle and transit buses), various delivery and service vehicles (such as panel and step vans), and garbage trucks and school buses are particularly well-suited for this type of propulsion system due to their relatively short operating routes, operation and maintenance from central sites. Furthermore, these vehicles contribute a proportionately large amount to metropolitan air pollution by virtue of their continuous operation in those areas. Thus, reductions of emissions from these vehicles can have a large impact on urban air quality. It is, therefore, a necessity to develop auxiliary power units (APUs) that minimize emissions and in addition, increase range of electric vehicles. This report focuses on the first phase study of the development of APUs for large, eletric drive commercial vehicles, intended primarily for metropolitan applications. This paper (1) summarizes the differences between available mobile APUs and Electric Vehicle APU requirements, (2) describes the major components in APUs, and (3) discusses APU integration issues. During this phase, three potential APU manufacturers were identified and selected for development of prototype units at 25-kW and 50-kW power levels.

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EXECUTIVE SUMMARY

Problem: APUs are used with electric drives to form hybrid vehicles, primarily because of inadequate energy storage capabilities with current battery technology. APUs allow the vehicles to operate for greater distances than batteries or other energy storage devices alone and can provide greater vehicle operating flexibility as vehicle use profiles change. At the present time, commercially available gensets are not adequately designed for vehicular application. As a result, there is a need to develop APUs specifically for hybrid electric vehicles.

Objective: The objective of this project was to design, build, and test APUs utilizing natural gas engine technologies for large, electric hybrid, commercial vehicle applications. The first phase (corresponding to this report) included the review of available technological options for APU components such as alternating current (AC) generator configurations, heat engine types, and APU control algorithms as well as some of the issues and concerns regarding the integration of APUs into a pure electric vehicle.

Importance of Project: Electric drive is being considered for a wide variety of urban vehicles. Larger urban commercial vehicles (such as shuttle and transit buses), various delivery and service vehicles (such as panel and step vans), and garbage trucks and school buses are particularly well-suited for this type of propulsion system due to their relatively short operating routes, operation and maintenance from central sites. Furthermore, these vehicles contribute a proportionately large amount to metropolitan air pollution by virtue of their continuous operation in those areas. Thus, reductions of emissions from these vehicles can have a disproportionately large impact on urban air quality. It is, therefore, a necessity to develop auxiliary power units (APUs) that minimize emissions and in addition, increase range of electric vehicles.

Technical Approach: The first phase of this project focuses on the development of auxiliary power units (APUs) for large, electric drive commercial vehicles, intended primarily for metropolitan applications. Such APU would be incorporated in a series hybrid vehicle configuration where the vehicle propulsion is accomplished solely through electric motor drives. This project does not consider the parallel configuration since it does not incorporate an APU as a stand-alone unit. Several APU technologies were researched. Then, several manufacturers were contacted, evaluated, and selected for procurement.

Accomplishments: This paper (1) summarizes the differences between available mobile APUs and Electric Vehicle APU requirements, (2) describes the major components in APUs, and (3) discusses the major issues associated with integration of an APU into a vehicle. During this phase, three potential APU manufacturers were identified and selected for development of prototype units at 25-kW and 50-kW power levels.

Military Impact: Availability of APU component technologies, weight, size, cost, performance, safety and reliability are as important in military vehicles as in commercial. Electric drive also provides a low-heat, low-noise signature option for military vehicles. Consequently, issues associated with APU development for commercial hybrid vehicles are readily transferable to military applications. In a military combat environment, however, component vulnerability issues must be considered as well. Nevertheless, the results of this research study can be valuable in military APU development. While it is generally expected to see component specifications in military system to extend the envelope of commercially-feasible practices, it would not be unrealistic for some military APU requirements to be relaxed in order to increase vehicle performance (by allowing greater emissions) and increase survivability (by compromising fuel-efficient operating conditions) during critical high-demand scenarios .

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FOREWORD/ACKNOWLEDGEMENTS

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I. INTRODUCTION

Electric drive is being considered for a wide variety of urban vehicles. Larger urban commercial vehicles (such as shuttle and transit buses), various delivery and service vehicles (such as panel and step vans), and garbage trucks and school buses are particularly well-suited for this type of propulsion system due to their relatively short operating routes, operation and maintenance from central sites. Furthermore, these vehicles contribute a proportionately large amount to metropolitan air pollution by virtue of their continuous operation in those areas. Thus, reductions of emissions from these vehicles can have a large impact on urban air quality.

This paper focuses on a first-phase study of the development of auxiliary power units (APUs) for large, electric drive commercial vehicles, intended primarily for metropolitan applications. Such APU would be incorporated in a series hybrid-vehicle configuration where the vehicle propulsion is accomplished solely through electric motor drives. This document does not consider the parallel configuration since it does not incorporate an APU as a stand-alone unit. Rather, parallel hybrid designs require load sharing between the electric and engine drivelines.

II. OBJECTIVE

The objective of this project was to design, build, and test APUs utilizing natural gas engine technologies for large, electric hybrid, commercial vehicle applications. The first phase (corresponding to this report) included the review of available technological options for APU components (such as alternating current (AC) generator configurations, heat engine types, and APU control algorithms) as well as some of the issues and concerns regarding the integration of APUs into a pure electric vehicle. During this phase, three potential APU manufacturers were identified and selected for development of prototype units at 25-kW and 50-kW power levels.

III. APPROACH

APUs are used with electric drives to form hybrid vehicles, primarily because of inadequate energy storage capabilities with current battery technology. APUs allow the vehicles to operate for greater distances than batteries or other energy storage devices alone and can provide greater vehicle operating flexibility as vehicle-use profiles change. Although an APU will increase local emissions compared to an all-electric vehicle, emissions should be significantly less than a comparable conventional, internal combustion engine (ICE) vehicle.

An APU consists of a heat engine driving an electrical generator, which in turn supplies additional electrical energy to supplement the battery or other on-board storage devices. A general schematic is shown in Fig. 1. The engine is one of the main components of an APU, and its selection has the largest impact on overall APU efficiency and operating flexibility. Connected to the engine is a

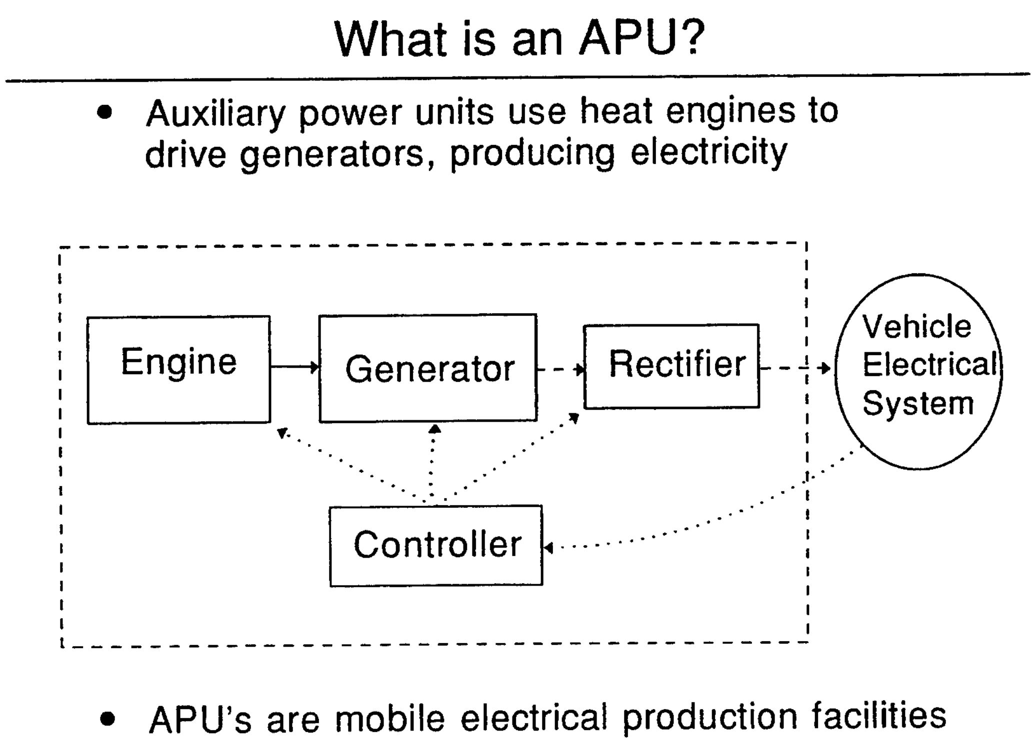


Figure 1. Auxiliary power unit configuration

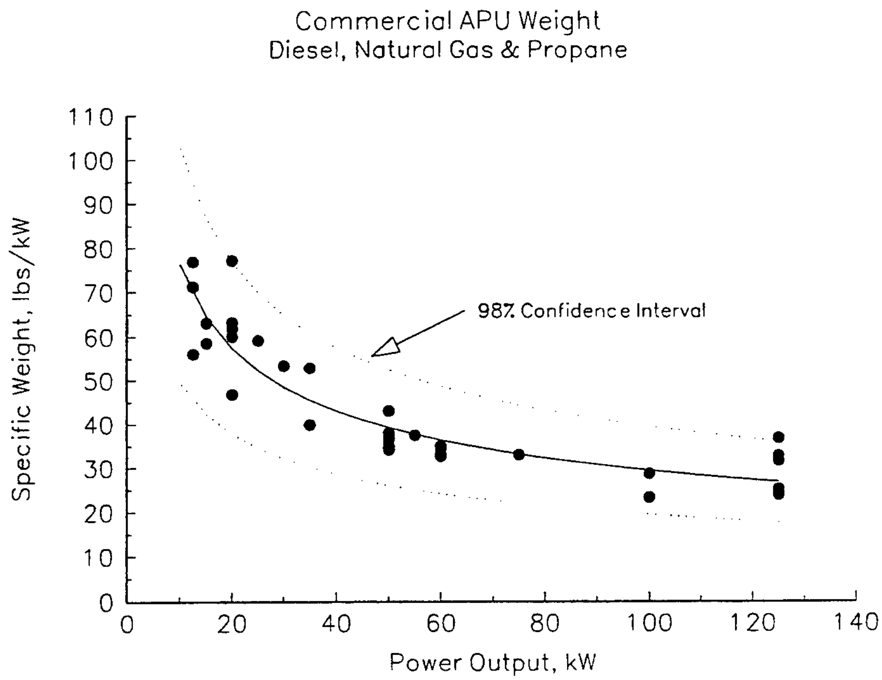
generator that can be chosen from a variety of technologies and can have a substantial impact on the APU size, weight, and cost. Associated with the generator is a power-conversion device. This could be a simple diode rectifier and filter for conversion from AC to direct current (DC) or a more complex system, such as an IGBT inverter, for rectifying and controlling the output voltage independent of the generator voltage. Finally, the APU must be connected to, and controlled by, the vehicle through some control interface unit.

IV. ELECTRIC HYBRID VEHICLE APU REQUIREMENT DIFFERENCES FROM AVAILABLE MOBILE APU

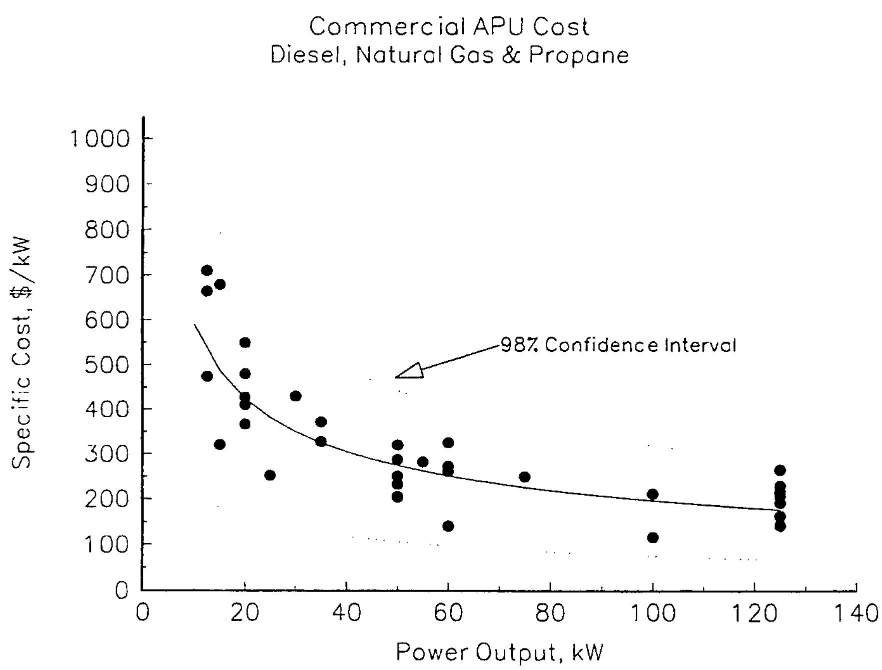
The requirements for vehicle APUs are different from conventional mobile generator sets (gensets) in a number of ways. Non-vehicle gensets place less emphasis on minimizing size and weight. The relationship between weight and power is illustrated in Fig. 2a, which summarizes data from a survey of commercial generator sets. With commercial units, size minimization in particular may be sacrificed to avoid maintenance compromises, and there is little financial incentive for weight reductions other than reductions in the cost of raw materials. There is a general trend to lower cost with increasing power output, as seen in Fig. 2b.

The most significant difference between available commercial gensets and hybrid vehicle APUs is the genset requirement for precise regulation of output voltage and frequency. This regulation is needed to satisfy the electrical requirements of equipment intended for operation from the electrical power grid. The constant frequency requirement is met on these units by tight control of engine speed, usually at 1,800 or 3,600 rpm. Voltage is controlled by varying generator-field excitation current in a field-generating coil within the unit. Variations in output power are accommodated by variations in engine load at the controlled speed.

This requirement for frequency control is eliminated in an hybrid vehicle APU, where the power is usually delivered to the vehicle as direct current. As a result, engine speed can vary, providing an additional degree of freedom in APU design, which can have a substantial impact on engine efficiency in some operating modes.



a. Specific weight vs. power



b. Specific cost vs. power

Figure 2. Commercial APU weight and cost relationships

APUs are being considered for use in two somewhat distinct types of vehicle applications. The simplest application will be referred to as range extension, in which the APU maximum continuous power is less than the vehicle average power requirement for the operating mode. In this configuration, the vehicle begins the operating day with a fully charged battery pack that discharges throughout the operation. The APU is started when the battery has depleted to some level and it operates continuously at peak power, supplying electricity to supplement the battery pack, thus slowing the battery discharge rate. Optimally, at the end of the day, the battery pack's available charge is depleted and the APU fuel exhausted as the vehicle returns to the service center to be refueled and recharged for the next day. Because of the need to balance vehicle energy storage with operating route requirements, this operation requires that the vehicle be designed with knowledge of the driving route. APU size is minimized, as is on-board fuel consumption. Electrical grid power consumption is maximized, and in the absence of opportunity charging, battery charging would likely occur during non-peak hours.

The other operating mode is state-of-charge (SOC) maintenance. In this application, the APU is larger and provides enough power to meet the average vehicle power demands over the driving cycle. On average, the stored energy in the vehicle does not fall below a specific level, hence the term "charge maintenance." The higher APU power output results in more on-board fuel consumption and increased local emissions, but provides more vehicle operating flexibility. Also, reducing large variations in SOC can greatly extend battery life for many battery designs.

In the sections that follow, APU component options and aspects of APU design will be discussed in greater detail. These system-control strategy options and the resulting impacts on vehicle performance and system design will be shown to play a key role in the selection of APUs.

V. APU COMPONENTS

A. <u>Heat Engines</u>

Heat engines for APUs were reviewed by the U.S. Department of Energy (DOE) during 1984 (Fig. 3). Various alternatives were ranked by power, efficiency, cost, size and weight, and were based on projections of then-current engine technology.(<u>1</u>) Some ten years later, some of the projections, most notably specific fuel consumption, appear overly optimistic.

Each of these engine types have advantages and shortcomings for APU applications, depending on how the APU is applied in the vehicle. TABLE 1 summarizes many of the characteristics of the various engine options.

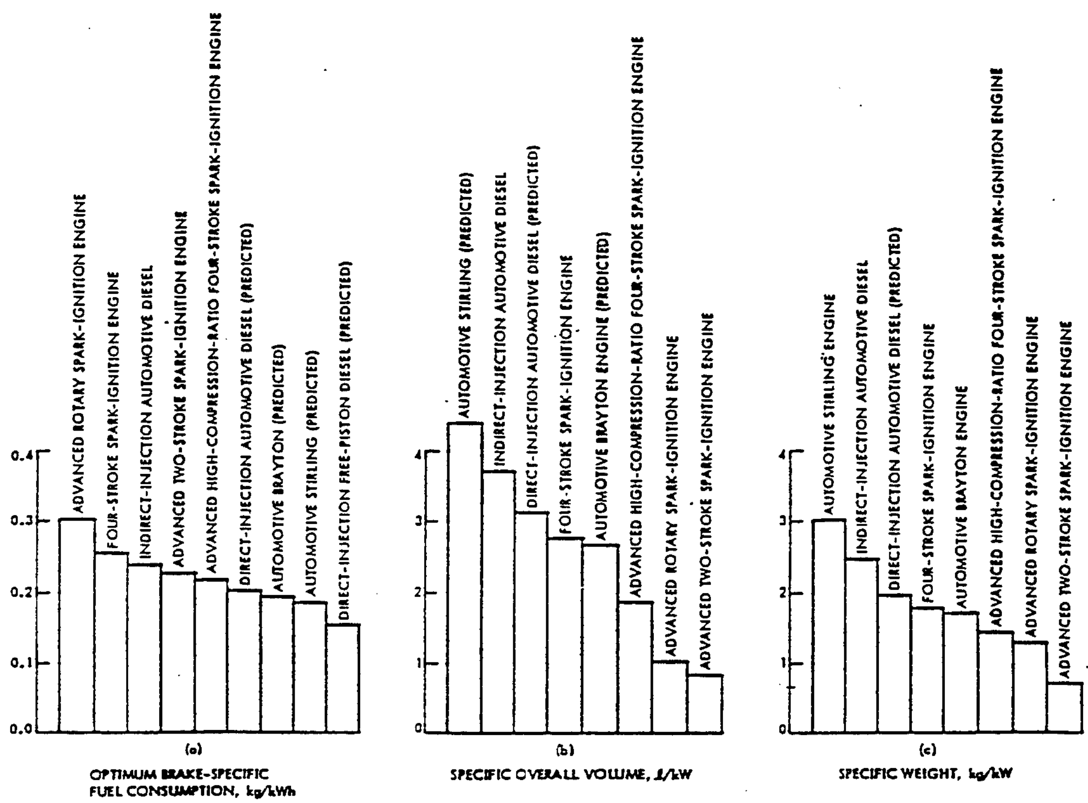


Figure 3. <u>Comparison of automotive heat engine parameters</u> (<u>2</u>)

* Underscored numbers in parentheses refer to the list of references at the end of this report.

TABLE 1. Some Advantages and Disadvantages of Heat Engines

Engine Type	Advantages	Disadvantages
Diesel	• Mature design • Proven durability • High efficiency, particularly at part power	• High NOx and particulate emissions • Power to weight, volume ratios
Four-Stroke Spark Ignition	• Mature design • Good power to weight, volume ratios • Well-developed emissions control systems • Low cost per kilowatt	• Current designs have less durability • Poor part throttle efficiency
Two-Stroke Spark Ignition	• High power to weight, volume ratios • Potential for low cost per kilowatt	• Less developed emissions controls • Current designs have less durability • Poor part power efficiency
Recuperated Gas Turbine	• High power to weight, volume ratios • Minimum maintenance, esp. with air bearings • Potential for good durability • Potentially low emissions, except for NOx • Low noise	• Historically high cost • Efficiency poor without heat recuperator or regenerator • Poor efficiency at low power • Reduced efficiency and durability in on/off cycling
Stirling	• Highest potential efficiency • Potentially low emissions	• Poor power to size, weight ratios • High cost • Unproved durability and reliability

1. Diesel engines. These engines have become the predominant power source in heavy-duty commercial vehicles due primarily to their high efficiency. Diesel designs are mature and reliable, with heavy-duty engine overhaul intervals exceeding 500,000 miles. Current diesel designs for automotive applications reach maximum efficiency at 40 to 50 percent of rated power, and efficiency remains high with increasing power. Engines for industrial applications can reach peak efficiencies at 50 to 75 percent of rated power but are usually heavier than automobile engines. The excellent, below-rated-power efficiency makes the engine particularly attractive for APU applications where wide variations in power are required. While the injection system and more rugged design make this engine class more expensive than spark-ignition engines of similar displacement, the high production volume keeps cost low.

The two-cycle diesel engine has undergone refinement to the point that it is a serious competitor to the four-cycle engine in weight, power, and fuel consumption. An example of this engine is the Detroit Diesel Corporation's 71 and 92 series. This competition with the four-cycle engine is paid for by complexity and weight.(3) For the large diesel engines, the inlet pumping is accomplished by a positive-displacement blower. Exhaust is accomplished by either valves placed in the cylinder or by the less common exhaust port, as in the gasoline engines. There are some examples of the crankcase-pumped diesel engine; however, these engines are not currently produced.

Diesel engines tend to be larger and heavier than spark-ignition engines of the same power level (Fig. 4). This is partially because of the need to design for extended durability. However, the increase in size is also due to the inherent lower-air utilization of the diesel heterogeneous combustion process.

Diesel emission control has been difficult, particularly control of NOx and particulates. While NOx would continue to be a problem in APU applications, the flexibility of engine control possible can allow the avoidance of rapid speed changes and other operations that contribute to particulate formation.

2. Spark-ignition engines. These engines are the predominant engine in light-duty applications and some medium-duty commercial vehicles. Spark-ignition engines mix fuel and air in closely controlled proportions, then meter the mixture into the combustion chamber. Power is controlled by throttling the intake to reduce the air (and fuel) combusted during each cycle. The lower engine compression ratio, dictated by fuel properties, results in lower peak efficiency than the diesel engine. Throttling for power control further reduces part power efficiency by increasing work lost to intake air pumping.

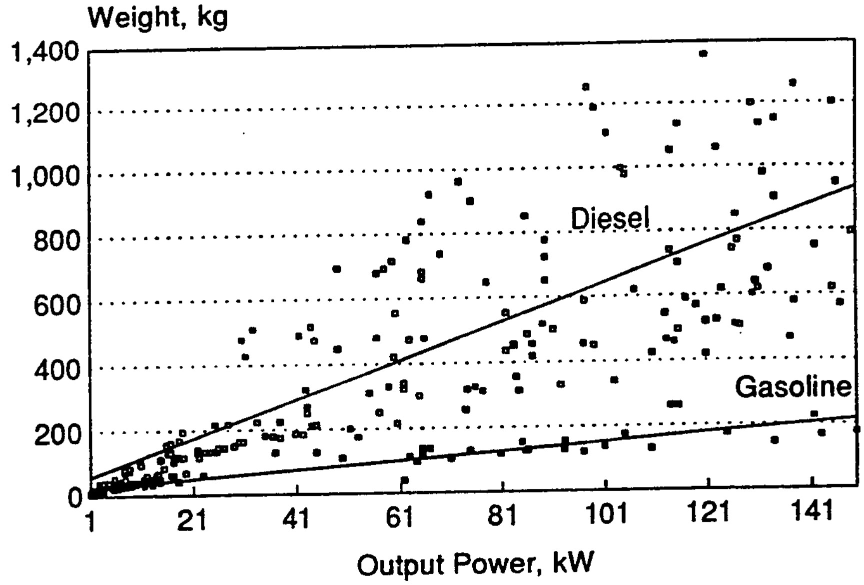


Figure 4. <u>Engine weights (bare engine with accessories)</u>

While genset engines operate at a fixed speed and varying load, APU engines either operate at a single speed, or if power is varied, can vary throughout their operating range. Particularly for the charge maintenance mode of operation, this can have a large impact on spark-ignition engine efficiency. The increased flexibility of a spark-ignition, engine-powered APU can overcome some of the efficiency penalty compared to diesel engines. This is illustrated in Fig. 5, where being able to operate at point C rather than point B improves fuel consumption by 6% while producing the same power. It can also have emission benefits, since partial power control points can be chosen to minimize exhaust emissions.

Currently, there are three configurations of spark-ignition engines in volume production: two-cycle, rotary, and four-cycle. The four-cycle engine has better thermal efficiency and lower inherent exhaust emissions than the other configurations. As a result, it is the predominant configuration and has a more developed emissions control system. The wankel rotary engine has better ratios of power to weight and volume than the four-cycle and is generally believed to have marginally lower production costs at equal production volumes. The rotary has lower inherent NOx but higher

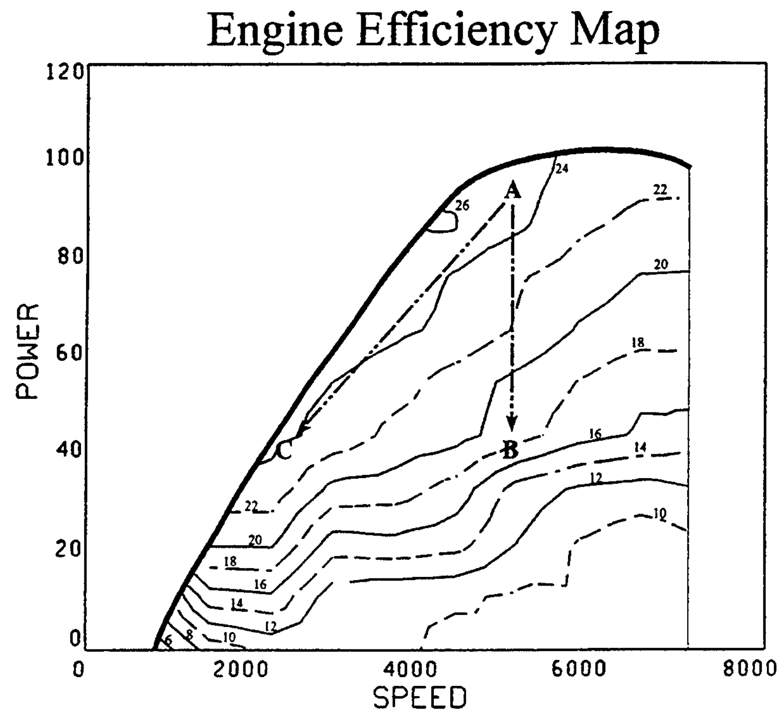


Figure 5. Typical engine efficiency map

unburned hydrocarbon emissions, plus lower thermal efficiency than four-cycle engines (Figs. 6 and 7) due to the combustion chamber geometry. In emission-controlled form, emissions levels are equal to those of four-cycle engines.

The rotary engine is a developed production powerplant that has gained acceptance in specialty markets. Many variants have been proposed; however, only two basic types have gained acceptance in the market. These engines are basically the same except for the cooling of the rotor. One has an oil-cooled rotor, and the other employs a charge-cooled rotor. Generally, the longer life and higher specific power engine is the oil-cooled rotor-type. The charge-cooled engine has the advantage of lighter weight per unit power.

The two-cycle engine has been used primarily in applications where its high ratio of power to weight and volume are advantages. It has been around longer than any of the engines investigated in this section. In its infancy in the industry, the two-cycle engine was competing directly with the double-acting steam engine with two power strokes per cycle. For low-power, small, carbureted two-strokes, the carry over of fresh charge into the exhaust gas port produces considerable unburned hydrocarbons in the exhaust and is one of the causes of high fuel consumption.

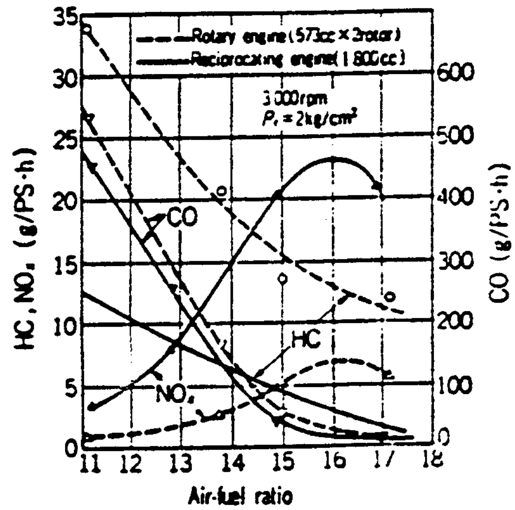


Figure 6. <u>Emissions of the rotary and reciprocating engines at similar power levels</u> (<u>4</u>)

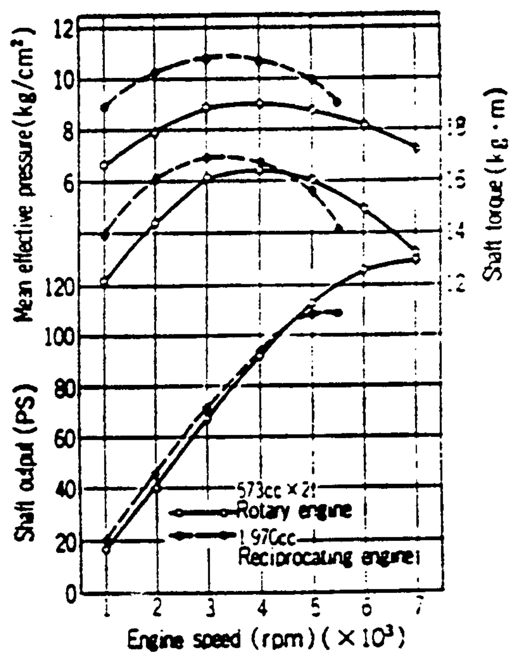


Figure 7. <u>Power levels for the rotary and reciprocating engines</u> (<u>4</u>)

The two-cycle engine with a crankcase inlet charge pump has to be lubricated by oil carried by the fuel or injected by a metering pump. This is also a source of exhaust hydrocarbons.(5)

Current design of the two-cycle engine has concentrated on the shortcomings of the engine. The two-cycle engine has low cylinder pressure for a specific power output. Cylinder pressure has a direct relation to the emissions of nitric oxides. If methods can be found to lower or eliminate the unburned hydrocarbons from the engine, it will be a serious contender for the low-emission category. Current designs have concentrated on injecting the fuel after the exhaust ports have closed. The most notable is a device that uses compressed air to deliver the fuel after exhaust port closure, developed by Orbital Engine Company. The oil consumption (usually burned in a "once-through" system) is lowered to the point where it is not a problem. While Orbital and others have been developing emission-controlled, two-cycle engine designs, none have been introduced into the market, so it is difficult to assess the efficiency and performance of an emission-controlled design.

The two-cycle engine has dominated the market in sizes primarily in the low-price category. This market thrives on simplicity. High fuel consumption is a trait for the two-cycle gasoline engine. This trait is tolerated for lower power output engines or recreational vehicles for the advantages of light weight and high power per unit weight. Potential exists for the two-cycle engine to be a strong competitor in the APU market. However, in a broad announcement soliciting APU options, no two-cycle powered systems were offered.

3. Recuperated or regenerated turbine-powered units. Turbine-powered units with shaft speed generators appear to offer excellent power-to-size and weight ratios. If the unit is properly controlled, and the generator is designed upstream of the turbine to reduce accessory cooling air flow requirements and to assist the pre-heating of turbine inlet gas to more favorable temperatures, these units appear to offer very good efficiency over at least the upper 50 percent of the power range. However, these units may not operate well below approximately 50 percent power without substantial efficiency degradation or compressor stall. Thus, the turbine may be inappropriate for charge maintenance applications where periodic low-power operation may be anticipated, although stopping the engine may be a way to handle this situation. However, the impact of frequent start/stop cycles on recuperator and heat-section durability and emissions are questionable. These engines should be relatively quiet since they produce little low-frequency noise, and the recuperators and regenerators tend to be effective mufflers for both the intake and exhaust.

Cost has been a problem with gas turbine engines. This is a result of the materials required for the hot section and the low-production volume. Cost projections shown in Fig. 8 indicate that these engines could be reasonably competitive with other engines at sufficient production volume. However, these cost estimates do not include costs of the generator and power conditioning. Capstone Energy, Allied Signal, and others have been developing turbine generators, using low-pressure ratio turbines to minimize turbine inlet temperatures and thus material costs, and maintaining engine efficiency through recuperation or regeneration. Heat recovery efficiency is a major factor in engine efficiency as shown in Fig. 9. Developing an efficient, durable, and low-cost recuperator or regenerator has been the limiting technology of this type of engine.

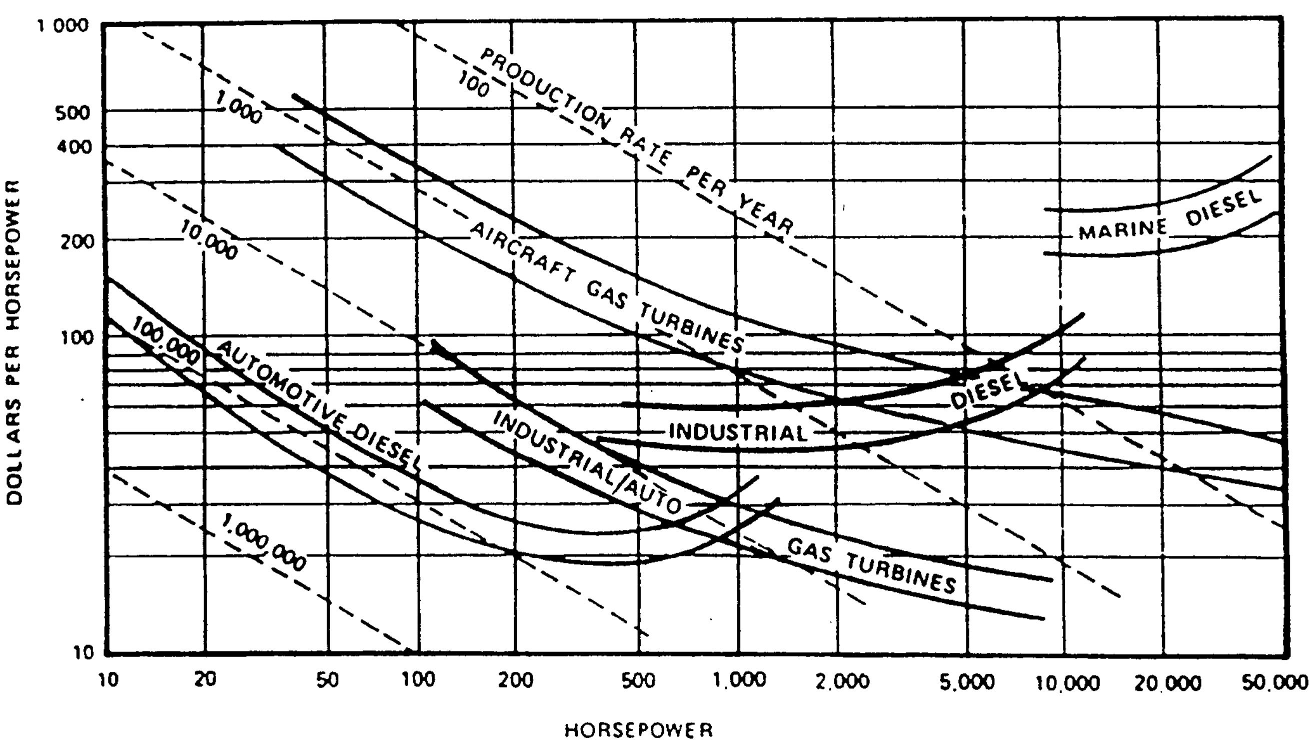


Figure 8. Cost projections (6)

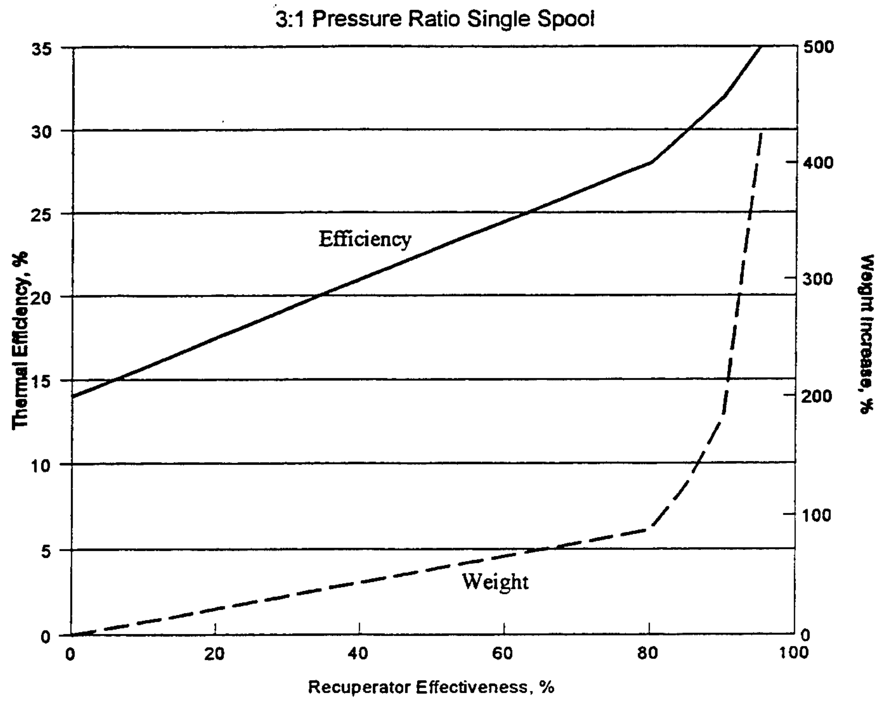


Figure 9. Turbine efficiency and weight impact (7)

4. Stirling Engines. Stirling engines have the potential for higher thermal efficiency than diesel designs. Recent studies with helium working gas demonstrated efficiencies as high as 40 percent, as shown in Fig. 10. The Stirling is fundamentally different from the other engines because its cycle consists of alternately heating and cooling a closed working fluid (usually hydrogen or helium) and using the volume change to drive power-extraction pistons. Power is controlled by varying the volume of the working fluid. The working fluid is heated by external combustion, which offers low emissions and multifuel capability. The working fluid is cooled through heat exchange with the surroundings. In addition to these two heat exchange processes, a regenerator is required to raise the thermal efficiency.

The external combustion feature of Stirling engines is a major advantage in alternative fuel applications because the very nature of the combustion process permits the flexibility for multifuel operation with low emissions. Preliminary measurements of these emissions, conducted on the STM4-120 engine (Stirling Thermal Motors, Inc. and Detroit Diesel Corporation) using natural gas fuel, indicate that the existing hardware already meets the proposed standards for both Heavy-Duty and Ultralow Emissions Vehicles (ULEV), as shown in TABLES 2 and 3.

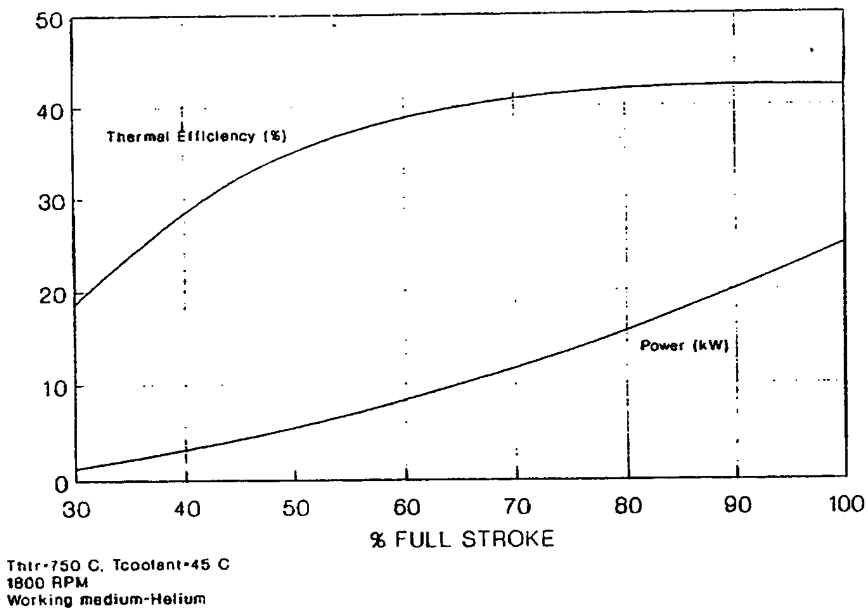


Figure 10. Efficiency of Stirling engines (8)

TABLE 2. Comparison of Typical Emissions for the STM4-120 Stirling Engine With Urban Bus Standards (9)

			STM4-120 Stirling Engine		
			Natural Gas*		Diesel**
Emissions†	California Urban Bus Standard (1996)	Federal Urban Bus Standard (1998)	0% EGR $\lambda = 1.5$	60% EGR $\lambda = 1.3$	0% EGR $\lambda = 1.5$
Hydrocarbons	1.74 (1.3)	1.74 (1.3)	0.29 (0.21)	0.037 (0.027)	0.073 (0.054)
NOx	2.69 (2.0)	5.37 (4.0)	0.57 (0.42)	0.20 (0.15)	0.43 (0.32)
CO	20.8 (15.5)	20.8 (15.5)	1.29 (0.95)	2.86 (2.12)	0.50 (0.37)
Particulate	0.068 (0.05)	0.068 (0.05)	0	0	0

* Emissions measurements conducted by TNO (National Technical Laboratories of The Netherlands) using Dutch natural gas fuel during July-September 1991. TNO conducts vehicle emissions certifications for the Dutch government.

** Diesel emissions data converted from Webasto Model DW 80 burner measurements, assuming 40 percent engine thermal efficiency.

† All emissions data in g/kW$_s$-hr (g/bhp-hr).

TABLE 3. Comparison of Typical Emissions for the STM4-120 Stirling Engine With Ultralow Emission Vehicle Standards (9)

		STM4-120 Stirling Engine		
		Natural Gas*		Diesel**
Emissions†	ULEV Standards	0% EGR $\lambda = 1.5$	60% EGR $\lambda = 1.3$	0% EGR $\lambda = 1.5$
Hydrocarbons	0.04	0.011	0.014	0.027
NOx	0.2	0.21	0.07	0.16
CO	1.7	0.48	1.07	0.19

* Emissions measurements conducted by TNO (National Technical Laboratories of The Netherlands), using Dutch natural gas fuel during July-September 1991. TNO conducts vehicle emissions certifications for the Dutch government.

** Diesel emissions data converted from Webasto model DW 80 burner measurements assuming 40 percent engine thermal efficiency.

† Emissions data in g/mi. Emission unit conversions are based on proprietary vehicle specific data.

Due to problems with heat exchanger size and effectiveness, material costs, complex engine controls, and sealing of the working fluid, these engines have generally been too costly to compete with other engine types. For APU applications, they are further hampered by their operating speed characteristics. Because of heat-transfer limitations, Stirling engines generally operate at low speeds, and efficiency falls as engine speed increases. This results in additional gearing or low generator rotating speed, either of which increases the APU package size. Stirling engines equipped with linear generators have been built, but the operating speed limitation impacts these configurations as well.

TABLE 4. Heat Engine Design Characteristics

Heat Engines	Power Range hp	Max. Efficiency % of Rated Power	Specific Weight lb/hp	Specific Volume ft^3/hp	Min. Fuel Consumption lb/hp-hr
Diesel					
Automotive, general	40 - 100	40 - 50	6 - 8	0.2 - 0.3	0.45 - 0.5
Automotive, specific	50	--	5.3	--	0.45
	70	--	4.0	--	0.44
Industrial, air-cooled	20 - 40	50 - 75	10 - 15	0.16 - 0.30	0.40 - 0.45
Industrial, water-cooled	40 - 100	50 - 75	7 - 10	0.13 - 0.24	0.38 - 0.45
Reciprocating Spark Ignition					
Automotive	40 - 120	40 - 50	4 - 7	0.13 - 0.2	0.45 - 0.6
Industrial	25 - 60	45 - 55	5 - 15	--	0.56 - 0.58
Aircraft	60, 100, 115	50 - 65	2	--	
Gas Turbine					
APU (simple cycle)	20 - 60	--	2 - 3	0.1	1.1
Automotive (regen)	100 - 200	25 - 50	2.5 - 3	0.08 - 0. 0.1	0.5
Stirling	10 - 150	--	7 - 15	--	0.38 - 0.52
Rotary					
Two Rotor	100 - 170	56	1.3 - 2.2	0.05 - 0.07	0.44 - 0.56
One Rotor	50 - 85		2.3 - 2.5	0.06 - 0.08	0.56- 0.60
	20 - 60		2.2 - 3.0	0.11 - 0.17	0.60 - 0.69

* Source: Collie, M.J.,"Electric and Hybrid Vehicles," Noyes Data Corporation, New Jersey, 1979

TABLE 4 summarizes relevant design and performance characteristics for each heat engine discussed above. The comparison includes each engine's power range, where maximum efficiency occurs, specific weight, specific volume, and peak efficiency. Figure 11 illustrates the variation of efficiency with power for several of the engine types.

The selection of an appropriate heat engine for hybrid vehicle applications is controversial, at best. Lack of more comprehensive data on Stirling, turbine, and rotary engines that have competitive fuel economy characteristics has forced many manufacturers to incorporate spark ignition and diesel engines into their hybrid vehicle designs. However, a study conducted in the late 1970s, the Near-Term Hybrid Vehicle Program, indicated that spark ignition engines are favored over diesel engines due to uncertainties associated with the diesel engine's likelihood of meeting proposed NOx and particulate standards. On the other hand, one of the program contractors found it advantageous to incorporate a turbocharged diesel engine based on a 38-percent fuel savings (annually) over a comparable, naturally aspirated, spark ignition engine operating under their specialized control strategy.

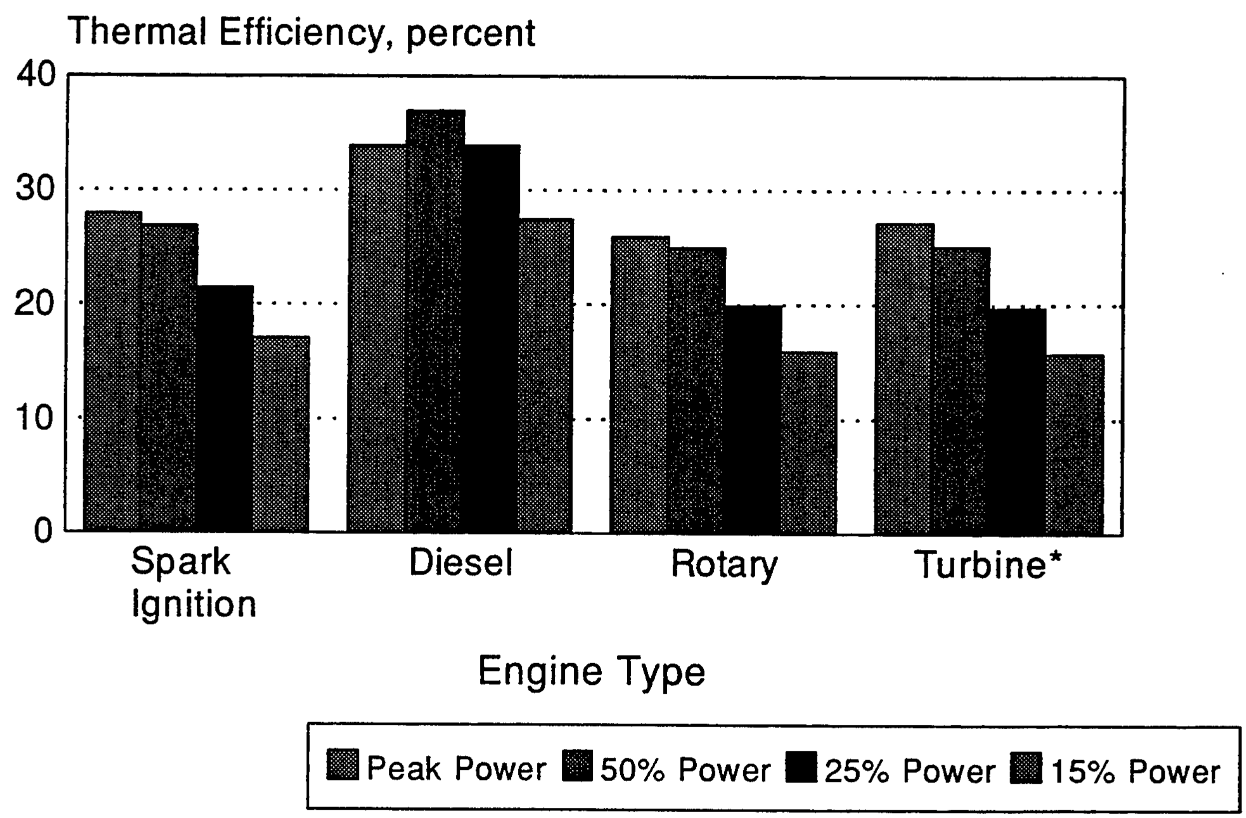


Figure 11. Engine efficiency

As previously mentioned, the initial phase of this APU development program included the selection and assignment of APU manufacturers to build natural gas-fueled prototype units of different technologies and power levels. Evaluation of available technologies led to the selection of three

APU systems: a four-cycle reciprocating piston engine, a four-cycle rotary engine, and a turbine engine. Availability, minimization of risk, technical potential, and manufacturers' experience with gaseous combustion power plants were the primary factors for the selection of the APU manufacturers.

B. Electrical Generators

The electrical generator used in the APU has a large impact on overall weight and package size. However, the efficiency variation between generators is considerably less than the variation resulting from different engine designs and control strategies. As a result, while the total system must be considered in designing an APU, generator efficiency is less of a factor than size and weight. While DC generators can be used, AC generators are superior in efficiency, weight, cost, and durability. Consequently, only AC generators will be discussed.

1. Options for Field Excitation

Two different methods are commonly used to produce the magnetic field in AC generators:

1) field coils requiring field excitation current to produce the excitation magnetic field, designated as wound-field AC generators; and
2) permanent-magnet assemblies that do not require excitation current to produce the excitation magnetic field, designated as PM AC generators.

Wound-field AC generators provide the capability to control the output voltage by controlling the field current. This field current control allows the output voltage of the generator to be controlled independently of the rotational speed. However, the need for field control is being obviated by the development of solid-state devices that can operate on the prevailing generator output voltage and efficiently control the power delivered to the load. Compared to the PM AC generator, the wound-field AC generators are larger and heavier.

As an example of the two different designs, comparative information about wound-field and PM AC generators made by the Onan Corporation are listed in TABLE 5.

TABLE 5. Comparison Between Wound-Field and PM AC Generators

Characteristics	Wound Field	Permanent Magnet
Power output, kW @ 6000 rpm	15	15
Volume, m^3	0.025	0.011
Weight, kg	29.4	12.2
Efficiency at 40 to 100 percent of rated load	82 to 87%	85 to 90%
Cooling method	Forced air	Forced air
Cost of production units (2,000 to 5,000 per year)	$559	$325

One of the major reasons for the size and weight reduction in the PM AC generator is the elimination of the size, weight, and power dissipation of the field coils. Because there is no need to allow space for the coils, the magnetic circuit components can also be smaller and lighter. However, magnetic field strength in PM machines is limited to about 0.5 Tesla, while current induced fields can reach the saturation limit for the materials (usually iron) of about 2.0 Tesla.

2. AC Generator Configurations

AC generators using PM materials are commonly available in two configurations, based on the direction of the magnetic field and the placement of the stator (AC output) coils. The common configurations are as follows:

1) The radial magnetic field has magnets mounted on the rotor shaft. The stator coils are mounted on an outer stator structure, and the direction of the magnetic field is perpendicular to the rotor shaft.

2) The axial magnetic field has magnets mounted on disks around the armature shaft. The stator coils are mounted between the magnets, and the direction of the magnetic field in the air gap is parallel to the rotor shaft.

Currently, AC generators using the radial configuration have the advantages of greater availability and lower cost compared to the axial design. Other configurations are in developmental stages and could be of greater interest in the next two to five years.

3. <u>Basic Mechanical Construction of AC Generators</u>

A basic mechanical drawing of a radial-type PM AC generator is shown in Fig. 12. For conceptual purposes, a two-pole machine with a single bar magnet as the rotor is illustrated. A wound field generator is conceptually the same, except a separate field coil is used to generate the magnetic field.

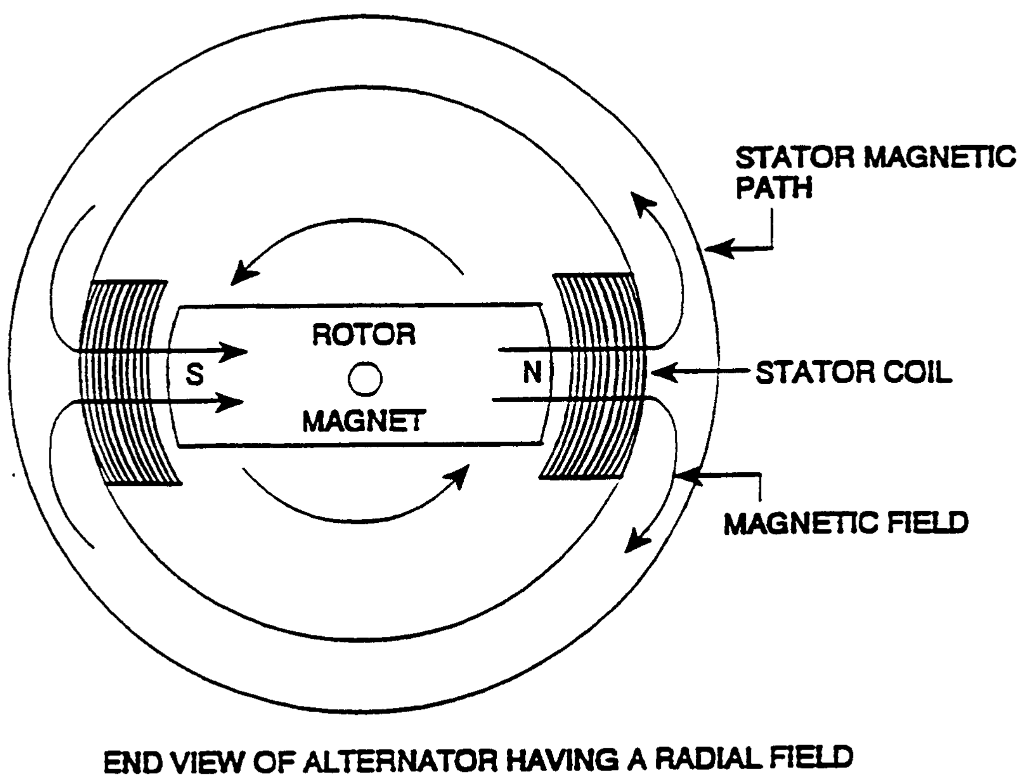


Figure 12. <u>**Fundamental operation of an alternator having a PM field**</u>

As the rotor turns, the magnetic field through the coils is maximum in the rotor position shown, and is minimum when the rotor has turned 90 degrees. When the rotor has turned 180 degrees, the magnetic field through the coils is again maximum but has the opposite direction. Thus, the voltage induced in the coils alternates in polarity as the rotor turns; the two-pole configuration will produce one complete voltage cycle for each revolution of the rotor.

Practical and highly efficient AC generators have advanced magnetic circuit designs and coil designs that maximize the output power in a desired rpm range. The number of poles can be varied to produce the desired output frequency vs. rotating speed relationship. As the design speed increases, the size of the generator can be reduced as shown in Fig. 13. In most cases the size reduction with speed is not sufficient to justify gearboxes for speed increase. This generator characteristic tends to favor high speed engines. Higher speeds should also reduce generator cost.

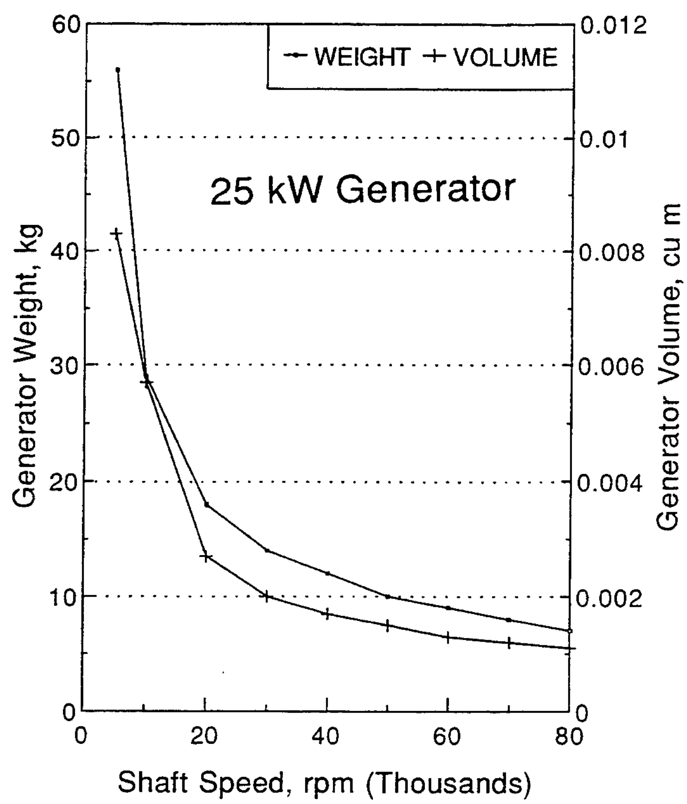


Figure 13. **<u>AC generator speed versus size</u>**

4. Electrical Equivalent Circuit of AC Generators

Figure 14 is an electrical equivalent circuit of a PM AC generator. In the equivalent circuit, the major elements are the windings where the voltage is generated, the inductance and resistance of the winding, and the losses in the magnetic circuit that can be simulated by an added series resistor. The induced voltage is proportional to a) the magnetic field strength, b) the rate of change of the magnetic field through the coil as determined by the rotor rpm, and c) the number of turns in the stator windings.

Losses in the AC generator occur in the electrical elements as described here:

1) The winding inductance causes a reduction in output voltage that is equal to the (output current) × (inductive reactance). Because the inductive reactance increases with frequency, the winding must be designed to have very low inductive reactance in the desired rpm range.

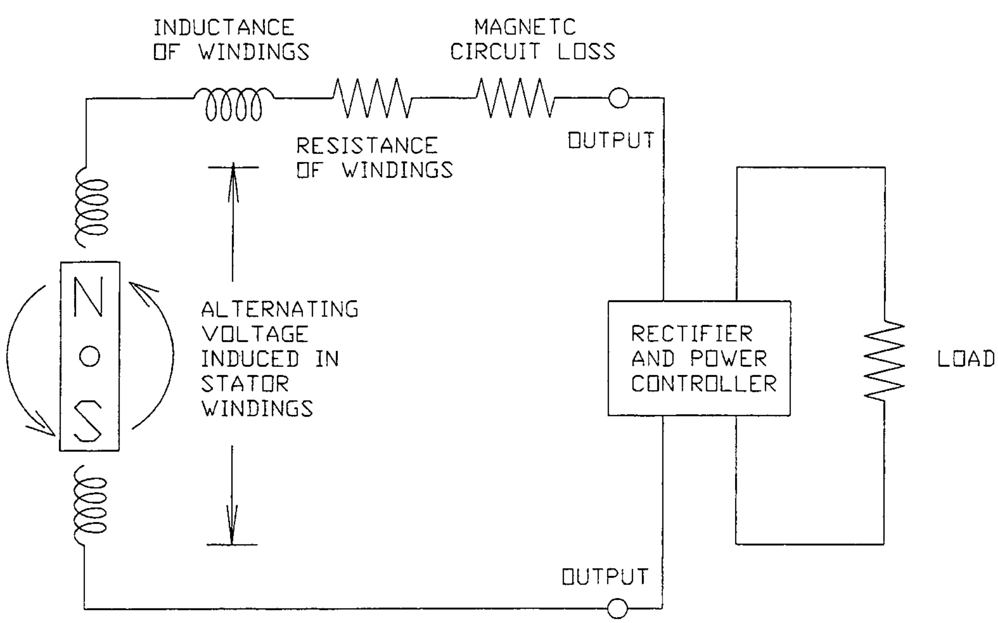


Figure 14. Equivalent circuit of an AC generator

2) Voltage loss in the winding resistance is equal to the (output current) × (winding resistance). The winding design must provide an acceptable resistive loss at the output current rating of the generator.

3) Magnetic circuit losses include "eddy current" losses that are a function of the rotor rpm. These losses cause heating of the magnets and the steel parts of the magnetic circuit. Acceptable magnetic circuit designs must minimize these losses.

A few AC generators having power outputs of 15 kW and 50 kW are provided in TABLE 6. This list is a result of a survey of many manufacturers. Those units listed use modern design practices and are also available as prototype or near-prototype models.

TABLE 6. Permanent Magnet AC Generators and Manufacturers

Rate Power, kW	Configuration of PM Field	AC Generator Volume, m^3	AC Generator Weight, kg	Manufacturer
15	Radial	0.11	12.2	ONAN Corporation
15	Radial	0.006	13.8	Fisher Electric Motor Technology, Inc.
15	Radial	0.0054	27	Neodyne Corporation
15	Axial	0.016	40.8	EML Research, Inc.
50	Radial	0.014	22.7	ONAN Corporation
50	Radial	0.009	15.9	Fisher Electric Motor Technology, Inc.
50	Axial	0.021	63.4	EML Research, Inc.

While PM AC generators would appear to be the preferred generator for APU applications, current PM generators usually require an additional power conditioning unit to convert from the output frequency and voltage to the DC voltage required for electric vehicle battery packs. Unlike wound field generators where output voltage can be controlled independent of rotational speed, PM generator voltage varies linearly with speed. In order to match the output voltage to that required by the load, a step-up transformer or up-chopper or other rectification and voltage boost device is required if the generator is to be operated at a range of speeds. Otherwise, the driving engine must operate at a constant speed and vary the load by throttling or fuel regulation only.

In applications such as an EV, where DC power is used to charge the batteries and supply power to the propulsion subsystem, a rectifier and power control unit are required. This unit performs the following functions:

1) conversion of AC power to DC power, and

2) control of the voltage and current applied to the load as a function of battery charging and propulsion power requirements.

A typical output voltage versus rotor speed characteristic for an AC generator is shown in Fig. 15. At lower speeds, a constant maximum current is available, limited by the generator wire size and internal resistance. Exceeding this current would result in overheating. Note that the output voltage increases in proportion to the rotor speed until the winding inductance loss and magnetic circuit loss, which increase with rotor speed, cause a reduction in the output voltage. This fall-off point is set by the specific design.

Currently, these power conversion devices for PM generators can more than offset any cost advantage of the PM generator, and may increase the total package volume and weight above that of a wound-field generator. A number of manufacturers are working to reduce the cost and size of these voltage step-up units. In addition, several organizations are working on approaches to varying

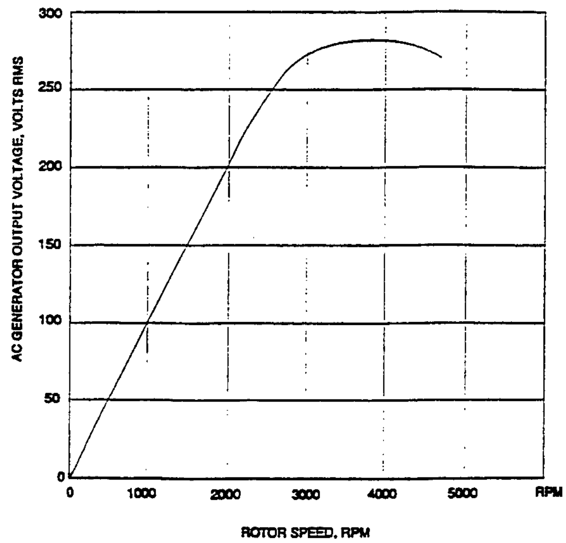


Figure 15. Typical AC generator output voltage

the field strength of PM generators during operation. Approaches being investigated include both electrical and mechanical (alignment control) field weakening. Mixed-mode generators have also been built that include a wound-field coil assembly to allow boosting the permanent magnet-produced field. Advances in PM-generator field control or in electronic power management are likely to have the greatest impact on APU size, weight, and cost.

VI. INTEGRATION OF APU WITH PURE ELECTRIC VEHICLES

A. APU Design Impacts in Commercial Vehicle Design

Conversion of an EV into an HEV, by introducing an on-board power generating unit (APU), requires that the existing EV components be considered with respect to the HEV's ultimate functionality. If the goal is to extend the range using electric power, the EV can be retrofitted in a series configuration. On the other hand, if the ultimate goal is to augment driving power and/or allow for multiple power source (engine only, battery only) operation of an HEV, then configuration changes would be extensive. Consequently, strategies for incorporating an APU into an EV will depend on the configuration selected.

An APU integration into a series configuration HEV would seem to be a simpler effort since the APU produces electrical power that an existing EV is accustomed to accepting and providing with its batteries. The additional complexity introduced would only be the modification of the batteries' charging circuit and the additional control logic to operate the engine and the generator. This means that there is no fixed mechanical connection between the engine and the drivetrain. Consequently, the design strategy (as mentioned in the preceeding section) is to operate the engine at those points in the engine-speed/torque map with highest efficiency and lowest emissions.

Design integration of an APU into an EV also requires that more efficiency arrangements be considered. An example of such strategy is to evaluate the possibility of bypassing the inefficiencies of battery charging by powering the traction motors directly from the generator output (instead of storing energy in the battery and then extracting that energy to drive the motors). This arrangement does not prohibit the charging of the batteries, but it may create significant control software and hardware difficulties.

B. Auxiliary Loads Issues in APU Designs

Auxiliary loads are typically classified into two categories: vehicle (such as accessories, lights, ignition, etc.) and instrumentation (computer and controllers). It is important that power to the computer and control units be uninterrupted and of a relatively high quality to avoid premature shutdowns and/or undesirable control problems. Several vehicle loads, such as starters and electric power steering, require high current and can easily cause serious voltage-regulation malfunctions if not designed properly. Control computer electrical loads are comparatively less demanding. A proposed GM hybrid electric minivan indicated that a dual, 12-volt auxiliary electrical system, each with its own separate battery and isolated grounds, would be sufficient to satisfy its requirements. GM maintained that a 600-watt, 300-volt to 15-volt DC-DC converter would supply power from the propulsion battery to each system. Additional circuitry was incorporated to limit the converter input voltage to 400 volts, which can occur during regenerative braking.

One significant advantage of a hybrid electric vehicle, which has a heat engine over a purely electric vehicle, is that the HEV engine provides waste heat for heating the interior of the vehicle. An EV would have to utilize electrical power from the batteries to accomplish the same task, decreasing the energy available for propulsion. Therefore, integration of an APU into an EV has a positive impact toward reducing electrical demand on the batteries. Air conditioning and ventilation requirements imposed on the vehicle's electrical power source, however, are not alleviated with the introduction of an APU. To place these requirements in perspective, it is sufficient at this point to mention that the ASHRAE Code recommends 15 cfm of ventilation air per person for transportation vehicles. According to some literature, 50 percent of the steady-state cooling loads in conventional air-conditioning systems corresponds to ventilation loads alone. TABLE 7 lists estimated steady-state cooling load requirements for a G-Van in BTU/hr.

TABLE 7. G-Van Estimated Steady-State Cooling Loads (BTU/hr) (10)

				Ventilation Load		Metabolic Load Occupants		
Operating Condition	Van Type	Solar Load 83% Trans.	Conduction Load	30 cfm	45 cfm	2	6	Total
Stationary	Panel	3,450	12,180	2,490		1,000		19,120
	Panel w/partition	3,450	4,390	2,490		1,000		11,330
	Window	3,450	5,060		3,730		3,000	15,240
35 mph	Panel	3,450	10,620	2,490		1,000		17,560
	Panel w/partition	3,450	3,550	2,490		1,000		10,490
	Window	3,450	3,880		3,730		3,000	14,060

The important issue when integrating an APU with an electric vehicle, as far as auxiliary loads are concerned, is to consider incorporating (or possibly integrating) cooling or heating components directly into the APU system. Past and current research has placed limited focus on the issue. As a result, the impact of this concept on overall efficiency, performance, and range of HEV is not fully understood. However, direct drive of mechanical accessory loads by the engine may be more efficient than adding an additional electrical motor and suffering the required conversion efficiency losses.

C. APU Noise Considerations

Vehicles radiate interior and exterior acoustic noise, which depends on the operating conditions: stationary/idle, acceleration, and constant speed modes. Although audible sounds can range from the threshold of hearing (0 dB) to the threshold of pain (over 130 dB), most vehicle-generated noise levels are typically below 80 dB.

Typical noise that reaches the driver's ears originates at the tires, transmission, engine, etc. The most predominant concern of APU integration with an EV is the APU engine-generated noise. TABLE 8 illustrates comparative noise levels between an all-electric vehicle and a conventional ICE vehicle.

TABLE 8. Sound Level Comparison (in dB) for an Electric Vehicle and an ICE Vehicle (11)

Vehicle and Ballast Condition	Stationary/Idle		Acceleration		Constant Speed Tests: 56 km/h		Constant Speed Tests: 72 km/h		Constant Speed Tests: 88 km/h	
	Interior	Exterior	Interior	Exterior	Interior	Exterior	Interior	Exterior	Interior	Exterior
Evcort Electric @ 1,700 kg	37.0	55.4	65.8	59.0	66.3	60.9	67.5	65.3	68.8	67.1
Escort ICE @ 1,700 kg	--	--	--	--	66.6	61.9	67.9	65.9	69.3	67.8
Escort ICE @ 1,200 kg	51.8	65.0	71.9	68.2	65.6	--	66.9	--	68.9	67.6

An interesting result observed from the tests is that for this vehicle at constant speeds, the pure electric and ICE vehicles both exhibited essentially equivalent interior and exterior noise levels. Control of noise from the APU may need to be a factor in the development of the vehicle power management strategy. Noise-control measures may include stopping or idling the engine at low-vehicle speeds, or increasing delayed engine power during accelerations.

D. Life Cycle Cost Impact

One of the unresolved issues of integrating an APU into an EV is its impact on life-cycle costs (LCC) of the vehicle. A preliminary comparison reported by personnel in the Argonne National Laboratory and Regional Transportation Authority indicated that LCC are slightly higher (8 percent compared to a parallel configuration) due to the added weight and cost of the battery, especially for a non-optimum series hybrid system. This implies, however, that a greater emphasis should be placed on reducing the weight and cost of the batteries to improve LCC. TABLE 9 shows LCC results for a pure internal combustion engine vehicle and two electric vehicle configurations.

TABLE 9. Life Cycle Cost Analysis Results (US cents/km) (12)

	Gasoline ICEV	Low-Performance EV	High-Performance EV
Purchased electricity (accounts for regenerative braking and battery thermal losses)		2.52	1.60
Vehicle, excluding battery	13.27	10.57	9.01
Battery plus tray and auxiliaries		11.09	6.51
Fuel, excluding retail taxes (except fuel used for heating and including taxes)	3.41	0.00	0.00
Home recharging station	0.00	0.06	0.06
Insurance (calculated as a function of vehicle *miles* traveled and vehicle value)	2.22	3.15	3.07
Maintenance and repair	2.89	2.31	2.31
Oil	0.07	0.00	0.00
Replacement tires (calculated as a function of vehicle *miles* traveled and vehicle weight)	0.25	0.40	0.21
Parking and tolls	0.67	0.67	0.67
Registration fee (calculated as a function of vehicle weight)	0.14	0.18	0.13
Inspection and maintenance fee	0.22	0.11	0.11
Fuel taxes	0.90	0.90	0.90
Accessories	0.11	0.11	0.11
Total consumer life-cycle cost, cents/km for light-duty vehicles	24.16	32.07	24.69
The break-even retail price of gasoline*	N/A	4.22	1.67

* The price of gasoline, including retail taxes of US $0.31/gal, that equates the full life-cycle cost per km of the EV with the full life-cycle cost per km of the GV.

It can be inferred from TABLE 9 that introducing an APU into an EV may not significantly increase the life-cycle cost of a "high-performance" vehicle. For example, an ICEV not operating at optimum conditions (as an APU heat engine would) incurs 3.41 cents/km, 0.07 cents/km in oil usage, and 2.89 cents/km in repairs. If we assume an improved configuration (20 percent better), the total life-cycle cost would be approximately 27.33 cents/km.

Other studies seem to substantiate these encouraging operating cost findings. Unique Mobility, for example, developed an electric van with extended range using a HONDA-powered APU. Comparison of operating costs using extensive manufacturer's and test data indicated that their van would incur less operating expenses than a pure ICE van (see TABLE 10).

TABLE 10. Vehicle Operating Costs (US cents/mile) (12)

	Unique Mobility Van	ICE Van
Energy Cost		
Gasoline	1.68	6.94
Electricity	1.10	--
Total	**2.78**	**6.94**
Tuneups	0.74	1.13
Oil, lubricants	0.24	0.35
Tires	0.73	0.58
Batteries (propulsion)	2.04	--
General maintenance	1.83	2.15
Total cents/mile	**8.36**	**11.15**

Both vehicles were modeled to operate 80 miles/day, 250 days/year, with their retirement at 100,000 miles. Cost of gasoline was assumed to be $1.25/gal, and vehicle fuel usage was estimated to be 18 mpg. Battery charger efficiency was assumed to be 85 percent with a cost of $0.05/kWh. The analysis also assumed that the required battery pack be replaced at 50,000 miles. Unique Mobility also investigated the impact of battery life, energy costs and conventional fuel economy on operating cost of their van compared to a conventional minivan. Figure 16 illustrates the results of this comparison.

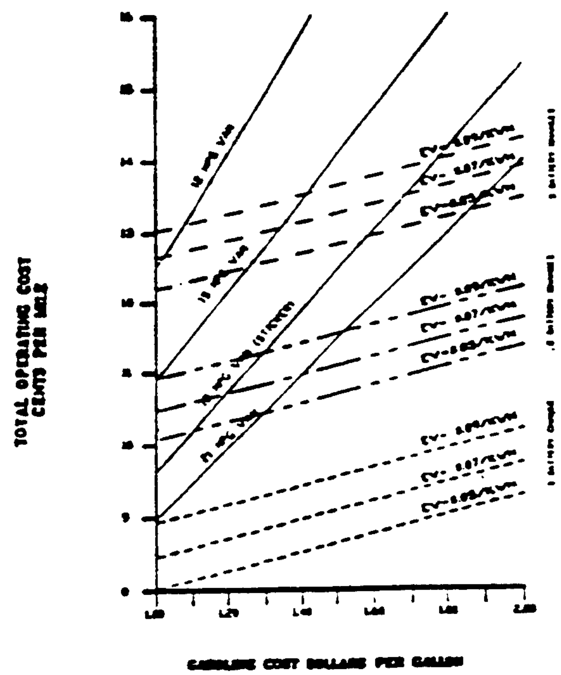


Figure 16. __Operating cost comparison__ (__12__)

VII. ENHANCEMENT NEEDS IN APU SYSTEM AND COMPONENT DESIGN

Heat engine technological advancement requirements for APU application include optimizing engine performance and durability for high power level operating modes. Designing for durability, however, tends to negatively impact engine size and weight. This indicates a need to investigate more exotic, light-weight materials for all APU system components (and possibly the engine itself) to assist in satisfying overall vehicle weight requirements. Alternative fuels that may become more available or inexpensive in the future, and that could power modified or newly designed engines, is also an identified area of research intended to reduce overall energy costs and air pollution. Ideally, an engine capable of operating with different types of fuel and blends would significantly improve APU flexibility. Other potential improvement requirements in engine design include a more efficient overhead valve design instead of side valve designs. In addition, it is imperative that reduction of formaldehyde and oxides of nitrogen be achieved within compliance levels. Finally, fuel cell development must continue as an alternate power source for futuristic APUs.

One of the main drawbacks in a series hybrid vehicle is the driveline inefficiencies. More specifically, the driveline components (engine, generator and motor) in a series hybrid system are configured in series (thus, the term "series"). As a result, mechanical energy of the engine is converted to electrical energy using the generator, and this electrical energy is then converted back to mechanical energy. Each conversion process subjects the system to additive energy losses resulting from these components' inefficiencies. Ideally, it would be desirable to attain combined generator and electric motor efficiency comparable to a conventional gearbox efficiency (typically, over 90 percent). It would certainly be beneficial to drive research toward achieving levels as high as possible in this respect. In fact, some companies are currently investigating this possibility by developing a generator-motor set using high-speed, synchronous generators and motors with new permanent magnets possessing a very high magnetic energy density. Integrating generator and drive motor functions implies that APU design will be affected as it deviates from conventional stand-alone philosophy to a more flexible combination of a series/parallel configuration approach.

As mentioned earlier, passenger cooling requirements affect vehicle range and performance. It is imperative that the transition be made from commercial air-conditioning systems to EV-specific cooling systems. This implies improving condenser performance levels over standard fin-tube condensers, using an efficient, continuously variable speed, motor/compressor system, etc. This is relevant in APU development since integrated APU/air conditioning systems may be beneficial for achieving superior, overall system efficiency.

Other technological advancement requirements are related directly to generators and inverters. Although manufacturers are proposing to replace AC generators in APUs with more efficient, brushless, motor/inverter combinations, details and specifications of these and other APU components (including advanced, integrated, vehicle/APU, control-unit algorithms) can still undergo several revisions and changes as new ideas are examined.

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ATTN: SFAE ASM S 1
SFAE ASM BV 1
SFAE ASM CV 1
CDR TACOM
WARREN MI 48397-5000

PROG EXEC OFFICER
ARMORED SYS MODERNIZATION
ATTN: SFAE ASM FR 1
SFAE ASM AF 1
PICATINNY ARSENAL NJ 07806-5000

PROG MGR
UNMANNED GROUND VEH
ATTN: AMCPM UG 1
REDSTONE ARSENAL AL 35898-8060

DIR
ARMY RSCH LAB
ATTN: AMSRL CP PW 1
2800 POWDER MILL RD
ADELPHIA MD 20783-1145

VEHICLE PROPULSION DIR
ATTN: AMSRL VP (MS 77 12) 1
NASA LEWIS RSCH CTR
21000 BROOKPARK RD
CLEVELAND OH 44135

CDR AMSAA
ATTN: AMXSY CM 1
AMXSY L 1
APG MD 21005-5071

CDR ARO
ATTN: AMXRO EN (D MANN) 1
RSCH TRIANGLE PK
NC 27709-2211

CDR ARMY NRDEC
ATTN: SATNC US (J SIEGEL) 1
SATNC UE 1
NATICK MA 01760-5018

CDR ARMY LEA
ATTN: LOEA PL 1
NEW CUMBERLAND PA 17070-5007

CDR ARMY TECOM
ATTN: AMSTE TA R 1
AMSTE TC D 1
AMSTE EQ 1
APG MD 21005-5006

PROG MGR PETROL WATER LOG
ATTN: AMCPM PWL 1
4300 GOODFELLOW BLVD
ST LOUIS MO 63120-1798

PROG MGM MOBILE ELEC PWR
ATTN: AMCPM MEP 3
7798 CISSNA RD STE 200
SPRINGFIELD VA 22150-3199

CDR FORSCOM
ATTN: AFLG TRS 1
FT MCPHERSON GA 30330-6000

CDR TRADOC
ATTN: ATCD SL 5 1
INGALLS RD BLDG 163
FT MONROE VA 23651-5194

CDR ARMY ARMOR CTR
ATTN: ATSB CD ML 1
ATSB TSM T 1
FT KNOX KY 40121-5000

CDR ARMY FIELD ARTY SCH
ATTN: ATSF CD 1
FT SILL OK 73503

CDR ARMY TRANS SCHOOL
ATTN: ATSP CD MS 1
FT EUSTIS VA 23604-5000

CDR ARMY INF SCHOOL
ATTN: ATSH CD 1
ATSH AT 1
FT BENNING GA 31905-5000

CDR ARMY ENGR SCHOOL
ATTN: ATSE CD 1
FT LEONARD WOOD
MO 65473-5000

CDR ARMY CSTA
ATTN: STECS EN 1
STECS LI 1
STECS AE 1
STECS AA 1
APG MD 21005-5059

CDR ARMY YPG
ATTN: STEYP MT TL M 1
YUMA AZ 85365-9130

CDR ARMY CERL
ATTN: CECER EN 1
P O BOX 9005
CHAMPAIGN IL 61826-9005

DIR 1
AMC FAST PROGRAM
10101 GRIDLEY RD STE 104
FT BELVOIR VA 22060-5818

PS MAGAZINE DIV
ATTN: AMXLS PS 1
DIR LOGSA
REDSTONE ARSENAL AL 35898-7466

Department of the Navy

DIR LOGISTICS PLANS & POLICY/
STRATEGIC SEALIFT PROG DIV (N42)
ATTN: N420 1
2000 NAVY PENTAGON
WASHINGTON DC 20350-2000

CDR
NAVAL SEA SYSTEMS CMD
ATTN: SEA 03M3 1
2531 JEFFERSON DAVIS HWY
ARLINGTON VA 22242-5160

CDR
NAVAL SURFACE WARFARE CTR
ATTN: CODE 63 1
CODE 632 1
CODE 859 1
3A LEGGETT CIRCLE
ANNAPOLIS MD 21402-5067

Department of the Navy/U.S. Marine Corps

HQ USMC
ATTN: LPP 1
WASHINGTON DC 20380-0001

PROG MGR COMBAT SER SPT 1
MARINE CORPS SYS CMD
2033 BARNETT AVE STE 315
QUANTICO VA 22134-5080

PROG MGR GROUND WEAPONS 1
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

PROG MGR ENGR SYS 1
MARINE CORPS SYS CMD
2033 BARNETT AVE
QUANTICO VA 22134-5080

CDR
MARINE CORPS SYS CMD
ATTN: SSE 1
2033 BARNETT AVE STE 315
QUANTICO VA 22134-5010

CDR
BLOUNT ISLAND CMD
ATTN: CODE 922/1 1
5880 CHANNEL VIEW BLVD
JACKSONVILLE FL 32226-3404

CDR
MARINE CORPS LOGISTICS BA
ATTN: CODE 837 1
814 RADFORD BLVD
ALBANY GA 31704-1128

Department of the Air Force

HQ USAF/LGTV
ATTN: VEH EQUIP/FACILITY 1
1030 AIR FORCE PENTAGON
WASHINGTON DC 20330-1030

AIR FORCE WRIGHT LAB
ATTN: WL/POS 1
1790 LOOP RD N
WRIGHT PATTERSON AFB
OH 45433-7103

AIR FORCE MEEP MGMT OFC 1
615 SMSQ/LGTV MEEP
201 BISCAYNE DR STE 2
ENGLIN AFB FL 32542-5303

SA ALC/SFT 1
1014 BILLY MITCHELL BLVD STE 1
KELLY AFB TX 78241-5603

WR ALC/LVRS 1
225 OCMULGEE CT
ROBINS AFB GA 31098-1647

Other Federal Agencies

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LEWIS RESEARCH CENTER 1
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DOE
CE 151 (MR RUSSELL) 1
1000 INDEPENDENCE AVE SW
WASHINGTON DC 20585

EPA
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