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Work performed for
U.S. DEPARTMENT OF ENERGY
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ELECTRIC AND HYBRID PROPULSION SYSTEM R&D

by Harvey J. Schwartz

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E-599

BACKGROUND AND INTRODUCTION

In 1977, the NASA-Lewis Research Center, at the request of the Department of Energy, conducted an assessment of the state-of-the-art of electric and hybrid vehicles.(1) One important finding was that "virtually no (propulsion) components are commercially available that have been designed specifically for electric vehicles." Of the 23 vehicles tested, the majority were powered by dc series motors designed to operate fork-lift trucks. Some used rebuilt aircraft starter motors, and only a few had motors modified to make them more suitable for electric vehicle (EV) use. Motor control was achieved either through voltage switching, or electronic controllers which were also primarily designed for fork-lift duty. Since almost all of the vehicles were conversions of conventional internal combustion engine-powered cars or trucks, they invariably used the transmission which came with the original vehicle. As a result, many of the vehicles lacked the perfomance drivers are accustomed to or were awkward to drive. All were expensive compared to conventional vehicles of equivalent or greater perfomance. One reason for the high price was that the cost of the drive motor and controller alone was often as much as $2000-$3000. Clearly improvement in the design, perfomance and cost of propulsion components was necessary for the development of a successful electric vehicle.

Since then, the NASA-Lewis Research Center has been charged by the Department of Energy (DOE) with responsibility for all propulsion system research and development work required in the conduct of the DOE's Electric and Hybrid Vehicle (EHV) Program. A broad-based propulsion component and system R&D project has been planned, organized, and is now in the implementation phase. The project involves participation by a broad spectrum of industrial organizations, by universities through grants, and by in-house work at NASA-Lewis. The project is designed to encourage and support DOE's overall programmatic objectives.

Within the context of the Department of Energy's Electric and Hybrid Vehicle Program, a propulsion system is considered to be an integrated group of components which transforms energy from the battery into shaft work at the drive axle of the vehicle. The propulsion system will normally include most or all of the following components: electric traction motor(s), motor controller(s), transmission/transaxle, heat engine (hybrid systems only), regenerative braking components, battery charger (when integrated into the motor controller), differential, instrumentation for monitoring and controlling the propulsion system, and auxiliary components (circuit breakers, fuses, etc.).

The propulsion system R&D project is divided into three areas of work; technology assessment, technology development and, commercialization. The status of each of these project areas will be discussed in succeeding sections of this paper, ending with an overall project summary.

TECHNOLOGY ASSESSMENT

Propulsion technology assessments have been undertaken for two purposes. First, to provide component performance data to current electric and hybrid vehicle (EHV) manufacturers which will assist them in selecting components for their vehicles. Second, to identify important component interactions within or resulting from the propulsion system, which influence its design or the design of other components in the vehicle. Work is presently under way on motor/controller testing, transmission testing, and studies of the interactions between the propulsion system and traction battery.

Most vehicles built today use series-wound dc traction motors with an electronic chopper to control the armature current, and therefore the motor speed. Testing at NASA-Lewis has shown[2] that a significant interaction exists between this type of motor and controller. Figure 1 shows that when a dc series motor is controlled by an armature chopper, the efficiency of the motor is lower when running on chopped current than it is if operated on pure dc current for the same power output. This difference in efficiency can be quite significant-as much as 10 percentage points-at part power. Since motor catalogs normally give motor performance when operating from a dc source, use of catalog data could result in a substantial shortfall in vehicle performance. Testing of four different types of commonly used traction motors with several controllers is now being performed for NASA-Lewis by the Eaton Corporation.

Using a standard SAE procedure, the Eaton Corporation, under a separate contract, has completed tests on four small automotive transmissions which could be considered for EV use. These were the Chevette, Pinto, and Omni automatics, and the Chevrolet LUV four-speed manual transmission. Tests were performed under conditions which the transmission would see if used in an electric vehicle. Typical results for one of the automatic transmissions is shown in Fig. 2. These tests show that while these transmissions may reach 90 percent efficiency in a conventional car, they may only operate at up to 80 percent in an EV, due to the fact that the transmission is oversized for electric vehicle service. Selection of a transmission can therefore significantly effect the range of an EV. Individual reports for each transmission will be written and published. Testing of a Citation automatic is under way.

Tests are also under way to define the interactions between propulsion systems and batteries. These tests are designed to provide statistically significant data on the effects of chopper controllers and of various load leveling and regeneration systems on the energy capacity and cycle life of lead-acid batteries. As with motors, in-house tests have shown that lead-acid traction batteries may suffer a significant performance loss when discharged in a pulsed mode.[3] Further tests being conducted at TRW are designed to quantify the performance of lead-acid batteries as a function of chopper frequency, peak-to-average current ratio and depth-of-discharge. In a related program, the Naval Weapons Support Center at Crane, Indiana is evaluating the effect of the design that the regenerative braking (energy recovery) system used in the propulsion system has on battery performance and life.

The National Bureau of Standards has started a project supported by the EHV propulsion project to calibrate wideband, high current instrumentation shunts and develop a primary standard instrument for the measurement of power in non-sinusoidal signals. The results of this effort will form a recognized and respected base for calibrating instruments used in the measurement of electrical power parameters in electric vehicle propulsion systems.

Power transistors are a critical element in a growing number of propulsion systems. A continuing assessment of their availability and applicability to EV propulsion systems is being maintained. A grant to Virginia Polytechnic Institute has been initiated to perform detailed evaluations of presently available and new power transistors.

Many commercially available components presently exist which could be used in electric and hybrid propulsion systems. However, there is no readily available means for system designers to identify or locate them. Therefore, a contract was recently signed with the Chilton Company to assemble and publish a catalog of components for electric vehicle propulsion systems. This catalog will be in the form of an assembly of short form catalogs or data sheets from individual suppliers. Requests for inputs to the catalog have been sent to over 4000 potential suppliers. This catalog should be published in early 1981. Catalog publication will be announced in STAR and will be available through NTIS.

TECHNOLOGY DEVELOPMENT

A variety of technology development projects are under way which seek to develop propulsion components and systems which will improve the performance and efficiency of electric and hybrid vehicles and reduce their cost to the consumer. The work is divided into two levels of technology; the first is intended to support commercialization of EHV's in the mid-1980's, and the second, which is more advanced, could support vehicles which might be produced in the early 1990's and beyond. It is recognized that no single approach will be best for the broad range of potential vehicle missions and that many potentially good solutions to a particular need exist. Therefore, in the first stages of most developments, multiple parallel contracts are being pursued. As development efforts progress, the number of supported approaches will be narrowed to those with the greatest commercial potential for low cost and attractive performance.

Figure 3 shows five different traction motors which are presently under development. The improved motors are examples of what existing technology can offer. Both are permanent magnet cylindrical rotor motors which require no external source of field excitation and use semiconductor power switches to replace the brush-commutator of conventional dc motors. Speed control is achieved within the electronic commutation and control circuits. The motors have been designed to provide sufficient torque and speed to drive a nominal 1600 kg vehicle over the SAE J227a Schedule D driving profile and to attain a constant 55 mph. One gear ratio change is allowed and regeneration is required. The two contractors used different approaches in achieving the goals. The AiResearch approach in Fig. 3(a) uses a small (16 kg) high-speed (26 000 rpm) motor, power transistors, and industrial thyristors. The Virginia Polytechnic Institute and State University approach in Fig. 3(b), uses a larger (40 kg), medium speed (9000 rpm) motor and high power transistors. Inland Motor, a leader in the manufacture of permanent magnet motors, under subcontract to VPI&SU, designed and built the electric machinery portion of their motor. Both contractors successfully built and tested functional models of their respective concepts in late FY 1979 and engineering models will begin testing in early FY 1981.

The advanced motor designs shown in the lower half of Fig. 3 emphasize approaches which are expected to lead to significant cost reductions in mass production.

Three parallel developments for advanced propulsion motors are under way. The contractors for these are: Garrett-AiResearch (3c), General Electric (3d), and Westinghouse (3e). The AiResearch and General Electric motors use permanent magnets and electronic commutation. The Westinghouse motor has an electromagnetically excited field and a mechanical commutator. All three are disk type motors.

The AiResearch approach uses a single high energy Samarium-cobalt magnet and operates at a maximum speed of 14 000 rpm from a battery voltage of 240 volts. The first functional model of the AiResearch motor demonstrated mechanical integrity and electromagnetic feasibility, but excessive windage and eddy current losses indicated a need for more development. The functional model is being modified to correct or minimize these problems. Because of its simplicity, this type of motor has high potential for low cost. The efficiency goal is 90 percent averaged over the SAE J227a Schedule D profile. This motor is expected to weight approximately 19 kg without electronics, which are expected to weigh an additional 40 kg.

The General Electric motor uses multiple magnets. A new permanent magnet material, manganese-aluminum-cobalt (Mn-Al-C), was intended to be used in this motor but is not yet available in sufficient quantity to build an operating machine. Therefore, the motor currently uses ALNICO magnets. Mechanical integrity and functional performance were demonstrated, but the magnet strength was not adequate for full rated performance as predicted. Mn-Al-C magnets are becoming more readily available and consideration is being given to modifying the present model to achieve predicted performance. The final motor will weigh about 42 kg without electronics, which are expected to weigh about 40 kg. The efficiency goal is 90 percent averaged over the driving profile. Because of the simplicity and use of low cost magnets, this motor also has potential for low cost.

Westinghouse has completed and successfully tested the functional model of their motor. The torroidally wound motor can also lead to low production costs. The functional model test data indicates an efficiency of approximately 90 percent or more over a major portion of the operating range. The finished motor is expected to weight of approximately 59 kg. Westinghouse is now proceeding to design, build, and test an engineering model based on the principles developed with the functional model. Preliminary design calculations for the engineering model predict a weight of approximately 45 kg, a maximum speed of 7200 rpm, and an efficiency about the same as the functional model. Figure 4 summarizes the characteristics and efficiency of the various designs tested to date and compares it with the contractors' predicted performance.

Although induction motors offer the potential of low cost and small size, present controllers for induction motors are large and costly. In parallel contacts, General Electric and Gould have developed engineering models of induction motor controllers designed for the same vehicle performance as the electronically commutated motors. The General Electric approach uses transistors similar to those used in the Department of Energy's Near-Term Electric Vehicle controller and the Gould approach uses readily available low cost thyristors. Figure 5 shows the Gould controller along with the associated induction motor. This motor is a modified conventional three-phase design. The GE controller is similar in size to the Gould controller. Both were designed for easy accessibility and serviceability and weigh approximately 69 kg each. In a final design for automotive use, they would be noticeably smaller and lighter. Test results on the Gould controller indicate efficiencies of above 85 percent over a major portion of the operating range. The efficiency of the GE controller is somewhat higher, reaching 95 percent. This difference was expected since SCR's and their commutating circuitry have more losses than transistors, which have a lower forward voltage drop and do not need commutation circuitry. Tests on the Gould controller are complete and the units will be shipped to NASA-Lewis for further evaluation. Contractor tests of the GE controller are nearing completion. These component developments have been described in several technical papers and final reports on the developments will be prepared.

It is recognized that dc commutator motors may be used in electric vehicles well into the late 1980 time frame. Therefore, two advanced dc controllers for such motors have been under development. One is by Franklin Research Center and the other by Chrysler. Franklin has designed a controller which uses a rotating motor-generator set in buck-boost modes to control the traction motor. This approach lends itself to simplicity and easy maintenance and does not use high power switching transistors or SCR's. The Franklin approach has been proven in principle, and engineering model design calculations indicate a workable, rugged controller can be built with a predicted weight of 64 kg and an efficiency greater than 80 percent over about one half of the operating range. However, it is heavier and less efficient than competing approaches which may outweigh the advantage of this controller design.

The Chrysler controller uses power switching transistors operating at 10 kilohertz and above. A notable feature of this controller is the very low audible noise level as a result of the high frequency operation. Chrysler has successfully built and is testing a full-rated functional model (shown in Fig. 6) which weighs approximately 27 kg. Test results indicate an efficiency of approximately 95 percent over a very wide operating range. Further development of this controller is planned.

A need for continuously variable transmission (CVT's) is anticipated for electric and hybrid vehicles, especially for those with flywheels. Development of such transmissions began with four parallel design studies which were completed in FY 1980. Garrett-AiResearch designed a torroidal variable ratio traction concept and Bales-McCoin a traction cone/roller arrangement. Battelle Columbus Laboratories designed a variable ratio pulley, compression, steel V-belt transmission and Emerson Kumm a variable ratio pulley flat belt transmission. Predicted weights for these CVT's are 41 to 70 kg and nominal full load efficiencies are 88 to 96 percent. Reports on these studies are being published.

While much emphasis is placed on propulsion components, total system development is not being neglected. In March 1979 a cost-sharing contract was started with the Eaton Corporation to develop an electric vehicle propulsion system using a two-speed automatically shifted transaxle, a three-phase transistorized power inverter, and a logic controller incorporating a microprocessor. The motor is rated at 25 horsepower. The computer controller supplied with the system is designed for maximum flexibility in that the pulse shaping logic can be adjusted to optimize system efficiency. The components and the complete system have been tested on dynamometers. A model of the system is shown in Fig. 7. The test results are extremely promising, indicating maximum system efficiencies over 80 percent at equivalent vehicle speeds of 40 to 60 mph. The system tests were completed at

Eaton in August 1980 and the system shipped to NASA-Lewis where it will be tested under simulated driving conditions on the Road Load Simulator (RLS). Negotiations are under way with Eaton to further develop the ac propulsion system and to incorporate it into test vehicles.

Propulsion system R&D related specifically to hybrid vehicles has thus far been limited to system studies and the development of computer analytical techniques and programs.

Three studies to analytically evaluate hybrid propulsion systems have been completed. The work was performed by Garrett Corporation-AiResearch Manufacturing Company, Mechanical Technology Incorporated (MTI), and South Coast Technology (SCT). The studies showed that hybrid propulsion systems can significantly reduce petroleum consumption while still providing a vehicle having acceptable cost and performance. Propulsion systems with conventional heat engines, Stirling heat engines, and rotary heat engines were investigated. The studies showed that hybrids with any of these engine types demonstrated good fuel economy and good performance providing they operated in an on-off heat engine mode. In order to achieve acceptable efficiency, all three studies concluded that the heat engine and electric motor must be operated in parallel as shown on Fig. 8. In this mode, most of the stop-and-go urban driving used electric power and the heat engine is turned on only when needed for power requirements in excess of the electric system capability. For long trips, when the battery could be depleted, the vehicle cruises on heat engine power and the electric system provides only peaking power. Characteristics and fuel consumption of the propulsion systems in typical passenger cars are summarized in Fig. 9.

The "SIMWEST" computer simulation program originally developed by the Boeing Company for analysis of wind energy systems is being modified under contract by Boeing so it can be used to simulate complex hybrid and electric vehicle propulsion systems. The program, called HEAVY, is especially useful in simulating complex operating strategies such as are used in the on-off hybrid systems. The program is now operational on the Boeing computer and is being checked out through the simulation of an electric drive (the GE ETV-1) and a complex on-off hybrid system. The program is expected to be complete and available for general use in early 1981.

COMMERCIALIZATION

Technology development by itself does not constitute complete "success," unless a path can be clearly identified which moves that technology from the laboratory to the market. The ultimate goal of the commercialization effort is to stimulate the voluntary involvement of industry in joint ventures with the Government to accelerate the early application and market introduction of commercially viable electric and hybrid propulsion system and components. For the past 18 months, NASA-Lewis has been working with DOE to develop a strategy for commercializing EV propulsion components and systems. It was recognized early that industry and not the Government must decide what constitutes a viable commercial product, and consultations with industry were held throughout development of the commercialization plan.

The key features of the plan are shown on Fig. 10. They are based on the concept of a joint, cost-shared industry-Government commercialization venture in which the Government would provide the majority of the funding early in a project when the risk is highest, with industry assuming an increasingly larger share as the project approaches production. Further incentives may be provided to industry in the form of special considerations for exclusivity in the patent and data areas. In return the Government would receive an appropriate payback of its investment if the project is successful and protection of the taxpayer's interests. In this way, we hope to stimulate commercialization of propulsion technology two or more years sooner than it might otherwise occur. This plan has been reviewed with DOE program and legal staff members and agreement to the approach achieved. The first application of the commercialization approach will be in 1981 when we plan to initiate a joint venture with industry to make available a low cost dc propulsion system.

SUMMARY

Studies conducted by our laboratory(4) and others show that the propulsion system rather than the battery may be the largest contributor to the purchase price of an electric car to the consumer, although the battery will be the major factor in the life-cycle cost. We execpt that propulsion R&D will significantly reduce these costs, lowering the potential vehicle purchase price by 20 percent or more. While achieving this goal, the work being conducted will also provide current electric and hybrid vehicle manufacturers with engineering design data and new components and systems which will assist them in building better vehicles. It will also generate a broader technology base from which future manufacturers can draw in designing vehicles for large scale production. And perhaps most importantly, we intend to use creative procurement approaches to stimulate commercialization of propulsion components and systems by industry.

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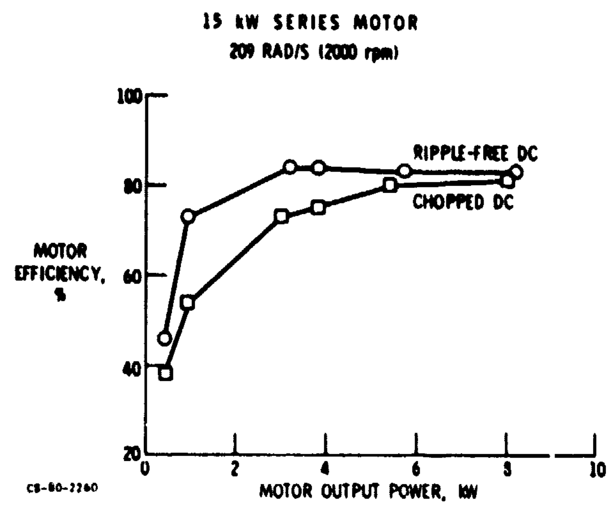

Figure 1. - Effect of chopped DC on motor efficiency.

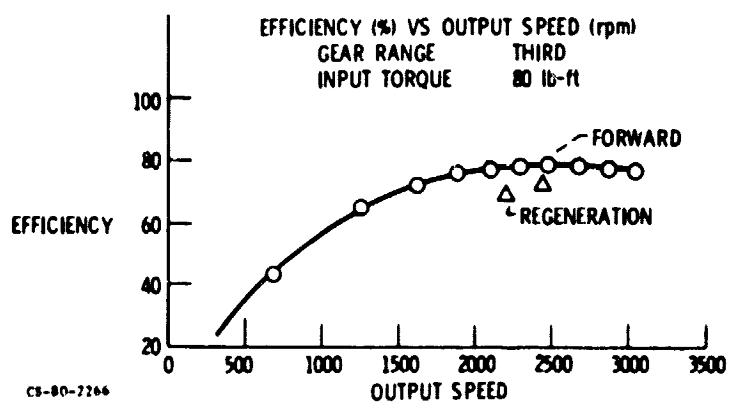

Figure 2. - Three-speed automatic transmission test data.

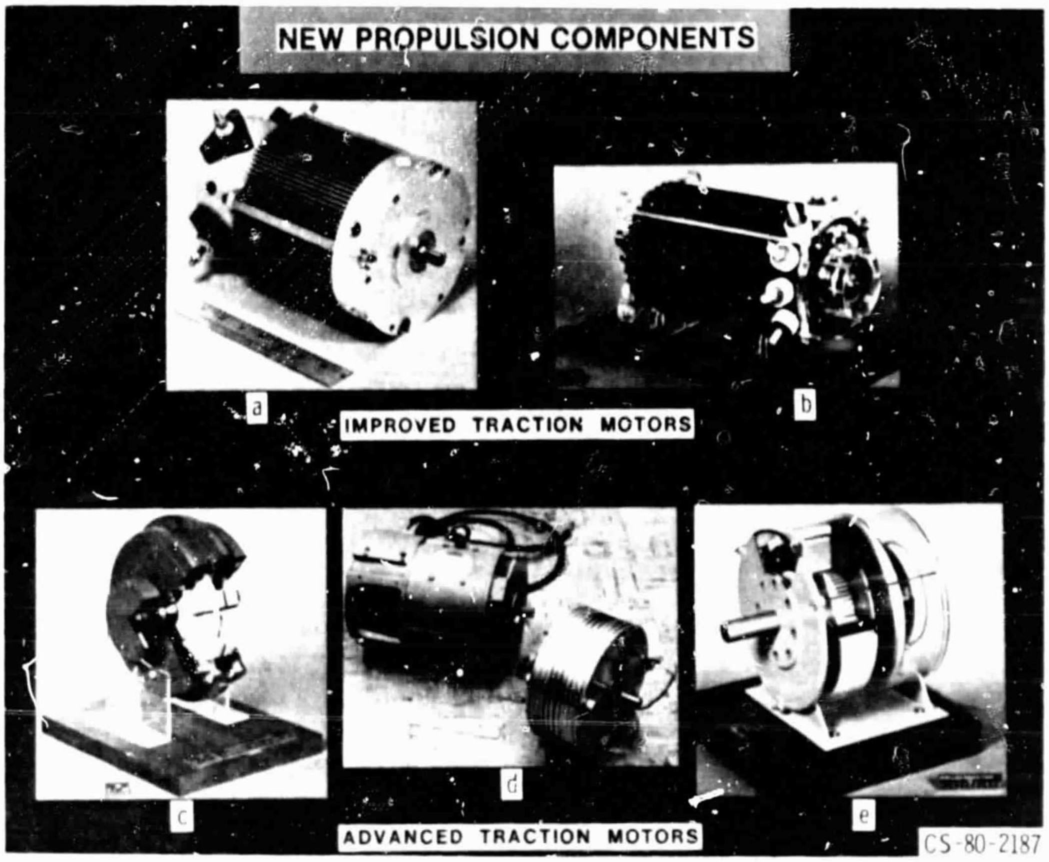

Figure 3.

CONTRACTOR	TYPE	CONSTRUCTION	rpm	WEIGHT, kg	EFFICIENCY, %	
					PEAK MEASURED	EFFICIENCY PREDICTED
VPI & SU	ELECT COMM TRANSISTOR	P. M. DRUM	8 000	40*	93	93
AIRESEARCH	ELECT COMM SCR	P. M. DRUM	27 000	16*	95	95
GE	ELECT COMM TRANSISTOR	P. M. DISK	11 000	42**	90	92
AIRESEARCH	ELECT COMM	P. M. DISK	14 000	19**	77	93
WESTINGHOUSE	DC SHUNT	GRAMME DISK	6 000	59**	90	90+

*PEAK POWER 23 kW

**PEAK POWER 27 kW

***AVERAGED OVER SAE J227a, SCHEDULE D DURING CYCLE

Figure 4. - Traction motor characteristics.

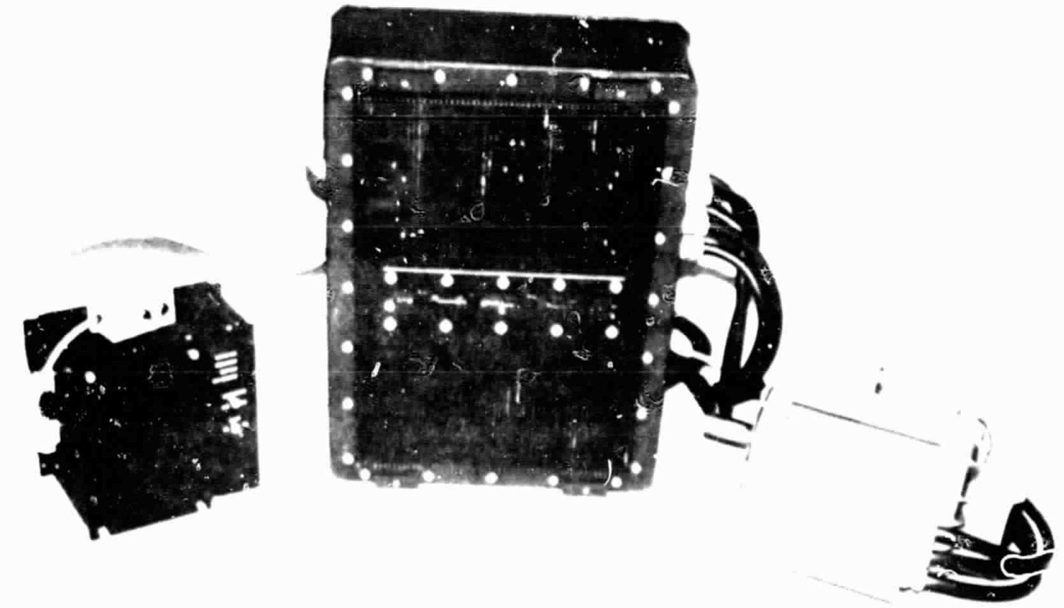

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Figure 5.

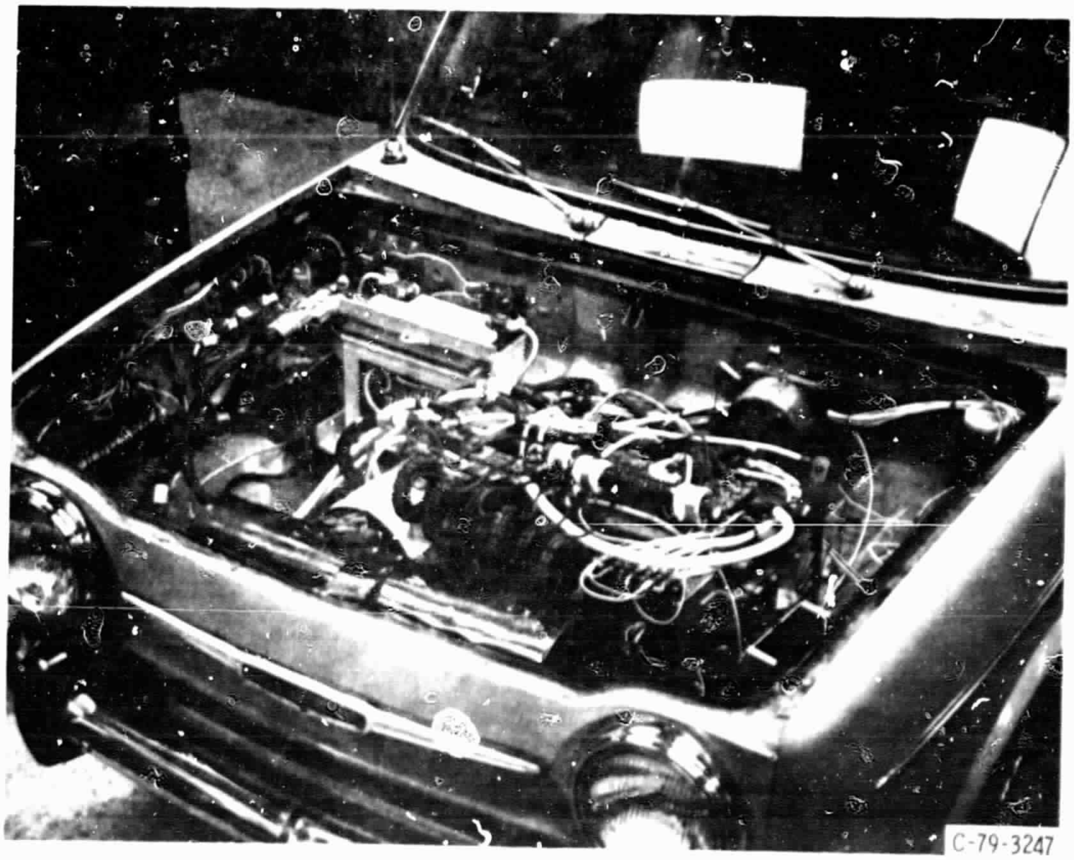

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Figure 6.

PROPULSION SYSTEM DEVELOPMENT

Figure 7.

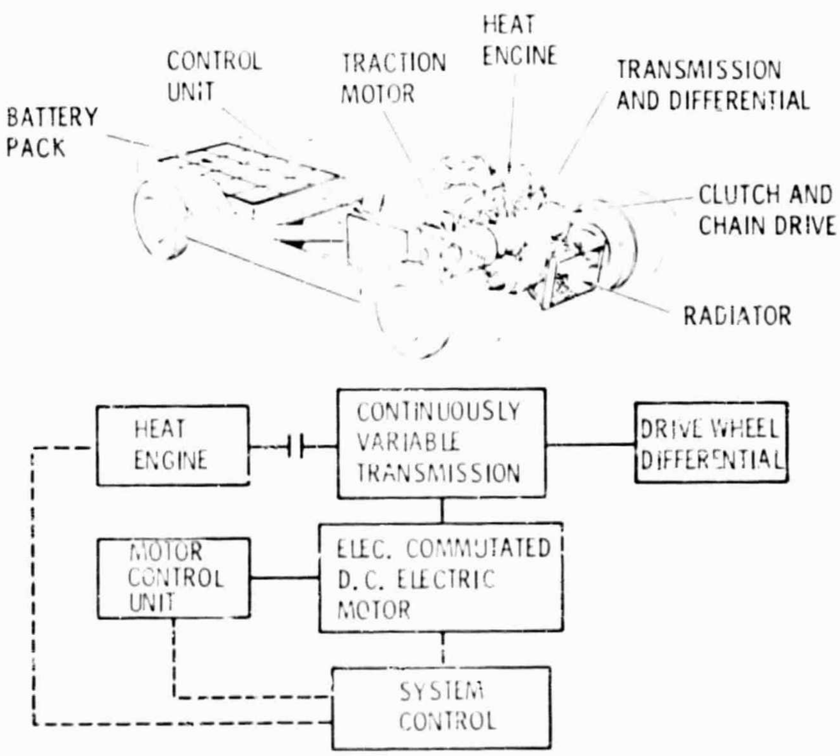

Figure 8. - AiResearch hybrid propulsion system.

	AIRESEARCH	MTI	SCT
VEHICLE	5-PASSENGER	6-PASSENGER	6-PASSENGER
HEAT ENGINE	CONVENTIONAL	STIRLING	ROTARY
HYBRID TYPE	PARALLEL	PARALLEL	PARALLEL
LEAD-ACID BATTERY WEIGHT, kg	386	175	390
ON-OFF ENGINE OPERATION?	YES	YES	YES
ACQUISITION COST, 1976 $ (PROPULSION SYSTEM, ONLY)	3214	2400	4132
LIFE CYCLE COST, $/km	0.054	0.035	0.070
FUEL CONSUMPTION LITERS/yr*	591	269	689

*COMPARE WITH 1390 LITERS/yr FOR CONVENTIONAL CAR AT 11.5 km/l (27 mpg) DRIVEN 16 000 km

Figure 9. - Advanced hybrid propulsion system studies. (General comparison of results.)

PROVIDE INCENTIVES TO INDUSTRY
- COST-SHARING
- RISK-SHARING
- EXCLUSIVITY

IN RETURN FOR
- PAYBACK OF GOVERNMENT INVESTMENT IF SUCESSFUL
- PROTECTION OF TAXPAYERS INTEREST

CS-80-2259

Figure 10. - New approaches to contracting in commercialization environment.