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The JPL Electric and Hybrid Vehicle System Research and Development Project, 1977-1984

A Review

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PREFACE

This report briefly describes the activities and accomplishments of the JPL Electric and Hybrid System Research and Development Project from its inception in 1977 to its conclusion in 1984. The major findings and lessons learned are viewed from an historical perspective dealing with broad issues which cut across the various technical disciplines. Many specific near-term and long-term recommendations are offered in the hope that programmatic insight and future planning can benefit from their discussion.

ACKNOWLEDGEMENT

JPL is justifiably proud of its accomplishments and contributions made to the DOE Electric and Hybrid Vehicle Program, but credit is due in great measure to the caliber of the individuals administering the Program. Paul Brown as Director of DOE's Electric and Hybrid Vehicle Division has surrounded himself with an outstanding cadre of program managers. Dr. Robert Kirk, Kenneth Barber, and Gerald Walker all provided the proper mixture of direction, freedom, and trust with a professional yet personal style. The authors and the rest of the JPL Project staff hereby express their appreciation for that relationship and wish them every success in the continuation of this important Program.

CONTENTS

CONTENTS (contd)

FIGURES

TABLES

EXECUTIVE SUMMARY

A. PROJECT SCOPE AND RESPONSIBILITIES

The JPL Electric and Hybrid Vehicle System Research and Development Project was established in the spring of 1977. Originally administered by the Energy Research and Development Administration [ERDA] and later by the Electric and Hybrid Vehicle Division of the U.S. Department of Energy [DOE], the overall Program objective was to decrease this nation's dependence on foreign petroleum sources by developing the technologies and incentives necessary to bring electric and hybrid vehicles successfully into the marketplace. The ERDA/DOE Program structure was divided into two major elements: (1) technology research and system development and (2) field demonstration and market development. The Jet Propulsion Laboratory [JPL] has been one of several field centers supporting the former Program element. In that capacity, the specific historical areas of responsibility have been:

(1) Vehicle system developments

(2) System integration and test

(3) Supporting subsystem development

(4) System assessments

(5) Simulation tool development

1. Vehicle System Development

In order to investigate the performance potential and economic viability of an advanced electric vehicle that could be put into production in the 1980s, JPL became technical manager for two contracts to design and build integrated test vehicles. Although no major technological breakthroughs were sought, the "ground-up" approach allowed the use of system engineering principles never before applied to electric vehicle developments. The two contracts complimented each other in that one used a sophisticated control with conventional drive approach (General Electric/Chrysler, ETV-1) and the other (Garrett AiResearch, ETV-2) incorporated a more complex electromechanical flywheel for increased performance and potentially longer battery life. The ETV-1, delivered to JPL in the fall of 1980, has since become the standard against which all other electric vehicle developments or concepts are measured.

Due to the range limitation exhibited by electric vehicles, they will not be directly competitive with general-purpose conventional vehicles. To exploit that market, where the majority of foreign petroleum is presently consumed, the hybrid vehicle concept was investigated with a third integrated test vehicle contract. The General Electric hybrid test vehicle delivered to JPL in 1983 uses two power sources (an electric motor and a heat engine) in a parallel configuration promising significant petroleum savings over conventional internal combustion engine vehicles in representative annual use patterns.

2. System Integration and Test

Many new technologies and disciplines grew out of the space program as several painful lessons were learned enroute to developing successful spacecraft. The concept of system-integrated testing is a prime example. The Jet Propulsion Laboratory and others found out early on that the practice of bringing together even carefully designed subsystems for final assembly and check-out always resulted in the discovery of unanticipated and often very challenging new problems due to "system interactions". The development of sophisticated electric and hybrid vehicles poses many of the same generic problems and can, therefore, benefit substantially from an integrated approach to system analysis, design and testing.

System testing at JPL has taken two forms:

(1) The investigation and evaluation of a particular component or subsystem (e.g., developmental batteries) in the system environment.

(2) The test and evaluation of the integrated vehicle system

Because of the variable nature of the natural outdoor environment, and the requirement for consistent engineering-quality data, vehicle system testing was performed on a chassis dynamometer. However, precision coastdown testing was performed on an outdoor track under controlled conditions in order to properly establish and set-up the dynamometer loss mechanisms. Results from these tests were fed-back to the industry and DOE, providing a credible evaluation of technology strengths and weaknesses, as a part of an integrated development process.

3. Supporting Subsystem Development

The Jet Propulsion Laboratory identified several subsystem elements (other than the propulsion components addressed by other field centers) requiring development for technology-transfer. These included:

(1) Vehicle mass reduction

(2) Road-load reduction

(3) Environmental control (passenger area)

(4) Battery charger and state-of-charge indication

(5) Battery packaging impact on vehicle dynamics

a. Vehicle Mass Reduction

Automotive performance is directly related to the mass of the vehicle. Although generally associated with improved acceleration performance, mass reduction pays handsome dividends through reduced braking, better gradability and lower rolling losses as well. Electric vehicles tend to be significantly heavier than their conventional counterparts due primarily to the low specific energy of the battery subsystem and the additional structure to support it. By the same token, a pound of weight saved is even more advantageous to an electric vehicle. With this incentive in mind, an activity was defined to develop and demonstrate the production feasibility of cost-competitive lightweight composite material automotive components by investigating improved fabrication concepts. A contract with the Budd Company demonstrated a new design/fabrication approach using continuous fiber material to reinforce a general chopped glass composite structure. This resulted in a door structure demonstrating a 43% weight savings through direct substitution and parts consolidation.

b. Road-Load Reduction

Aerodynamic drag and rolling resistance account for most of the dissipative loss experienced by a vehicle in motion. At a steady 45 mph, the road-load power requirement is approximately evenly divided between drag and rolling losses. Even over a low speed driving cycle, such as the SAE J227a D cycle, nearly 70% of the road-energy may be consumed by these mechanisms. Although these facts were understood by the established automotive community, little information was available to electric vehicle manufacturers to improve their aerodynamic designs. For these reasons, an activity was defined to refine this technology and present application principles in a format that was useful to the electric vehicle developers. This task culminated in a guidebook for the aerodynamic design of electric and hybrid vehicles using a system approach.

c. Environmental Control

It has been argued that for electric vehicles to successfully compete in the marketplace, they must offer the same level of comfort as their conventional counterparts. For many areas of the country, air conditioning is considered to be a necessity. The power requirements of conventional air conditioning subsystems however, would have a severe impact on electric vehicle performance. For these reasons, JPL investigated several alternative solutions and found that precisely because of an electric vehicle's limited daily range, certain offboard coolant charging schemes were feasible which would dramatically decrease onboard energy requirements.

d. Battery Charger and State-of Charge Indication

Operating any vehicle with an unknown amount of fuel is always unsettling. Given the limited energy storage and slow recharge of an electric vehicle, an inaccurate "fuel" gage is even less acceptable than for conventional vehicles. Remaining range is a complex function of many parameters including most recent charge experience and projected rate of discharge. A task was, therefore, undertaken to design, build and test an integrated battery charger/state-of-charge indicator. A contracted effort with Gould, Inc., resulted in a successful state-of-charge indicator and a battery charger requiring additional development. The state-of-charge indicator is now being upgraded for integration, installation, and evaluation in two service vehicles owned by General Telephone and Electronics.

e. Battery Packaging Impact on Vehicle Dynamics

At the conclusion of a preliminary vehicle design exercise, the subsystem and component performance specifications are established. Before a successful system can be integrated, however, a packaging design effort must be performed. Since batteries are not only a large volume item but constitute a significant portion of the vehicle mass, their influence upon vehicle dynamics was studied. Correct weight distribution is the single most important factor in achieving acceptable vehicle handling characteristics. A contract with Pioneer Engineering resulted in the conclusion that high front-weight-bias vehicles can be tailored to achieve acceptable handling characteristics whereas high rear weight bias vehicles present severe handling penalties which cannot be overcome.

4. System Assessments

One of the more important roles played by any organization having system guidance responsibility is the performance of periodic assessments. These can take any form from strategy, planning, and goal development exercises to review and evaluation of technology status. Often these views are combined in order to provide the insight necessary to efficiently focus program resources. The Jet Propulsion Laboratory has performed four major electric and hybrid vehicle assessment tasks since 1978:

(1) The 1978 electric and hybrid vehicle state-of-the-art assessment

(2) The hybrid vehicle potential assessment

(3) The advanced vehicle system assessment

(4) The hybrid vehicle assessment

a. The 1978 Electric and Hybrid Vehicle State-of-the-Art Assessment

The 1978 electric and hybrid vehicle state-of-the-art assessment was an extension of the 1977 assessment conducted by Lewis Research

Center to evaluate the technology status and market readiness of electric and hybrid vehicle concepts. It was based upon site visits to users, manufacturers and administrative agencies in the United States, the United Kingdom, Germany, France, Italy and Japan.

b. The Hybrid Vehicle Potential Assessment

The multiyear hybrid vehicle potential assessment initiated in 1977 investigated the potential petroleum savings achievable if hybrid vehicles were introduced into the national fleet. Technology needs and development requirements were evaluated against various socioeconomic and political scenarios involving predictions of future fuel pricing and market penetration. The results of this study provided the justification to embark on the hybrid vehicle program resulting in the General Electric hybrid test vehicle.

c. The Advanced Vehicle Systems Assessment

The advanced vehicle system assessment was the broadest and most comprehensive study performed in support of the DOE Electric and Hybrid Vehicle Program. Using a top-down approach, its purpose was to identify personal transportation needs in the 1990s, investigate the potential improvements in alternative technologies and marry the two in order to focus resources on the most viable paths. The effort was begun in late 1980 and concluded in 1984. It was highly interactive in the sense that field center activities were integrated and review forums were provided throughout the study period.

d. The Hybrid Vehicle Assessment

Because it was recognized during the advanced vehicle assessment that there were literally hundreds of feasible hybrid configurations, a separate activity was initiated in 1981 devoted to the investigation of these options. Sharing much of the same data base with the advanced vehicle assessment (mission analysis, energy storage technology, etc.) this study quantified the energy and petroleum saving potential of the most promising configurations.

5. Simulation Tool Development

To support the assessments just described, the evaluation and assessment of test results and the design of prototype vehicles, comprehensive vehicle/component simulation tools are absolutely essential. Rather than building such a tool from scratch, JPL contracted with General Research Corporation to highly modify a previously existing program named ELVEC. The ELVEC program has been continually expanded, improved and documented to meet the needs of the various JPL, field center, and DOE activities on a national timeshare system.

Other simulation tools were developed by JPL to suppport more specific activities. The HYVEC program, originally created to analyze various design options of the complex Garrett ETV-2 electromechanical flywheel powertrain, was further expanded to support the analysis of even more complex hybrid vehicle configurations for the hybrid vehicle assessment. Several smaller programs for cost and configuration analyses were developed as needed.

B. MAJOR FINDINGS AND LESSONS LEARNED

During the course of this 7-yr project many studies, developments and tests were completed. Each resulted in specific information or conclusions which are well documented in the various deliverable reports and other papers referenced in the body of this report. Moving back "one level of abstraction", the major findings and lessons discussed herein deal with broad issues which cut across the various technical disciplines.

(1) Strategic Planning and Comprehensive Goal-Setting Are Critical. Perhaps the single most important element in the performance of any task is the development of the guiding objectives and requirements. The cornerstone of these objectives must be the strategic plan based upon the overall program goals.

The DOE Electric and Hybrid Vehicle Program goal to reduce this nation's dependence upon foreign petroleum, by facilitating the introduction of electric and hybrid vehicles into the national transportation fleet, has remained constant; the strategy adopted to achieve that goal has not. The changing political environment (a malady often faced by government-funded projects), has resulted in a lack of continuity and focus in many areas.

(2) Successful Electric and Hybrid Vehicle Technology Developments Must Address a Broad List of System Issues. The term "research and development" is often used to describe a single activity; however, the two terms have quite different philosophical thrusts. Research is exploratory in nature and is relatively unconstrained. The transition to development occurs when some potential application is identified. At that point the full consequence of the system constraints should be applied. Only in this way can a technology's potential strengths and weaknesses be identified so that development efforts can be intelligently focussed. The technology development activities supported by the Program have all identified electric and hybrid vehicles as a potential application. Unfortunately, early efforts were often treated as research projects or were developed around incomplete or inappropriate system requirements. This has resulted in major disappointments when components underwent system testing. Shortcomings which should have been addressed

early in the development process had been overlooked, ignored, or inappropriately deferred. Nowhere does the integrated system approach pay more handsome dividends than in component and subsystem development. Tied by an unbroken chain to the overall DOE electric and hybrid vehicle goal and strategic implementation plans, the subsystem requirements are, in fact, derived from them. Many evaluation loops are necessary in order to continually verify or adjust this alignment.

(3) The Technical and Economic Environment has Changed Significantly Since the Start of the Program. The DOE Electric and Hybrid Vehicle Program was spawned in an atmosphere of petroleum shortages and highly inefficient vehicles. Against that backdrop, many believed that any produceable electric vehicle would be quickly snapped up by a public anxious to get out of their gas guzzlers. In the subsequent period, while the DOE and its field centers have been hard at work, the international automotive community has made some impressive improvements. In many ways the competition may have moved faster than the electric and hybrid vehicle state-of-the-art.

The high cost and shortage of gasoline, a major driver to produce electric vehicles in 1977-78, has disappeared to a great degree. Whether real or only perceived, personal electric and hybrid vehicles cannot hope to compete in the present environment. Simply stated, successful deployment of electric and hybrid vehicles into the national fleet (in any meaningful numbers) will require significant increases in the real cost of petroleum and/or decreased availability.

(3) Battery Development Has Been Slower Than Projected. Although other technologies and subsystems required improvement, it was recognized from the start that development of vastly improved battery subsystems was the critical element. Following a cursory analysis of vehicle missions, goals were established for energy and power density, cycle life and cost. Although this was an incomplete list, it does contain some of the most important attributes. Those energy and power goals are being approached but the desired life-cycle cost remains elusive. The oal of 800 cycles at $70/kWh established in 1978 appears nearly as remote now as it did then. In addition, it is not enough to target energy and cycle life goals under some benign conditions (such as C/3, constant current). Even if these goals were met, they would likely bear little resemblance to what could be expected in a vehicle duty-cycle environment. In addition, such battery attributes as reliability, maintenance and safety have been unwisely subordinated in many development programs. These qualities must be addressed early in the development process as some of these inadequacies could result in potential show-stoppers.

(4) Commercial Success Will Come Only Through Involvement with the Established Automotive Industry. When the Electric and Hybrid Vehicle Program was launched in 1976, the focus was clearly on developing a new industry. Government sponsored markets, loan guarantees and other incentives were created to make the opportunity more attractive for entrepreneurs. This approach, however, has proved to be unsuccessful for several reasons including high unit cost, poor quality control and nonexistant repair and warranty service. Solutions to these problems are precisely what the established automotive industry uniquely offers. High unit cost can only be overcome through high production; and high production of automobiles can only be accomplished with huge capital expenditures. The established distribution and dealer network is what makes the parts/repair, service/warranty operations work. Grass roots competition can be successfully developed in the component supplier industry for such things as batteries, motors, controllers, etc. Chassis development, integration, production, and sales however, is best left to those currently in the business.

C. RECOMMENDATIONS

In response to the findings and lessons learned over the 7-yr life of this project, several recommendations are offered. These are presented in two categories: a shortrange time frame (1985-1990) which is amenable to more specific recommendations and a long-range time frame (1990-2000) which is, by necessity, more general and dependent upon preceding events.

The overriding theme for all continuing activity is to integrate the planning, analysis and hardware work through an active system function. Efforts for the short range should concentrate on improving the sophistication of analysis techniques and supporting hardware developments with a high probability of success.

In a general sense, many of the activities suggested in each of the following categories are in progress. The attempt in this document is to emphasize recommendations in light of new information and/or perceived needs for enhanced efforts.

(1) Planning and the Development of Short Range Goals Should be Revisited. Two observations suggest a change in planning and implementation strategy: the temporary abundant supply of cheap fuel and the critical need for revised component (particularly battery) performance goals based on integrated system studies. Emphasis should be given to the evaluation of probability of success and cost-risk-benefit tradeoffs of the developing technologies.

(2) Coordination Efforts Need to be Expanded in the Areas of Standardization, Joint Development Ventures and Seminars.

Although great strides have been made in standardizing ambiguous definitions surrounding test procedures, results and reporting formats, much remains to be done. The requirements which a component must satisfy in a vehicle system necessitate that time dependent and cycle-oriented missions must be standardized and used as a basis for their evaluation.

It is clear that while the individual researcher and small company can make important contributions to the electric and hybrid vehicle technology, it is extremely important to encourage the involvement of the potential manufacturers through joint ventures. This applies not only to the basic vehicle manufacturers, but also those of critical components such as batteries, motors, controllers, etc.

With decreased emphasis on R&D for electric and hybrid vehicle related projects, there will be fewer publications and technical meetings for communication among interested groups. Thus, it is more important than ever to coordinate a "core" of meetings and seminars to keep the information flowing.

(3) Several Small Technical Panels Should be Established to Assist in the Evaluation of Analysis Procedures, Test Procedures, New Technologies, Probability of Success and Component Performance in a System Environment. Evaluation activities provide the feedback for the insight necessary to direct all other activities. Because of their critical nature and the fact that every analysis or test effort is subject to limitations, an independent review and consultant panel is necessary to insure the quality, credibility and consistency of such efforts.

(4) Highly Visible Projects Should Have a High Probability of Success; Low Visibility Activities Should Seek Higher Payoff Accepting Higher Risks. Those highly visible activities such as the EPRI/DOE and Eaton Van efforts can do much toward generating positive feelings about electric and hybrid vehicles if the demonstrations are successful. They can do considerable damage by generating negative feelings if the demonstrations are not successful.

The almost invisible technology developments are much more benign and as such are subject to less pressure for successful demonstrations. Thus, higher risk (with potentially higher-payoffs) developments can and should be undertaken in this category, if they support the success of relatively short range technology goals.

(5) Analysis and Simulation Support Studies, which are Less Expensive and Broader Than Hardware Work, Should be Continued and Expanded to Provide Guidance for Technology Priorities. There has been a trend of increasing

sophistication in analyses and simulation which needs to be continued. Partially, this trend has come about as a result of vastly improved and more accessible computer facilities, and partly because many earlier results were simply shown to be invalid. The three areas which deserve special attention are continued system assessments, improved component and battery models and more realistic vehicle use models.

(6) A Systems Function Must Be Established to Rationally Connect Planning, Goal Setting and the Development Activities. The system function is that activity which gives coherent direction and meaning to all the other activities. Contrary to common belief, the mechanism must be formalized to be effective.

The Jet Propulsion Laboratory has been providing some system leadership, but to date it remains fragmentary. The Electric and Hybrid Vehicle Battery Test Working Task Force grew out of recommendations to integrate the battery test activities and the system assessment activities. The advanced vehicle assessment and the hybrid vehicle assessment have provided the evaluation functions, but unfortunately, have been perceived by the community development as a one-time, largely unilateral exercise. In any case, an operational mechanism which ties the whole development process together is not yet in place. The system advocacy, necessary to cause this to happen, may grow silent when JPL leaves the Program.

While many of the short range activities properly support long range goals, there are additional long-range goals to be considered:

(7) A Critical Base for Self-Sustaining Technology should be Developed. The electric and hybrid vehicle community is in a precarious position due to the present lack of a competitive market for their products or services. The market "pull" associated with expensive or short-supply fuel is presently gone and developing the technical base necessary for the "push" is expensive and time consuming.

The challenge, then, is to massage the electric and hybrid vehicle community and their individual activities to the point where even without the type of pull and push referred to, their progress will be self-sustaining. The most likely way of accomplishing this formidable task is to find applications for the technologies outside electric and hybrid vehicle, and conversely to look for electric and hybrid vehicle adaptations of otherwise developing technologies.

(8) Appropriate High-Risk Technologies should Receive Long-Term DOE Support. Making use of the results of system studies such as the advanced vehicle assessment, certain carefully

selected high-payoff, high-risk technologies should be pursued. Because of these characteristics, it is unlikely that they would find support outside of the DOE Program. Since these specific technologies are presently in their infancy, most of their promise may be based upon speculation. For that reason it is necessary to continually evaluate the status, strengths and weaknesses with continuing assessment studies.

I. INTRODUCTION

A. BACKGROUND AND HISTORY

Only a short time after the automobile was developed as a personal transportation concept, a noisy, complex, and dirty engine had driven all other power sources out of the industry. Its appeal was based on its tremendous specific power capability which allowed a level of performance and optional accessories otherwise unattainable. In an era when fuel was plentiful and pollution concerns nonexistent, it was perfectly suited to the times. Today, technical, social, and economic forces are working counter to its existence and provide the opportunity to reconsider alternatives long since rejected.

Personal transportation burns over one-fourth of all the petroleum consumed in this country and is therefore a major factor in our dependence on foreign sources. In 1976, following the Arab oil embargo which dramatized the nation's vulnerability to interruptions in the supply of petroleum, Congress passed Public Law 94-413 calling for the development of electric and hybrid vehicles. The nature of the bill and the resulting DOE Program administered initially by the Energy Research and Development Administration, was to create a new industry dedicated to the development and production of electric and hybrid vehicles. The Program was divided into two main elements: (1) the development of near-term technologies possibly suitable for electric vehicle applications and (2) the promotion/demonstration of currently available electric vehicles. Until recently, these elements remained virtually independent of each other.

JPL has been one of several field centers supporting the former Program element. In that capacity, the primary areas of responsibility have been:

(1) Integrated test vehicle developments

(2) System integration and test

(3) Nonpropulsion subsystem development

(4) System assessments

NASA's Lewis Research Center and DOE's Argonne National Laboratory have had primary responsibility for propulsion subsystems and near-term battery developments respectively.

In more recent years JPL has sought to provide the overall program with a system engineering function. In this role, attempts have been made to coordinate the activities going on at other field centers with JPL technology assessments and system evaluation efforts.

During the past 7 yr, the political and economic winds have changed several times and the resulting DOE Program thrusts were compelled to keep pace. Spawned in an atmosphere of petroleum shortages and inefficient vehicles, the early Program activities were directed at getting electric vehicles on the road as quickly as possible. Public and private sector demonstration fleets and incentives were adopted to create a "market pull" while research and development support provided a "technology push." These early efforts were aimed largely at stimulating the existing, if immature, electric vehicle industry or enticing entrepreneurs (and venture capital) into the arena. As these efforts failed to produce the desired impact, a major change in the philosophical approach evolved. Recognizing that significant petroleum savings would require production rates achievable only by the established automotive industry, the so-called commercialization thrust was launched. Using this approach, government programs would strive to develop technologies to near-prototype maturity and actively encourage the industry to move into commercial production. However, an administration change in January 1981 established policies necessitating a more distant government/industry relationship. By 1982 commercialization activities had officially ceased as new programs were limited to "long-range, generic-research."

During the same period, the public's view of energy conservation changed as well. The Arab oil embargos of the 1970s, resulting in the inconvenience of long fuel lines and high prices, brought pressure on the government to provide for alternatives. As shortages eased and consumers adjusted to the new prices, the public outcry all but disappeared. These factors and a general economic recession in the early 1980s have combined to squeeze the Program support and funding level in recent years.

This chronology is reviewed, not to be critical, but to provide the necessary perspective from which to view the activities and accomplishments of the JPL Electric and Hybrid Vehicle Project over these past 7 yr.

B. THE JPL SYSTEM ROLE

The DOE Program has had many elements with technical development projects focused exclusively on such areas as the powertrain and energy storage subsystems. It was also properly recognized that the "system discipline" was an absolutely essential element for the successful development of anything so complex as an electric vehicle or hybrid vehicle. Most of the electric vehicles that have been introduced in the U. S. and around the world in recent years have not had the benefit of any real system engineering. They have been compromise vehicles assembled by hopeful entrepreneurs from standard automobiles with whatever electric vehicle components were available. The electric vehicle is, in fact, a very different animal from its internal combustion engine counterpart. Its available specific power and energy, are respectively, five and fifty times lower; precisely the disadvantages which led to its demise more than 60 yr ago. Because of this disparity, the system role in goal identification, requirements definition, performance specifications and implementation is even more critical. The Jet Propulsion Laboratory was assigned the system research and development responsibility for the Program and, as such has developed proof-of-concept vehicles, conducted in-vehicle testing and provided guidance for subsystem development based upon assessments of current and advanced concepts. Nowhere is the system role more important than in the determination of development requirements. This provides the link between the overall DOE Electric and Hybrid Vehicle Program objectives and the implementation of a structured development plan. The activity, however, must be an ongoing xercise. Because of the many trade-off parameters which must be orchestrated, component requirement sets are interdependent and unique to each technology. In an effort to simplify this process, early subsystem development goals were often inappropriate and incomplete. Although these goals were occasionally approached by individual components, in-vehicle system evaluations usually yielded disappointing results due to the inevitable mismatched subsystem interfaces.

In more recent years, JPL has actively sought to instill a system philosophy throughout the entire DOE Program. This has involved goal setting, the development of trade-off methodologies, data requirement policies, testing, evaluation feedback loops and decision analyses.

C. PURPOSE AND SCOPE OF THIS REPORT

The purpose of this report is to briefly review, from historical and technical perspectives, the major activities, accomplishments and "lessons learned" by the JPL Electric and Hybrid Vehicle Systems R&D Project over its 7-yr life span. By necessity, descriptions of the individual tasks must be brief; each resulted in specific information or conclusions which are well documented in the various deliverable reports and other papers referenced in Section VI. The major findings, discussed herein, primarily deal with the broad issues which cut across the various disciplines. Many of these issues are "system related" and therefore pertain not only to the JPL Project but to the overall DOE Program as well.

Because of the broad perspective gained in the pursuit of these activities and the termination of any vested interest, JPL is in a unique position to provide recommendations for future thrusts. Many valuable lessons have been learned during the past 7 yr and it is hoped that programmatic insight and planning can benefit from their discussion.

II. PROJECT ACTIVITIES AND ACCOMPLISHMENTS

As previously indicated, the charter of the JPL Electric and Hybrid Vehicle Systems R&D Project has been sufficiently broad that tasks were undertaken and accomplished involving virtually all the technologies germane to electric and hybrid vehicles. Some of these activities were designed to facilitate the initial "technology transfer" program, others supported the commercialization thrust and ·me (like the assessment activities) emphasized the longer range view. The most significant of these efforts are highlighted below.

A. VEHICLE SUBSYSTEMS

1. Powertrains

From 1977 until 1983, the NASA Lewis Research Center had Program responsibility for electric and hybrid vehicle powertrain development. In 1983, Lewis Research Center transferred its remaining activities to JPL. As a result, JPL has managed several contracts and an in-house activity to develop a trio of AC motor/controller concepts and a continuously variable transmission concept. A significant effort was devoted to the investigation, analysis and assessment of current and projected electric and hybrid vehicle powertrain components in association with the advanced vehicle assessment (Ref. 1). That study, which will be highlighted later, determined that although today's electric vehicles, rely, almost exclusively, on chopper-controlled DC brush-commutator motors, the situation is changing rapidly. Due to the electronics revolution, the AC induction and DC brushless machines, heretofore impractical for electric vehicle applications, will soon be the overwhelming choice. Enjoying the advantages of lighter weight, higher efficiency, and increased reliability, the cost, weight and volume of the necessary inverter/controller has been its only impediment. The three motor controller activities described below take advantage of new developments in the high-power switching electronics world to bring these obvious benefits to electric vehicle applications.

a. Motor/Controller Developments

Alternating current motors have several inherent advantages over their DC counterparts such as size, weight, and cost. The necessary associated high-cost inverter electronics, however have limited their appeal for electric vehicle applications. Although electronic component costs have dropped dramatically, they remain high. Therefore motor/controller concepts which retain the advantages of the AC simplicity but strive to reduce or eliminate a number of expensive components were targeted.

The variable reluctance motor requires only one-half of the electronic switching components necessary for a conventional AC induction motor (Ref. 2). Variable reluctance motors have seen some application as small stepping motors, far below the power requirements of a vehicle powertrain. Therefore, in 1983 a contract was placed with the Massachusetts Institute of Technology to design, build and test a 30-kW (continuous) variable reluctance motor subsystem using overall cost as an important design driver. Development has been in two phases, first designing, building and evaluating a scaled-down motor (5 kW) before moving on to the full-scale system. Final test and evaluation will be completed in December 1984. A final report will be issued as a deliverable to DOE.

The half-wave induction motor is another approach at solving the same high-cost electronics problem. It too uses only one-half of the switching components necessary in conventional AC inverter controllers. To investigate the practicality of this approach, a contract was placed with the University of Missouri, Columbia. At the completion of the feasibility-design phase, it was decided to limit the effort to analysis and paper design of a buildable system since no motor manufacturers had responded to an RFP. Reference 3 describes the results of this activity.

Yet another approach to reducing the cost of AC powertrains has been supported through an internal JPL task. Building upon experience with hybrid topology inverter designs, the logical extension was to apply these techniques to AC drive subsystems. A hybrid topology uses two or more different power semiconductors in a synergistic way in order to overcome the weaknesses inherent in the individual components. These weaknesses result in a high cost as well as poor operation. Two distinct hybrid topologies providing the same 40 kW capacity (60 kW for 3 min) have been designed. One uses a conventional bi-junction transistor (BJT) in conjunction with a field-effect transistor (FET); the second combines a silicon-controlled rectifier (SCR) in conjunction with an FET. These designs are discussed in some detail in Reference 4. The BJT/FET inverter will be completed and tested in 1984. The SCR/FET inverter is being proposed as an independent task at JPL during 1985.

b. Transmission Developments

In order to maintain high efficiency, DC brushless and AC motors prefer to operate at high rotational speeds (i.e., 10,000 rev/min and more). Speed control could be accomplished with electronic control and fixed gear reduction or with a variable-ratio transmission, which would relieve a great deal of stress from the electronics. Manually shifted transmissions are the simplest and most efficient but fail to provide the convenience of automatic shifting desired by 80% of the motoring public. Continuously variable transmissions combine the convenience of an automatic with efficiency near that of a manual transmission. Although some concepts are now approaching production, continuously variable transmissions have historically be plagued with reliability problems and have not been cost-competitive with the alternatives. Lewis Research Center placed a contract with Kumm Industries for the development of a continuously variable transmission using a novel, flat rubber belt. This approach significantly reduces the internal stresses necessary with steel-on-steel drives and simplifies maintenance. The Jet Propulsion Laboratory took over management for the testing portion of the contract and final report (Ref. 5). Although this development demonstrated a workable continuously variable transmission concept, it was plagued with reliability problems. In retrospect, much engineering work should have been done before committing to a concept demonstration.

2. Weight Reduction

As any student of automotive performance has discovered, the reduction of vehicle weight pays handsome dividends. Although generally associated with acceleration performance, weight reduction plays a significant role during cruise through reduced tire-rolling losses, braking losses and grade losses (The latter is universally ignored in all standard driving cycle testing and is a major cause of discrepancies between Environmental Protection Agency estimates and actual experience). Weight has an even greater effect on electric vehicles, whose specific power source is a factor of about 5 less than that of a comparable internal combustion engine vehicle.

Low-density, high-strength composite materials have long been recognized as a means to reduce automotive structural weight and thereby improve fuel economy for the combustion engine vehicle or improve range and performance for the electric vehicle. However, until composite components can be fabricated at costs competitive with their steel counterparts, they are unlikely to attain significant inroads. The least exotic composite materials cost about twice as much as steel; therefore, real cost competitiveness may only be achieved through the benefits of parts consolidation, i.e., by molding, in a single step, a component which would otherwise require production and assembly of several steel parts. Not all parts, however, are amenable to parts consolidation and must therefore be compared on a substitution basis. The other key element in the equation is the production procedure and the resultant costs associated with fabricating this composite component.

With this as a background, a task was defined to develop and demonstrate the production feasibility of cost-competitive lightweight composite material components by investigating improved fabrication concepts. The approach taken was to contract with the Budd Company to manufacture, using production techniques, a composite automotive component and compare its utility and cost with its counterpart baseline steel component. After some consideration, the component of choice was selected to be an outer door panel from a 1977 Chevrolet Impala. The justification for this choice included the availability of (1) baseline costing data, and (2) a real vehicle environment useful for fit and finish evalu ion and crash testing.

The redesign of the outer door panel consisted of a 14-lb single-piece structure composed of a chopped glass/polyester outer skin, co-molded with a continuous glass fiber polyester intrusion protection in the form of a strap. This structure replaced four pieces in the original steel baseline door weighting 25.5 lb for a total weight savings of 11 lb or 43%. With some minor modification, the door panel will be able to pass the Federal Motor Vehicle Saftey Standards for intrusion.

The approach demonstrated the ability to selectively and locally reinforce a general chopped glass composite structure with continuous fiber material (Ref. 6). The concept, if carried to its fullest potential, could not only account for thinner, lighter door structures but ushers in a multitude of automotive part applications. The especially corrosive environment generally surrounding the battery would make battery trays and supporting structures particularly good candidates for such composites.

3. Road Load Reduction

By convention, a vehicle's road load is defined to be the force required to overcome aerodynamic and rolling resistances. The aerodynamic resistance, or drag, is a function of the vehicle's size and shape and is proportional to the square of the velocity. The rolling resistance includes the tire resistance as well as bearing losses and such things as brake drag. While it does have some speed dependency, it is often assumed to the first order to be simply proportional to the normal force or vehicle weight.

At a steady speed of about 45 mph, the road-load power requirement for a typical subcompact class vehicle is approximately evenly divided between the aerodynamic drag and rolling losses. But even over a low speed driving cycle, such as the SAE J227a D cycle, aerodynamic drag and rolling resistance may respectively consume about 35% and 30% of the total road energy requirement. Significant improvements are possible in both of these parameters which could combine for electric vehicle range improvements of 30% or more. Therefore, a task was initiated to examine the avenues and develop the procedures by which real road-load reduction could be accomplished by the emerging electric and hybrid vehicle industry. Early on, it was concluded that no significant tire development tasks needed to be funded by the Project. The tire requirements of a electric and hybrid vehicle were quite similar to those of a standard automobile and most of the major tire manufacturers were already pursuing low-loss tire programs. However, progress of these programs was monitored, data was shared, and some specific tests were performed to determine such simulation input requirements as tire energy consumption during warm-up and over certain cyclic (torque) loading.

The Project involvement in aerodynamic drag reduction was viewed quite differently. If a prospective electric and hybrid vehicle manufacturer were to begin developing a new vehicle, he would either convert an existing heat-engine automobile or develop a new concept from the ground up. In either case, the tools necessary to minimize aerodynamic drag were not readily available. The concept of an aerodynamic design guidebook, which could be an aid to the electric and hybrid vehicle designer and builder with little or no aerodynamic background, was adopted. The approach was to develop a system-level aerodynamic design sequence composed of logical path elements which terminate at one of three levels of design. These design levels (described as subjective, empirical, and experimental processes) are progressively more refined and successively characterized by a higher probability of yielding a low drag design. The second level, or empirical process, is shown in Figure 1 as an example. Developing these logic paths exposed many technological voids and information gaps inherent in various path elements. In the course of this endeavor, several supporting studies and test programs were undertaken to alleviate the uncertainties and to provide the necessary tools and procedures required to implement the strategy.

The process is a framework upon which the design development is built. The procedures are highly dependent upon many subjective determinations which rely heavily upon common sense and experience. There may be many alternative solutions to the same set of design requirements.

The objective behind the creation of the design guide (Ref. 7) is to encourage electric and hybrid vehicle designers to address aerodynamic drag as an important design parameter and, once goals are targeted, to systematically evolve a design which is aerodynamically matched to the anticipated mission while minimizing unnecessary effort.

4. Environmental Control Subsystems

It has been argued that for electric vehicles to successfully enter the marketplace, they must offer creature comforts on a par with the current heat-engine competition (Ref. 8). Air conditioning leads the list of these comforts and potentially has the most severe impact on electric vehicle performance. For these reasons, a task was identified to: (1) determine electric and hybrid vehicle environmental control requirements, (2) identify potential solutions, (3) develop an evaluation process, and (4) select, for potential concept development, those elements comprising the environmental control subsystem which best match the requirements.

Design criteria for the sizing of appropriate environmental control subsystem elements were established from the following: demand thermal loads, ambient temperatures, time required to reach steady-state operation, relative humidity, number of air exchanges, safety (defogging and defrosting), and state-of-the-art surveys. The design point conditions for the passenger compartment were derived from mathematical modeling of the physical and psychological processes involved in the determination of thermal comfort. Duration of environmental control was another important parameter in determining the functional requirements. Travel scenarios depicting typical U.S. driving patterns were constructed in order to establish the subsystem design load specification.

Thermal storage schemes that were evaluated used either sensible heat or latent heat of phase change, i.e., salts, oils, parafins, sand, and liquified gases. Certain reversible thermochemical reactions were

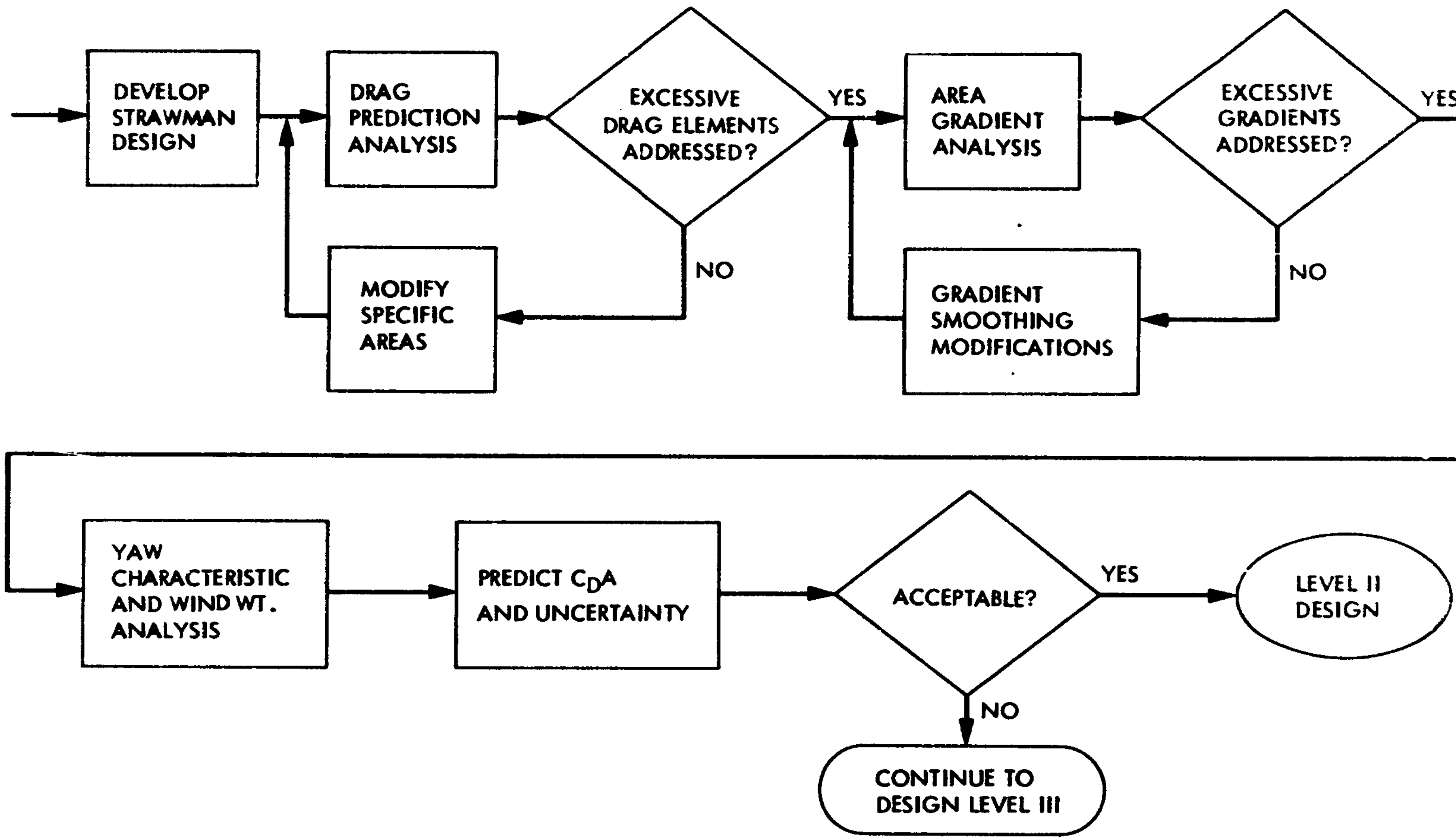

Figure 1. Aerodynamic Design Logic Path (Ref. 7)

identified as having the potential for heat storage in excess of 3000 Btu/lb; however, published information was insufficient to enable a feasibility determination.

In order to be considered for ranking and possible recommendation, candidate environmental control subsystem elements were screened for feasibility; each was required to meet the energy usage criteria and performance specifications.

Based on the results of the ranking exercise, a subsystem using water thermal energy storage was the preferred configuration for near-term development (5 to 10 yr). Although this type of subsystem offered only a limited storage period, other functional characteristics made it a superior choice for product development within the next 3 to 4 yr. Such an environmental control element required no onboard use of petroleum fuel and could be effectively applied to both heating and cooling cycles. Other advantages included simplicity and similarity with present automobile heating subsystems, low noise level, and a short development period.

Preliminary calculations indicated that an ammonia-water split heat pump met all functional requirements in a cost-effective manner; hence, it was selected as the "best" configuration for long-term (beyond 10 yr) development (Ref. 9). This subsystem, which also can be applied to both heating and cooling cycles, requires no moving parts on board the vehicle and no onboard use of petroleum fuel. It offers low overall weight, as well as long storage periods that are comparable to subsystems using gasoline engines. In the split heat pump subsystem, the thermodynamic process rates can be operated independently. It is thus possible to design the home-base equipment to perform the regeneration function over a time period approaching one day, while the maximum operating time of the vehicle-base equipment is 2.5 h. This approach could supply adequate environmental control 99% of the time for 99% of the population.

5. Subsystem Packaging

At the conclusion of a preliminary design exercise, the subsystem and component performance specifications are established. Before a successful system can be integrated, however, a packaging design effort must be performed. These issues directly impact such vehicle attributes as seating comfort, cargo capacity and handling response. To provide some guidance to the emerging electric and hybrid vehicle industry for making packaging trade-offs, a work element was initiated. The objective was to investigate alternate battery locations and packaging strategies which specifically did not require the use of a central backbone battery tunnel concept. For economic reasons, many electric and hybrid vehicles will be based on an internal combustion vehicle conversion which will therefore limit packaging alternatives. Several questions needing attention were addressed, including:

(1) What is the effect of battery module shape, size, and numbers?

(2) Where might battery location alternatives interfere with satisfactory vehicle handling?

(3) What are some practical integrated battery support structures?

The resulting study used a current subcompact internal combustion engine vehicle as a baseline. Alternative packaging solutions for a derivative electric vehicle were evaluated with the objective of retaining vehicle dynamic handling characteristics, passenger space, and cargo area comparable to the base vehicle.

The major results of the study (Ref. 10) were that it is entirely feasible to design a near-optimum packaging of electric drive components in a subcompact car and retain the dynamic handling characteristics, passenger space, and cargo area of the base vehicle. Correct weight distribution is the most important single factor in achieving acceptable handling characteristics. High-front-weight-bias vehicles can be tailored to provide satisfactory handling responses. High-rear-weight-bias vehicles offer severe handling penalities which cannot be overcome.

Several alternate battery types were evaluated and, in general, were found to be more difficult to package than the present golf-cart lead-acid modules, particularly if constant battery voltage was the determining criteria.

Detailed installation studies were conducted to verify that the recommended battery packs could be mounted in the locations indicated without significantly changing the structure of the base vehicle. Necessary changes to the structure, suspension, and control components of the base vehicle to accommodate the additional weight of the electric drive components were analyzed and specified. A mock-up was constructed to verify the optimized installation in three-dimensional form.

B. BATTERY SUBSYSTEMS

1. System Testing of Near-Term Batteries

In the early stages of the DOE Program, four battery technologies were identified as having the potential for production electric vehicle applications by the mid-1980s. These battery couples, classified as near-term, were (1) improved lead-acid, (2) nickel-iron, (3) nickel-zinc, and (4) zinc-chlorine. Argonne National Laboratory had the primary responsibility to manage the development contracts for these technologies. The JPL involvement was generally limited to in-vehicle, system-level testing at the conclusion of each effort. In 1979, JPL performed a series of tests on the available battery technologies in conjunction with evaluations of four vehicles. These tests were conducted to determine requirements and specifications to be used in procuring vehicles for deployment in the DOE Electric and Hybrid Vehicle Technology Demonstration Program. The results indicated significant range and energy storage improvements over the baseline system but identified serious development deficiencies in these batteries and in the prototype vehicles.[1] As the result of a JPL recommendation, this procurement and deployment activity was delayed indefinitely.

For comparison purposes, the baseline system was the South Coast Technology Rabbit, supplied with a 108-V battery pack assembled from 18 6-V ESB XPV-23 lead-acid batteries weighing 531 kg. Speed control of the separately-excited DC motor was accomplished by actuating contactors in the armature circuit (with a starting resistor) in conjunction with a transistorized field chopper. Torque was transmitted through the standard Volkswagen four-speed manual transaxle.

The batteries chosen for the vehicle/battery testing program were two nickel-zinc batteries produced by Energy Research Corporation and by Yardney, Inc., a Westinghouse nickel-iron battery, and an improved Globe-Union lead-acid battery. The Energy Development Associates zinc-chlorine battery was unavailable for testing.

The Energy Research Corporation nickel-zinc battery was based on a cell construction unique to this manufacturer. The positive plate (cathode) was manufactured from an active material composition of nickel hydrozide and a conductive dilute which was rolled and pressed with a plastic binder onto a metal current collector. Zinc oxide and additives were combined and bound in the same manner to form the negative plate (anode). Sixty-six cells were assembled into a nominal 108-V battery pack which weighed 549 kg.

Yardney supplied a nickel-zinc battery pack constructed of cells using more common electrochemically impregnated sintered nickel positive plates. The negative plate was bound in the same manner as the Energy Research Corporation cell. The separator was a three-part system utilizing proprietary Yardney separators. A nominal 108-V pack was assembled from 66 cells and weighed 523 kg.

The nickel-iron battery, manufactured by Westinghouse under contract to JPL, used plates of hot-pressed nickel-plated steel wool. The positive plate was electrochemically impregnated, while the negative was pasted ferric oxide. A nominal 120-V battery pack of 90 cells was supplied which weighed 490 kg. This battery used a circulating electrolyte system which allowed a recharge time of as little as 3.5 h.

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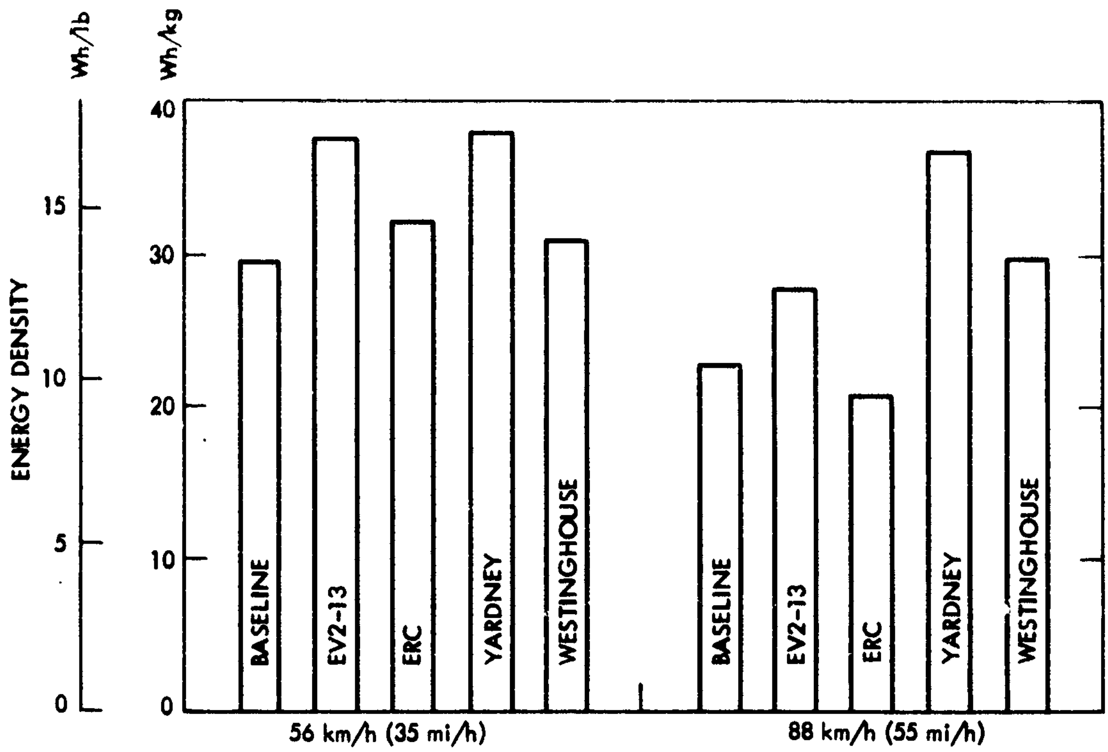
[1]The so-called 2 x 4 vehicles included the South Coast Technology converted Volkswagon Rabbit, the Electric Vehicle Associates converted AMC Pacer Wagon, the Jet Industries Electra Van 600, and the Battronic Truck Corporation pickup truck.

The Globe-Union lead-acid battery (EV2-13), developed for the ETV-1 program (see Section III.C) was constructed in the same manner as their conventional batteries. However, the cells were rotated 90° to increase the surface area and aspect ratio. The negative plate is free of antimony. The 6-V batteries were designed within the dimensional constraints of a standard golf cart battery. A nominal 108-V pack weighing 490 kg was assembled from 18 of these batteries.

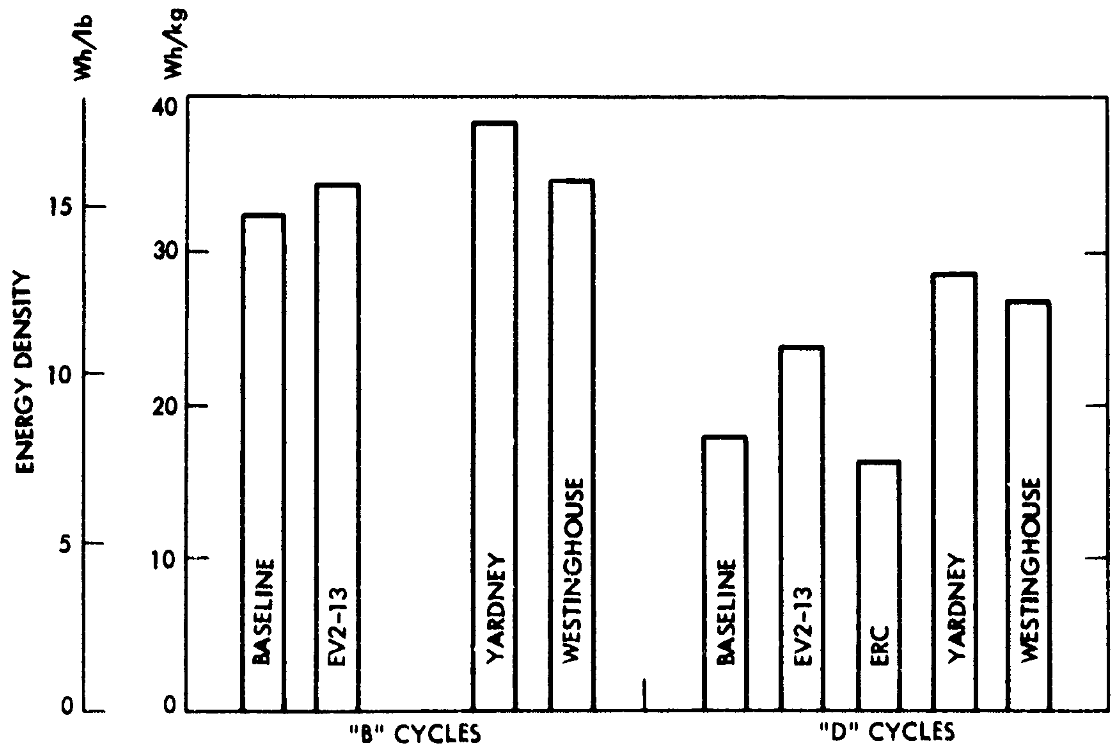
The tests, which consisted of both constant speed and SAE J227a D driving cycles, were conducted on the JPL Clayton twin-roll dynamometer. The South Coast Technology vehicle was fairly reliable in over 6500 km of testing at JPL. However, the motor required replacement andintermittent problems with the controller hampered normal operation early in the test program. Some results are shown in Figures 2.a and 2.b, (Ref. 11) indicating energy capacity exhibited by the batteries in the various vehicles under some standard driving conditions. It is evident that a battery's energy density is a strong function of the duty cycle. Most battery developers prefer to measure energy density at some rather benign constant current (such as the ubiquitous C/3 rate) which often bears no relationship to energy which could be delivered under some vehicle duty cycle. It should also be noted that some of these batteries lasted less than 20 cycles these vehicle-load conditions.

During 1981, an Eagle-Picher nickel-iron battery and a second-generation Westinghouse nickel-iron battery were tested with a similar South Coast Technology vehicle and the ETV-1. A Globe (now a division of Johnson Controls) improved state-of-the-art lead-acid battery, employing electrolyte agitation, was evaluated as well. Several aspects of battery performance were investigated including capacity, recharge efficiency, voltage response, and self discharge. Each of the three batteries exhibited some strengths and some weaknesses. Although the Eagle-Picher battery subsystem lacked certain features necessary for satisfactory vehicle integration (single-point watering, hydrogen gas generation management, etc.), it demonstrated a significant improvement in capacity (especially at higher power levels) compared to the earlier Eagle Picher batteries. The second-generation Westinghouse nickel-iron battery subsystem was plagued by reliability problems and tests could only be run following a mild charge profile which improved charge efficiency but reduced the maximum energy capacity. A composite plot of the specific energy as a function of average power (corresponding to several constant speed vehicle tests) was created from Reference 12 and is shown in Figure 3. A characteristic of the nickel-iron couple is high self-discharge which has the effect of significantly reducing the available energy if the battery is left to stand following charge or between discharge segments. This feature is quantified in Figure 4 (Ref. 12).

The final battery tests performed at JPL involved an updated Eagle-Picher nickel-iron subsystem, a downsized module-based Globe improved state-of-the-art lead-acid subsystem, and the General Motors (Delco) nickel-zinc subsystem. The Delco nickel-zinc battery was especially interesting in that it was the only battery tested to meet and exceed the claims of the manufacturer. This success was in large



a. Demonstrated in Constant Speed Tests (Ref. 11)



b. Demonstrated in SAE J227a Driving Schedule Tests (Ref. 11)

Figure 2. Battery Energy Demonstrated in Two Types of Test

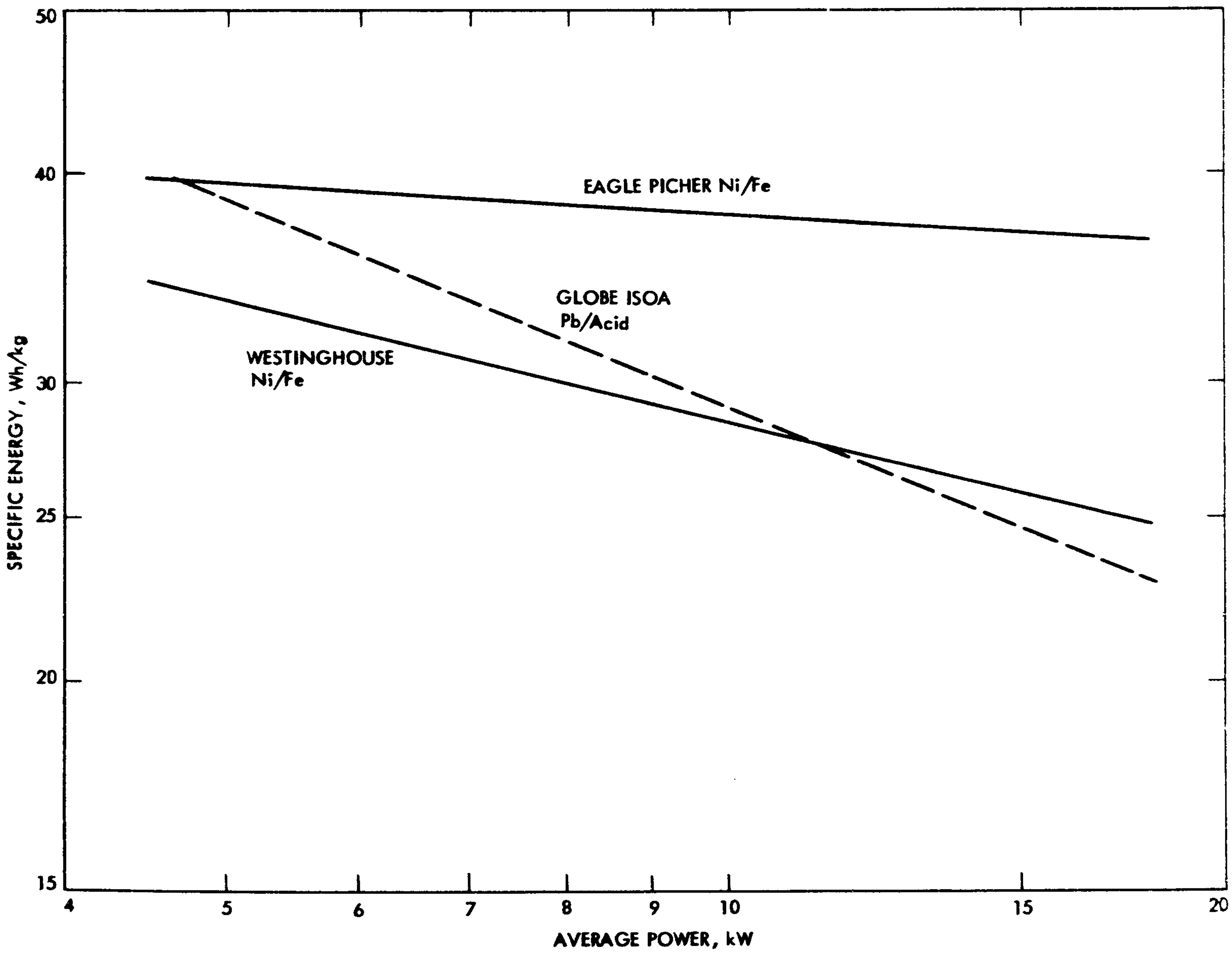


Figure 3. Specific Energy vs Average Power Characteristic for Three Near-Term Batteries in Vehicle Tests (Ref. 12)

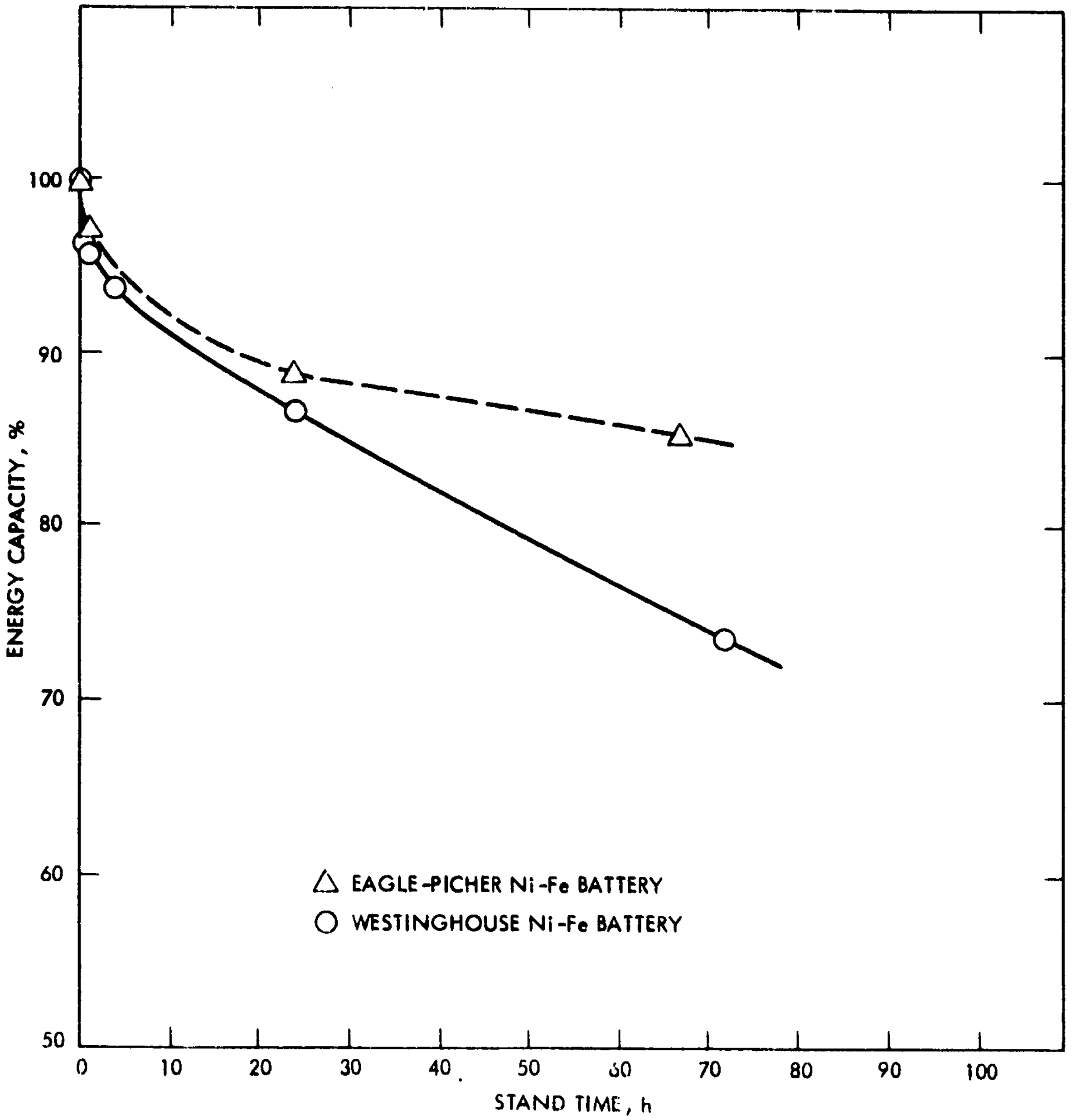


Figure 4. Effect of an Open-Circuit Stand Between End of Charge and Start of Discharge (Ref. 12)

part due to the automotive and system engineering approach to the development process and establishes a performance baseline for other technologies to meet. A comparison plot of the specific energy versus average power for these three batteries is shown in Figure 5 from Reference 13.

2. Elevated Temperature Electrolyte

It has long been recognized that lead-acid battery capacity is a strong function of the electrolyte temperature. Great effort has been expended at JPL to ensure that the battery electolyte temperature stabilized at approximately 22°C before testing was initiated. There is nothing unique about that particular temperature except that it represents a standard SAE automotive test temperature. There is also no reason to suspect that this temperature would be optimum from either a battery capacity or battery life consideration. Some module testing has been performed at elevated electrolyte temperatures over the years but much of the data is suspect and little of it can be compared or extrapolated. In an effort to quantify the potential gain in lead-acid battery capacity at elevated temperatures with a complete pack in a vehicle-system environment, a test program was initiated. A battery chamber was designed and built to house eighteen EV 106 battery modules, heaters, blowers and thermocouple instrumentation. After subsystem tests indicated that initial electrolyte temperatures could be uniformly established at temperatures from 26°C to 56°C, system tests were performed on the JPL dynamometer using the DOE ETV-1 test vehicle with an umbilical arrangement. The results (Ref. 14) indicated that battery energy capacity (and hence range) over the SAE J227a D cycle increases by approximately 1% per °C over that temperature range; the improvement is somewhat nonlinear, i.e., there is a diminishing return as the temperature is increased. It is commonly believed, however, that battery life suffers at high temperatures. Unfortunately, the experts cannot agree on the temperature regime in which this effect becomes important. Because the possible benefits from control of this parameter were even greater than any lead-acid design improvements being proposed, JPL promoted elevated temperature cycle-life tests conducted at Argonne National Laboratory.

3. Battery Charger and State of Charge Indication

It is fair to say that no electric vehicle offered today has an adequate onboard battery charger or state-of-charge indicator. It has also been observed that few battery developers understand how best to charge their batteries for optimum efficiency and life. In an effort to shed light on these mysteries, JPL performed a task to explore the effects of various charge parameters on efficiency (Ref. 15). Recognizing the need for a smart charger which could sense battery state-of-charge and tailor the current profile accordingly, a contract was issued to Gould, Inc. to develop such a device. The requirements were for an onboard system having a maximum power output of 3 kVA, over 90% efficiency, high power factor, low line noise and low weight. The system delivered to JPL for test (Ref. 16) was made up of two discreet

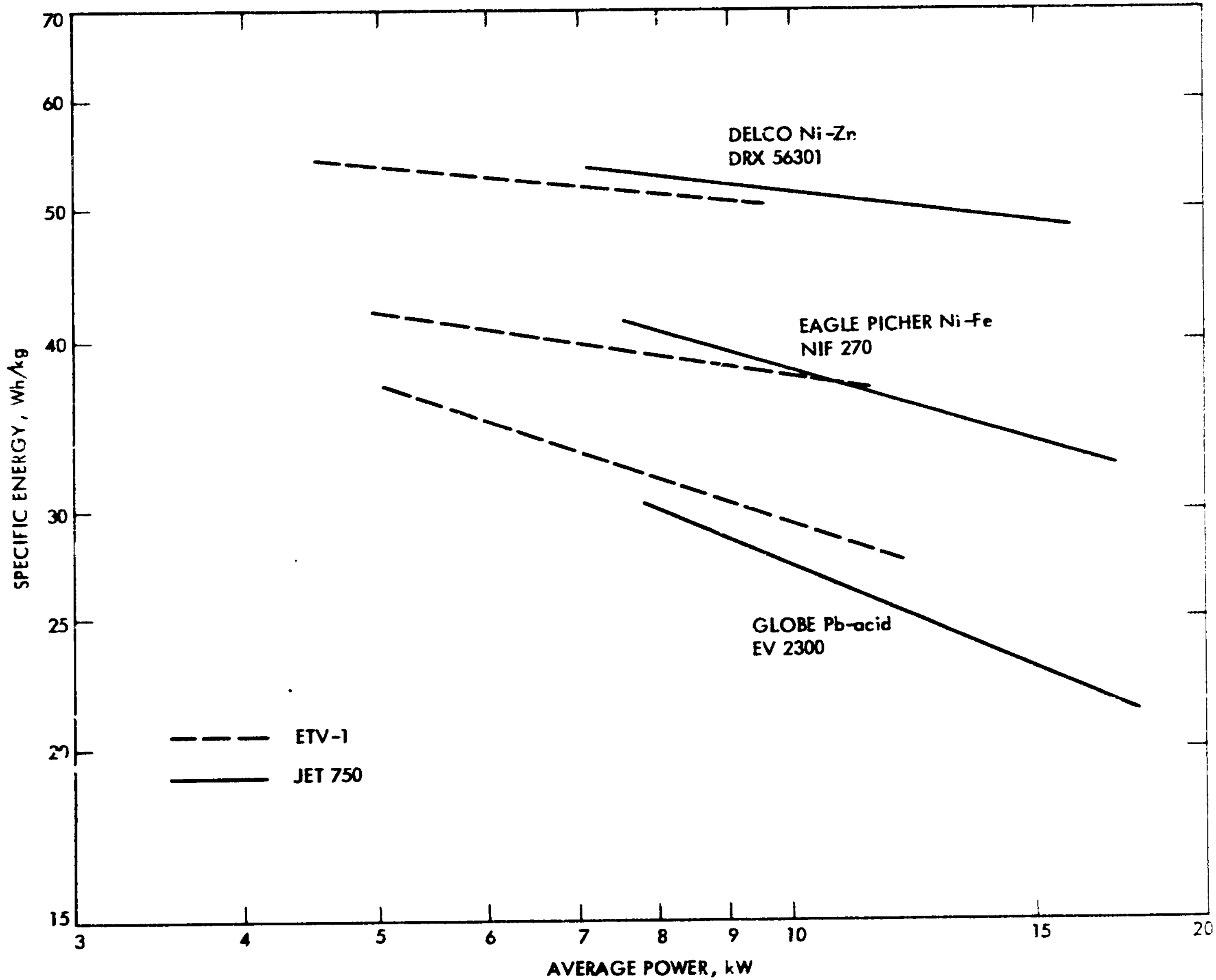


Figure 5. Specific Energy vs Average Battery Power Characteristic for Three Near-Term Battery Types (Ref. 13)

but electrically integrated components; the under-hood charger and the dash-mounted state-of-charge indicator. Unfortunately, the charger had to be limited to operate at a peak of 2 kVA. The state-of-charge indicator, however, has shown significant potential and has become a central element in an effort to upgrade the utility of vehicles presently in use as a part of the DOE Site Operator Program. This latest effort increases the state-of-charge indicator capability by introducing an adaptive algorithm which automatically accounts for a battery's degradation with age.

4. Safety and Maintenance Issues

Perhaps the number one concern a manufacturer has today is product liability. The Detroit OEMs are continually in the news concerning safety-related class-action suits and costly recall programs. They will not put electric vehicles on the streets until they are convinced that their reliability, maintenance and safety characteristics are at least as good as the present internal combustion engine fleet. Although it could be argued that many of the current maladies visible in these development subsystems would be ironed out in a production activity, several problem areas are generic to the design approach.

Hydrogen gas generation, and the resulting possibility of explosion, is a concern for all aqueous batteries. In JPL tests, the situation, however, is far worse for couples involving nickel. The Eagle-Picher and Westinghouse nickel-iron batteries produced respectively 23 and 30 times as much hydrogen per charge/discharge cycle as the Globe improved state-of-the-art lead-acid subsystem in JPL tests (Ref 12). As a result, Eagle-Picher was given a contract to investigate the flame quenching capabilities of several candidate devices to prevent the propagation of flame within batteries having central watering/venting subsystems. No satisfactory solution has been identified to this point.

By far, the most time-consuming maintenance item experienced by JPL and fleet operators as well, is battery watering. Semiautomated, single point watering subsystems have been a part of the most recent battery subsystems evaluated by JPL. None of these, however, worked very well and the related safety issue which results when all cells are connected by common plumbing may be unacceptable. An alternative is the development of sealed technologies. There is little doubt that if the major automobile manufacturers were to produce electric vehicles, they would have to be based on a sealed battery technology. Unfortunately, few battery developers are taking that approach choosing, rather, to modify current designs in an evolutionary manner.

In the meantime, in an effort to support the current electric vehicle fleet being operated by several utilities (DOE Site Operator Program) JPL managed two contracts to supply a prototype battery management subsystem. The effort relies on the state-of-charge indicator previously developed by Gould, Inc. (with the adaptive algorithm) married to a charge and management subsystem developed by General Telephone and Electronics Laboratories.

C. COMPLETE VEHICLE SYSTEMS

Because the automobile is such a complex system, the industry has traditionally only regarded tests of a complete vehicle as the ultimate proof of concept. Although much effort is applied to the development of components and subsystems, it is little more than a laboratory curiousity until that component/subsystem has been fully integrated and proven in the system environment. The electric vehicle is an equally complex system. It has many of the same complexities as a conventional vehicle, and while it eliminates several undesirable features, it adds new ones of its own.

JPL has managed three major programs resulting in complete vehicle systems. The first two, initiated by ERDA in 1976, were run concurrently and investigated the performance potential and economic viability of a near-term electric vehicle amenable to mass production in the 1980s. Recognizing that all-electric vehicles would not be directly competitive with general-purpose conventional vehicles due to range limitations, the Near-Term Hybrid Vehicle [NTHV] Program was initiated in 1978. All three developments were phased activities and are briefly described below:

1. Near-Term Electric Vehicle Program

The goals of the NTEV Program included the following:

(1) Respond to the Public Law 94-413 requirement that DOE determine an optimum overall electric vehicle design.

(2) Assist industry in accelerating advancements in electric vehicle technologies.

(3) Provide analytical and test methodologies and tools for application by industry to electric vehicle system technology.

(4) Identify areas requiring increased R&D attention.

(5) Provide a national data base to enable determination of technology advances and provide standards of performance.

The vehicle performance objectives established for the Program required considerable improvement overall, compared to the performance of vehicles previously developed (Table 1). For example, the urban/suburban driving range of 120 km (75 mi) between battery recharges was roughly 50% better than had been demonstrated to date. The Phase I trade-off and preliminary design studies by contractors on the NTEV Program showed that such significant improvements were possible by incorporating current and near-term technology in all elements of an integrated vehicle system. Major technology breakthroughs were not a requirement; however, different vehicle design concepts identified during the studies did require the evolutionary

Table 1. Near-Term Electric Vehicle Program Objectives

Performance	
Suburban driving range	120 km (75 mi)
Passenger capacity	4 Adults
Cruising speed	90 km/h (55 mph)
Passing speed	100 km/h (60 mph)
Acceleration, 0-50 km/h (0-30 mph)	9 s
Merging Time 40-90 km/h (25-55 mph)	18 s
Speed on 5%, 1.6-km (1-mi) grade	80 km/h (50 mph)
Cost (1975 Dollars)	
Initial	$5000
Life Cycle	$0.09/km ($0.15/mi)
Scheduled Maintenance	$0.01/km ($0.02/mi)
Operation and Maintainability	
Life	10 yr 160,000 km (100,000 mi)
Unserviced Park Duration	7 d
Ambient Temperature Range	-29to+50°C (-20to+125°F)
Recharge Energy	300 Wh/km (500 Wh/mi)
Recharge Time; 110 V/30 A Service	6 h
Safety	
Safety Standards	Meet all 1977 Federal Motor Vehicle Saftey Standards

development of specific components from available technology. Thus, the near-term electric vehicle was a vehicle designed (rather than adapted) to: (1) the particular requirements of the electric powertrain, (2) the use of existing and near-term technology, and (3) the use of fabrication techniques which were amenable to mass production in the mid-1980s.

Following the Phase I studies, the General Electric Company and Garrett/AiResearch Manufacturing Company of California were selected from among the Phase I contractors to continue into Phase II. Phase II required that the contractors prepare detailed designs of their proposed cars and that they develop and fabricate complete integrated test vehicles for evaluation. The two contractors chose philosophically different design approaches, as discussed below and shown in Figures 6.a and 6.b.

The design optimization process involved trade-offs between powertrain, suspension, body and structure, and other elements of the car. Because of the limited energy storage of current and near-term batteries, the car's weight, aerodynamic drag, and rolling resistance were reduced to increase range and reduce motor power requirements. Energy losses in batteries, cabling, motor, and transmission were reduced, and as much as possible, the energy dissipated during coast and braking was to be recovered and stored for future use.

While the bulk of the performance increase realized in the NTEVs resulted from this optimization process, each contractor also identified areas where limited, short-term development could significantly aid in meeting cost and performance goals. For example, General Electric developed the first potential low-cost, high-power (400 A) transistor module for application to armature choppers, and Garrett developed a lightweight fiberglass/Kevlar flywheel to store energy to aid in load-leveling the battery. While specifically developed for the NTEV Program proof-of-concept vehicles, these devices have general application to electric and hybrid vehicles of many designs and have already resulted in the acceleration of several technologies which are crucial to the ultimate success of the electric car.

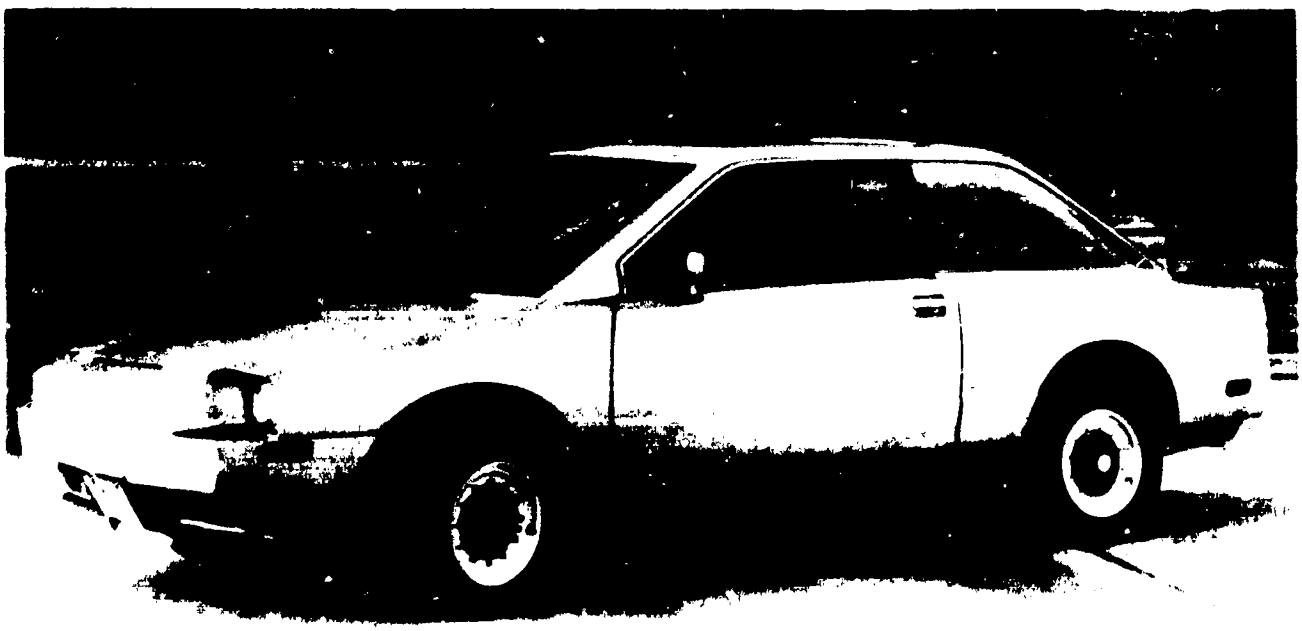
As part of the NTEV Program, improved lead-acid batteries were also developed. Higher energy densities (20-30% better than golf-cart and electric vehicle batteries formally marketed) and longer life were among the goals.

a. General Electric/Chrysler Electric Passenger Car

The General Electric/Chrysler electric test vehicle (ETV-1) used a relatively conventional but highly optimized design for both the powertrain and the body/chassis. System design was controlled by an overall system specification, subsystem specifications, and interface specifications between major subsystems. Weight control and powerloss accounting were also controlled by specifications. Particular emphasis was placed on minimizing energy losses because of the limitations inherent in using lead-acid batteries.

A single, separately-excited DC motor was used, driving the front wheels through a fixed-ratio transmission. Speed control was by means of field and armature choppers, and regenerative braking was incorporated. Eighteen improved lead-acid propulsion batteries were packaged in a tunnel extending from behind the drivetrain and front

a. General Electric/Chrysler ETV-1



b. Garrett AiResearch ETV-2

Figure 6. Two Electric Test Vehicles

suspension into the rear compartment. The tunnel width was minimized in the passenger compartment by using a single row of batteries. This reduced width resulted in less frontal area than is possible with side-by side batteries. Extensive wind-tunnel testing produced a body design with a low drag coefficient. Low frontal area, combined with the final body design, resulted in exceptionally low aerodynamic drag. Changes to the exterior were coordinated with styling and manufacturing to ensure a final design that was aerodynamically clean as well as attractive and producible. Details of the development and design can be found in the Phase II report produced for JPL by General Electric (Ref. 17).

b. Garrett Electric Passenger Vehicle

The Garrett AiResearch electric test vehicle (ETV-2) used advanced technology in both the powertrain and the body/chassis. The system design approach emphasized the development of an innovative powertrain subsystem and its integration into the vehicle design. Weight and power budgets were used as tools to aid in achieving performance objective.

The powertrain incorporates a flywheel to provide transient power for high-power modes such as acceleration and hill climbing. Regenerative braking energy is stored in the flywheel. Using flywheel-stored energy reduced the peak current rating required of electrical components, such as switching devices and the main traction motor. The load-leveling effect of the flywheel reduces battery peak current drain and aids in extending battery life. An additional benefit is that the acceleration capability of the car does not degrade as the battery pack is discharged during daily use. The 18 tubularplate lead-acid propulsion batteries were packaged in a tunnel extending from the front of the car through the passenger compartment. The powertrain was packaged in the rear compartment. Batteries were mounted two-abreast throughout the tunnel, except for the two rear batteries, which were mounted in tandem in order to provide more hip room in the rear seat.

The body is of unitized design and was made of light weight fiberglass-reinforced plastic. Plastic glazing was also used along with other weight-saving features. These features resulted in a potential 10% reduction in curb weight compared to conventional automotive design practice. Reference 18 contains the ETV-2 development details.

Both the ETV-1 and ETV-2 vehicles were delivered to JPL for Phase III Test and Evaluation. The ETV-1 represented a significant step forward in the development of an acceptable electric passenger vehicle. Developed using a total system design approach, the various electrical and mechanical subsystems were properly integrated to produce an aesthetically pleasing vehicle having outstanding energy economy. The ETV-2, assisted by its electromechanical flywheel, demonstrated rather impressive acceler on performance while providing a load-leveled environment to the batte y subsystem. The energy lost in overcoming the flywheel parasitic drag, however, caused the overall system efficiency and energy consumption to be poor. Both vehicles suffered from battery subsystems which delivered less performance than expected. The complete results of the JPL test programs are reported in References 19 and 20, respectively.

Although the current overall Electric and Hybrid Vehicle Program emphasis has changed, the major goal of the NTEV Program was to convince both industry and the consumer that the electric vehicle could be a viable and desirable transportation option. The direct way to achieve that goal was to demonstrate the technology at the vehicle system level. The consumer buys total system performance and is not sensitive to whether that performance is derived from a better battery, a better transmission, or a better controller. The system approach assures that the pieces fit together to fulfill consumer performance demands.

Application of the system engineering approach in the NTEV Program produced a marked enhancement in performance, styling, maintainability, and safety of electric vehicles. While system, subsystem, component, and battery development programs continue to offer promise of even better electric vehicles in the future, this first step showed that electric vehicles had the potential to progress from curiosities to a marketable reality in the near future.

2. Near-Term Hybrid Vehicle Program, Phase I

Because of the complexity and potential diversity of possible hybrid vehicle candidates, four contractors were selected to conduct mission analysis, engineering trade-off analysis studies and preliminary vehicle design. At the conclusion of this effort, each contractor submitted proposals for a Phase II final design and vehicle build activity. All studies concluded that parallel hybrid propulsion configurations (where both the heat engine and electric motor are mechanically coupled to the drive wheels) were superior to series configurations (all drive power provided by the electric motor). Each design projected significant petroleum savings which were a function of the cost and performance; the sensitivities to these parameters varied, however, due to differences in battery life and cost assumptions.

After a rigorous procurement evaluation, the General Electric Company (Corporate R&D) was selected to proceed with a 2-yr effort to develop a hybrid test vehicle. The general objective of the Hybrid Test Vehicle Program was to develop an experimental integrated powertrain, consisting of both an internal combustion engine and an electric motor and to evaluate the powertrain in a passenger car application. The Phase I study had indicated that a hybrid vehicle could save 50-75% of the petroleum used by a conventional vehicle without sacrificing mobility, performance or comfort. Mission analysis had shown that hybridizing a 5 or 6 passenger vehicle offered the greatest potential for saving fuel. The reference vehicle selected for comparison with the hybrid test vehicle was a projected 1985 version of the General Motors intermediate-size (A-body) car; although it was recognized that the hybrid test vehicle would necessarily be limited by its 1980 chassis technology.

The primary hybrid test vehicle requirements included:

(1) Capacity for five adult passengers

(2) Equivalent cargo capacity to the internal combustion engine baseline

(3) Continuous cruise speed of 90km/h (56 mph)

(4) Acceleration from 0 to 90 km/h (56 mph) in less than 15 s

(5) Capability of climbing a 37% grade at 90 km/h (56 mph)

(6) Ability to meet applicable Federal Motor Vehicle Safety Standards (September 1978)

(7) Ability to meet 1981 Federal Statutory Emission Standards

An important design goal for the hybrid test vehicle was to achieve a vehicle design with an average life-cycle operating cost (¢/mi) competitive with the reference internal combustion engine vehicle at projected 1985 gasoline and electricity prices.

To minimize development cost, the hybrid test vehicle was designed to make maximum use of existing production components. The body center section and the interior were taken from a General Motors A-body Buick Century (1980). The hybrid test vehicle was stylized both front and rear. It features front-wheel drive, independent front suspension, power rack-and pinion steering (modified Chrysler K-car) trailing arm and beam rear suspension, power brakes (General Motors E-body), and air conditioning. Morse Hy-Vo type 2300 chains are used to transfer torque from the heat engine and the electric motor.

Because of the inherent complexity, two mule vehicles, employing progressive degrees of sophistication, were created and tested enroute to the final hybrid test vehicle.

The hybrid test vehicle powertrain schematic (Figure 7) shows the various components in the hybrid powertrain. As indicated, both the gasoline engine and the electric motor can be coupled into or decoupled from the driveline using clutches whose operation is controlled by the microprocessor.

The heat engine is a 1.7 liter, fuel injected gasoline engine manufactured by Volkswagen/Audi developing 74 SAE horsepower at 5000 rev/min. A key feature of the hybrid test vehicle is the on/off operation of the engine, which means that the engine is operating only when its output is needed to power the vehicle. A special fast-acting

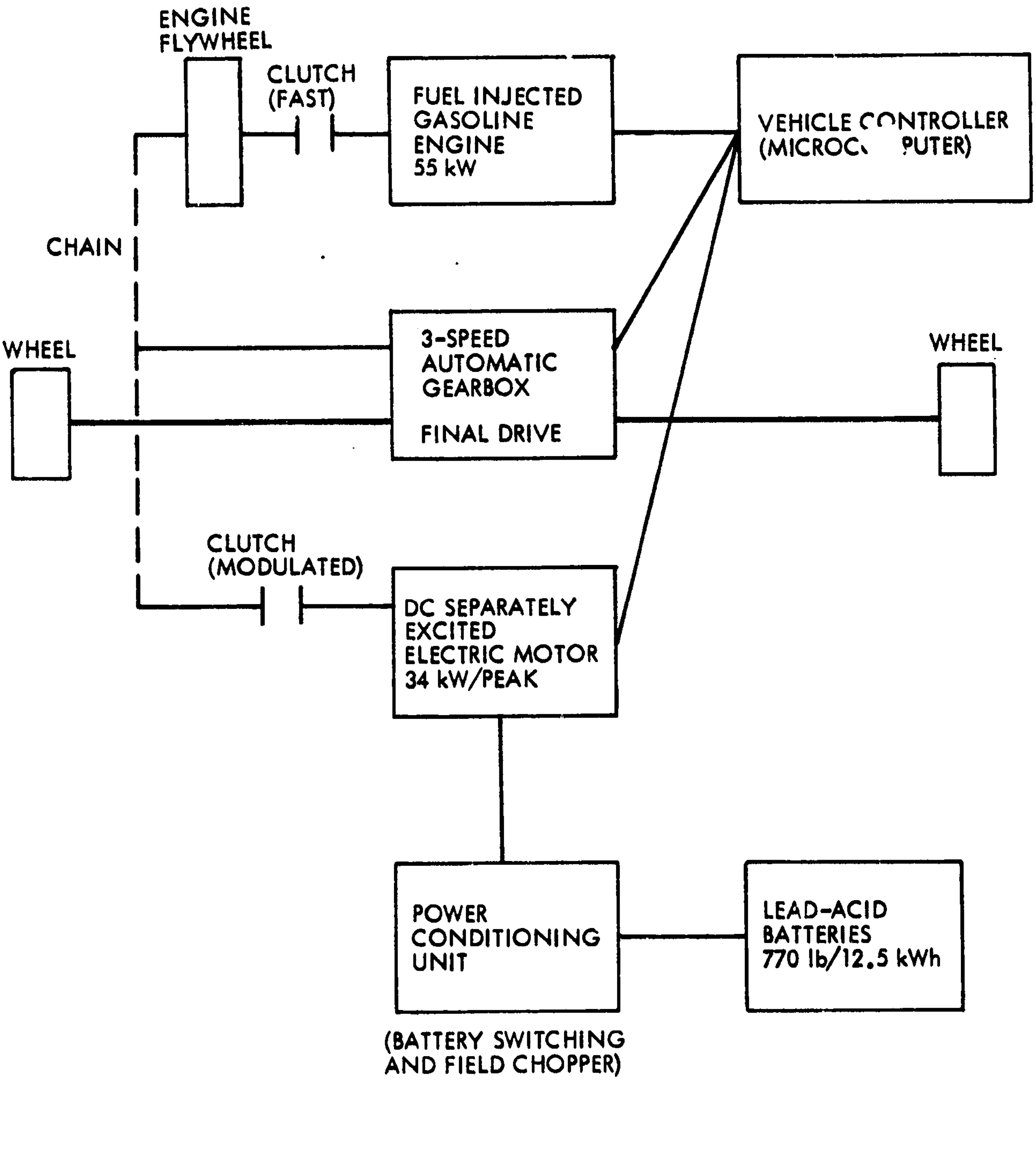


Figure 7. Schematic of the Hybrid Test Vehicle Propulsion Subsystem (Ref. 21)

clutch was designed which permits starting and stopping the engine in less than 0.3 s.

The electric motor is a General Electric DC, separately excited motor with a continuous rating of 24 horsepower and a speed range of 2400 rev/min (base speed) to 6000 rev/min. The motor is controlled by battery switching and a transistorized field chopper.

The batteries were a special high-power-density design developed by the Globe Division of Johnson Controls. The battery pack consists of ten 12-V modules weighing approximately 830 lb (including the container and support equipment).

Details of the development and design of the hybrid test vehicle (Figure 8) can be found in Reference 21.

After delivery to JPL, the hybrid test vehicle underwent the Phase III Test and Evaluation part of the program (Ref. 22). The hybrid test vehicle was found to have successfully demonstrated the integration and application of several new or previously unproven technologies, including on/off internal combustion engine operation in a hybrid-vehicle application, dual power subsystem blending with acceptable drivability, and a microcomputer-based complex vehicle control subsystem performing closed-loop power control, transmission shifting, and starting clutch modulation.

D. SYSTEM-LEVEL TEST AND EVALUATION

1. Background

Many new technologies and disciplines grew out of the space program. Several painful lessons were learned en route to developing successful spacecraft. The concept of system-level testing is a prime example. The Jet Propulsion Laboratory and other aerospace contractors found out early on that the practice of bringing together even carefully designed subsystems for final assembly and check-out always resulted in the discovery of unanticipated and often very challenging new problems due to "system interactions". The development of sophisticated electric and hybrid vehicles poses many of the same generic problems and can, therefore, benefit substantially from an integrated approach to system design, development and testing.

2. System-Level Testing

Although a vehicle's natural environment is outdoors and on the road, it is virtually impossible to conduct precision tests under those conditions. The vagaries of weather, road conditions, and the requirement for onboard test instrumentation combine to thwart any serious attempt to quantify subsystem operations making up the total system performance. Although not simple, precision dynamometer testing provides the only reasonable alternative.

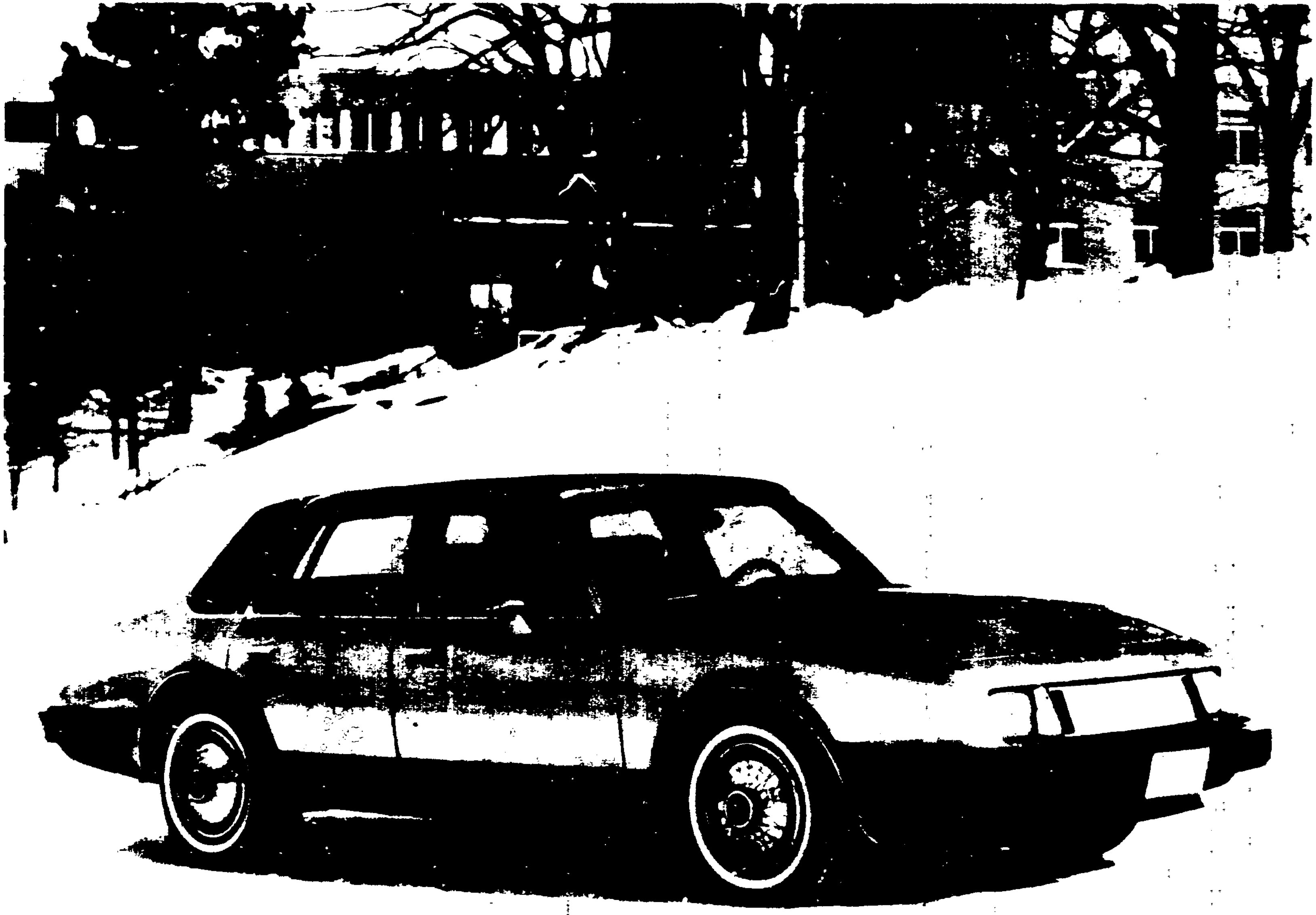


Figure 8. The General Electric Hybrid Test Vehicle

The key to accurate dynamometer testing lies in the setup procedure, based on road-load determinations. Coastdown testing is the most direct method by which to obtain the necessary information. Although it is a simple principle, properly conducted tests are, in reality, very difficult to perform; the wide range of weather and seasonal effects require that sufficient precision is adopted in order to deduce aerodynamic and rolling resistance coefficients so that standard condition principles can be applied[1]. This very demanding procedure has been under development at JPL since 1975 and was first reported in Reference 23. Testing of battery-powered vehicles, however, added a new and difficult dimension to these well-developed automotive test procedures. New instrumentation had to be designed in order to measure the high-frequency chopped current signals. Battery-charging procedures and test termination criteria had to be developed through iterative processes. Standardized test procedures were developed (e.g., initial electrolyte temperature). In addition to these, one must deal with an energy source (the battery) which varies with age and use pattern (each discharge is dependent on the profile of the previous discharge). Nevertheless, by appreciating and addressing all of these problems, the system-level engineering test activity at JPL has provided the electric and hybrid vehicle community in general, and component (mainly battery) manufacturers in particular, with a credible test capability for making subsystem and total vehicle evaluations. Because dynamometers have often been used in the past as imprecise loading devices for relative measurements, a skepticism exists in the minds of many regarding dyno results. Often uncontrolled vehicle tests on city streets and highways carry more credibility with the uninformed. In an effort to address that issue, carefully conducted track (road) tests were performed on the ETV-1 following dyno testing (Ref. 24). The results indicated that when both types of tests are carefully controlled and performed, the results will be identical, although track testing is far more difficult and expensive to perform properly.

During FY79, dynamometer tests were conducted with the so-called 2 x 4 vehicles in order to determine requirements for vehicle integration of the batteries from the near-term program (nickel-zinc, nickel-iron, and improved lead-acid). It was anticipated that these requirements could be incorporated into specifications to be used in the procurement of vehicles for deployment in the DOE Electric and Hybrid Vehicle Technology Demonstration Program. The engineering tests indicated that although significant range improvement relative to standard golf-cart lead-acid batteries could be demonstrated, there were serious development deficiencies in both the batteries and the 2 x 4 vehicles (Ref. 11). As a result, it was recommended that DOE indefinitely postpone its plan to procure a number of these "upgraded" vehicles for the Demonstration Program.

More recently, the system-level test activities have taken two distinct forms:

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[1]If this approach is not taken, even carefully conducted coastdown tests could introduce dyno setup errors of huge proportions.

(1) The investigation and evaluation of a particular component or subsystem (i.e., developmental batteries) in the system environment.

(b) The test and evaluation of the vehicle itself.

The first, and perhaps most notable, complete vehicle system evaluation performed by JPL was on the DOE ETV-1 (Ref. 19). This vehicle represented a true state-of-the-art electric vehicle and it was recognized that it would become the benchmark against which all other electric vehicles would be compared for years to come. It was also anticipated that following test and evaluation, the ETV-1 would be an ideal testbed for system-level tests of developmental batteries. For these reasons, particular emphasis was placed on understanding the detailed operation and energy flow throughout the vehicle. Figure 9 shows, by component and loss mechanism, how the energy leaving the battery terminals is consumed during an SAE J227a D driving cycle. As a minimum, this sort of system-level engineering data is absolutely required to evaluate the operation of a complex vehicle system. Having such a detailed knowledge of the operation of this state-of-the-art vehicle made it an ideal choice as a testbed for developmental batteries. Batteries were not installed but were run through the ETV-1 powertrain by the use of an umbilical power cable.

Because batteries are to some degree dependent on the load waveform , a second testbed was used as well. The Jet Industries 750 converted Rabbit pickup was chosen since it employed a simpler, lower frequency controller typical of current limited production electric vehicles. In some cases the batteries were actually installed in the pick-up bed in anticipation of limited dynamic environment (road vibration, g-loads, etc.) evaluation. Tests of developmental batteries in system environments provided by these two vehicles are reported in References 12 and 13.

The ETV-2 (built by Garrett AiResearch), with its electromechanical flywheel, was a much more complex drive-line. Designed primarily to load-level the required battery output, the system worked, but at great cost in overall efficiency due to parasitic and standby energy demands. Acceleration performance was also enhanced due to the additional short-term power available from the flywheel. A complete report on the operation and evaluation of this vehicle is in Reference 20. Because of the added complexity and variable states of the flywheel, the ETV-2 was never used as a testbed.

The final vehicle development managed by JPL was the General Electric hybrid test vehicle. This powertrain (Figure 7) was by far the most complex system produced under the DOE Program. Testing and evaluating it under the Phase III activity at JPL presented many new challenges. The transient behavior of the various elements as a function of power demand and battery state of charge required novel approaches to the data gathering and interpretation process. To address these issues, a dedicated task was identified at JPL to devise a hybrid test methodology while the hybrid test vehicle was still a paper concept (Ref. 25). Two mule vehicles were developed as a part of

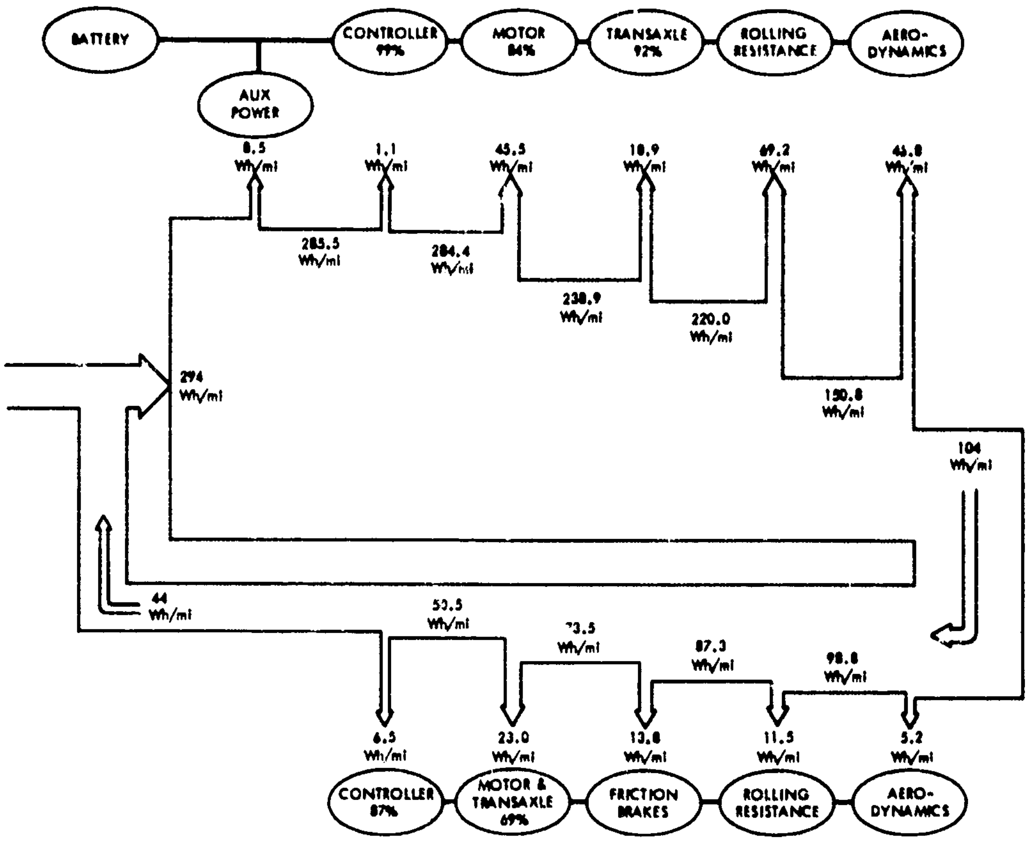

Figure 9. ETV-1 Energy Flow Distribution Over SAE 227a Driving Cycle D (Ref. 19)

the Hybrid Test Vehicle Program to checkout and refine certain features of the drivetrain prior to the final vehicle build. These vehicles were also delivered to JPL and provided pathfinder roles in the refinement of the hybrid test procedures.

The design objectives of the hybrid test vehicle were to provide a general purpose, 5-passenger vehicle which would save a significant amount of petroleum (compared to a conventional internal combustion engine counterpart) while meeting the various statutory regulations for emissions and safety. Because of the power management strategy adopted by the hybrid test vehicle which requires the heat engine to start instantly (or remain off for long periods), it is both formidable and unfair to require that emission standards be rigidly interpreted and enforced at every point in time. Rather, one must look at the contribution over some longer, more meaningful length of time; say, on an annualized basis. It follows that fuel economy (and fuel savings) should be viewed in much the same manner since it varies directly with daily miles driven (battery state-of-charge). In order to analyze data from this context, it was necessary to develop statistically valid annual travel patterns and then synthesize the test data from Federal urban and Highway cycles over the annual pattern.

The hybrid test vehicle, even though based on 1980 technology, demonstrated the capability of a hybrid vehicle to achieve significant net petroleum savings while maintaining the performance and range characteristics of internal combustion engine vehicles. Table 2 indicates that the hybrid test vehicle did, in fact, meet its primary goal of significant petroleum savings over the reference vehicle[1]. The complete results of the JPL Phase III testing can be found in Reference 22. Future hybrid vehicles could increase these petroleum savings by such improvements as: (1) reduced weight and improved aerodynamics as used in current (1984) internal combustion engine vehicles; (2) a power management subsystem that emphasizes petroleum savings by making additional use of the microprocessor control subsystem and of driver-controlled performance selection; and (3) better matching of components to the hybrid vehicle system (transmission, internal combustion engine, accessories, and especially the battery).

E. SYSTEM ENGINEERING

JPL has been providing the DOE Program with system engineering on several fronts. Systems principles are always present in any successfully managed task. Nowhere is the system role more important, however, than in the determination of development requirements. This provides the critical link between the overall Program objectives and the implementation of a structured development plan.

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[1]This was accomplished by using Delco nickel-zinc batteries which were a much better match to the system requirements than the Globe lead-acid batteries delivered with the hybrid test vehicle.

Table 2. Hybrid Test Vehicle Annual Average Performance (Derived from Ref. 22)

Driving Cycle	Fuel Economy, mi/gal			Petroleum Saved, %[a]	
	HTV	1980 Ref	1985 Ref	1980 Ref	1985 Ref
Federal Urban	43	21	24	51	44
Federal Highway	34	29	34	15	0
Combined Urban and Highway	39	23	27	40	31

[a]Includes that portion of equivalent fuel required to generate the necessary electrical energy.

1. The Systems Role

The phrase "system engineering" is clearly overused and often misunderstood. Although it is a somewhat nebulous concept, having many interpretations, it is essential to any efficient engineering process. A close cousin to "common sense", the system approach is a structured method by which to iteratively move from the general goals and requirements to the specific system implementation.

In order to guide technology development and provide some measurement of progress, intelligent goal-setting is absolutely essential. The system approach to goal setting, promoted by JPL, focuses on the primary goal of the DOE Program; namely, significant petroleum displacement through the introduction of electric vehicles into this nation's personal transportation fleet. This requires an analysis of the probable missions or use patterns of vehicle concepts, followed by the application of tradeoff studies to determine which elements of the vehicle subsystems contribute most significantly to the performance objectives. The success equation has many other dimensions beside the obvious performance parameters of range, acceleration rate, and energy consumption. Equally important are the broader implications suggested by such items as:

(1) Cost (initial and operating)

(2) Safety

(3) Reliability

(4) Comfort and drivability

(5) Supporting infrastructure

(6) Materials availability

These and other considerations must be identified and factored into the subsystem development process.

2. Subsystem Development

More than any other component, the battery subsystem affects and is affected by the rest of the vehicle system. Because of its pivotal role, it provides an excellent example of why subsystem development must be guided by a strong system activity. A development process philosophy must exist, either formally or informally, for a subsystem to be successfully developed. A major white paper and several presentations to DOE and the field centers were delivered by JPL during 1982 in an effort to bring the system discipline to the overall DOE Program. Figure 10, a schematic representing an idealized subsystem development process, was used for discussion purposes.

The DOE goal is the process driver which suggests a range of appropriate vehicle/mission targets from which the related subsystem goal sets are developed. An analytical methodology was developed to evolve battery subsystem requirements consistent with these objectives. Figure 11, from Reference 26, is a simple example of how Program goals, interacting with system constraints, combine to yield subsystem goal sets for a particular battery development activity. These goals cannot simply be passed "under the door," never to be reexamined. Figure 10 indicates how interactive the process really is. The Jet Propulsion Laboratory has continued to make the case that by using such a methodology, subsystem and component development can be properly guided and influenced. This approach, if supported, maximizes the probability of matching the subsystem development to the goals of the Program and minimizes the unwelcome discovery of eleventh-hour "show stoppers".

F. SYSTEM ASSESSMENTS

One of the more important roles played by an organization having the responsibility for system guidance, is the performance of periodic assessments. These can be used to determine baseline status, measure progress against established plans or to generate the goals upon which strategic planning is based. Often these purposes are combined in order to provide the insight necessary to efficiently focus program resources. The Jet Propulsion Laboratory has performed four major assessment tasks since 1978:

(1) The 1978 state-of-the-art assessment

(2) The hybrid vehicle potential assessment

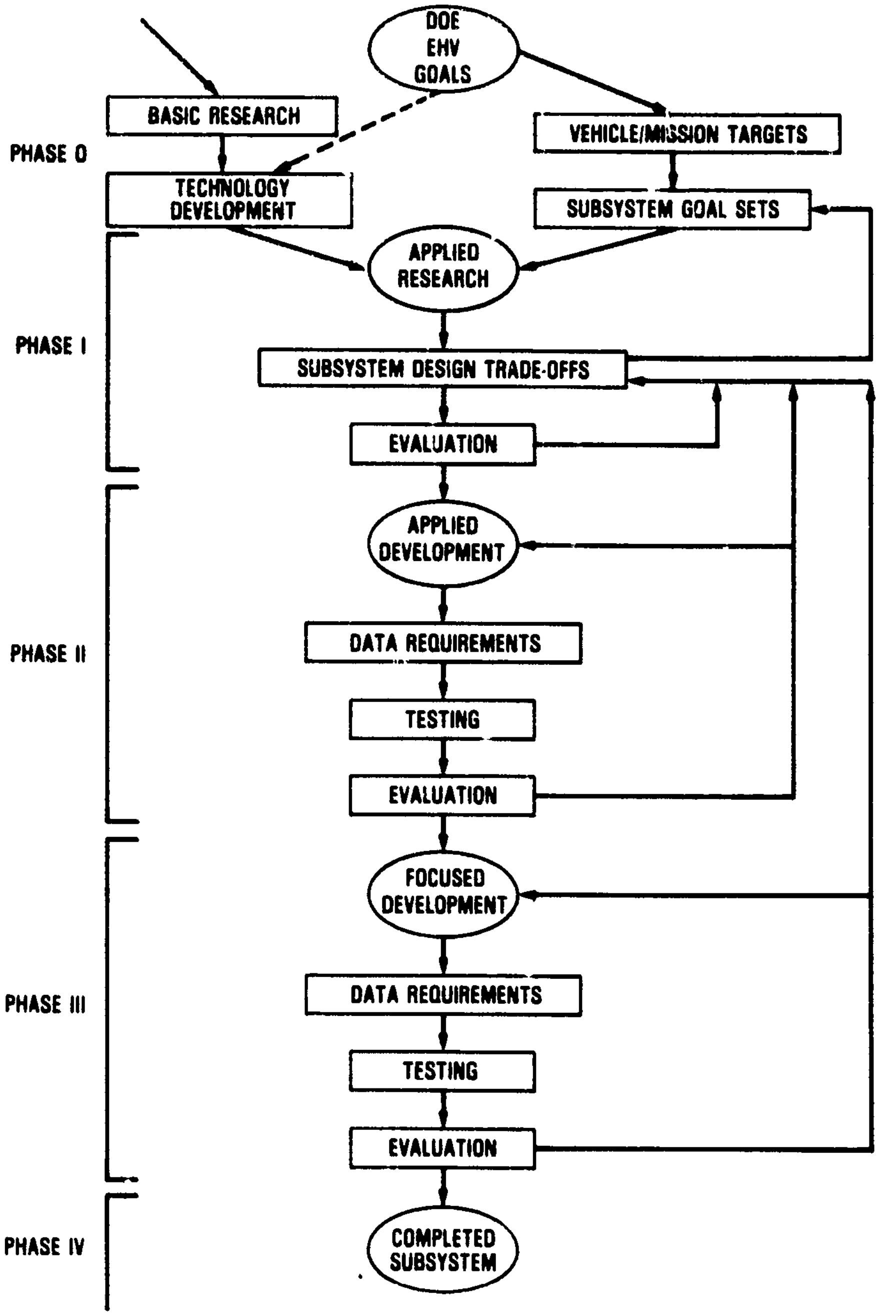

Figure 10. An Idealized Subsystem Development Process (Ref. 26)

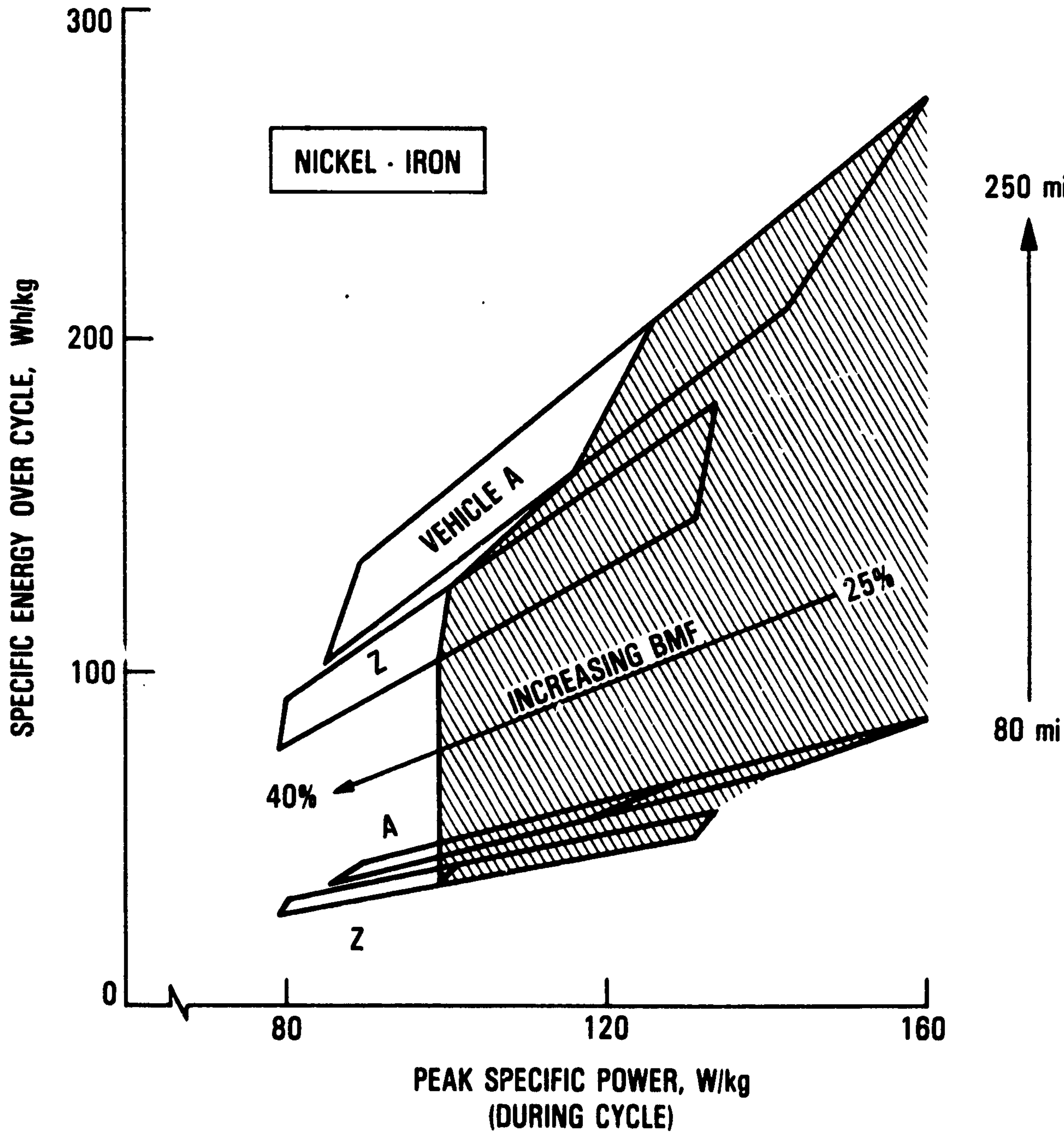

Figure 11. A Typical Battery Subsystem Requirement Envelope (Ref. 26)

(3) The advanced vehicle assessment

(4) The hybrid vehicle assessment

1. The 1978 State of the Art Assessment

An important input to planning any new program thrust is a confident knowledge of the current status. To this end, JPL undertook a task to identify electric and '/brid vehicles which were currently in use, and to determine their strengths and shortcomings from the perspective of individual and fleet users. Information was gathered through the use of questionaires, telephone interviews and site visits. The effort was truly international in scope including site visits to users and manufacturers of electric and hybrid vehicles, battery and component manufacturers, and administrative agencies in the United States, United Kingdom, Germany, France, Italy, and Japan.

The resulting report (Ref. 27) concluded that although there was significant enthusiasm evidenced by many individual and small corporate enterprises, these ventures had not been able to produce electric vehicles having widespread public acceptance; and that the underlying reasons for this went well beyond the limited performance demonstrated by these efforts. Specifically, the most severe impediments to the acceptance of electric vehicles were initial cost, reliability and the infrastructure necessary to support maintenance and repairs.

2. The Hybrid Vehicle Potential Assessment

Combining the best features of one system with the best features of another has been an intriguing idea since the dawn of invention. Flywheel assisted internal combustion engines were investigated in the late 1800s in order to improve performance. Twenty years later, internal combustion engines were combined with highly developed and successful electric drivetrains as a means of increasing range and powering accessories. More recently (mid-1960s), the same combination was reevaluated as a means to reduce atmospheric pollution. This 1978-1980 JPL hybrid study addressed the potential of the hybrid concept to save petroleum. In particular, the study objective was to determine if there were hybrid designs and applications offering large enough reductions in petroleum usage to warrant major expenditure of DOE R&D funds. A secondary purpose was to identify those critical technical areas where R&D could be most usefully concentrated.

The study results (Ref. 28) indicated that the hybrid concept had significant potential to save 50 to 80% of the petroleum presently burned in conventional vehicles. Early results from this activity served as the technical basis for the DOE decision to move into the hybrid test vehicle development previously discussed.

3. The Advanced Vehicle Assessment

In support of the DOE Advanced Vehicle Development Project, JPL was given a task to provide the technical foundation and make recommendations for research to support the most promising nonpetroleum electric or hybrid vehicles from a system perspective. The target was a family of general purpose petroleum-fueled heat-engine vehicles in the mid-1990s time frame. The approach was top-down and systematic in the sense that the analysis was based on the functional requirements of the mission and vehicle rather than the capabilities or limitations of the subsystem technologies. The flow chart of Figure 12 summarizes the assessment methodology which was followed. This approach also introduces the influence of industrial and consumer preference in the development of technologies.

The task was initiated with the Electric and Hybrid Vehicle Advanced Technology Seminar (Ref. 29) held at Caltech in December 1980. This provided a forum for the discussion of advanced concepts and development projections. Accurately projecting the march of technology is a difficult assignment at best. However, significant effort was expended to involve the technology developers and the cognizant field centers in an evaluation and projection process conducted by JPL (Ref. 30).

The system evaluation effort involved far more than simple performance characteristics. The analysis endeavored to take into account the many real but nebulous attributes which seriously affect the operation or suitability of a system. For instance, driving profiles were characterized by 24-h and annual use patterns to evaluate the impact of start-up, shut-down, charging and other time-related characteristics. Other factors included reliability, maintainability, safety and aftermarket support requirements. Multi-attribute decision analysis was used in order to determine the advanced vehicle attribute values and relative weightings that reflect the preferences of high-level decision makers associated with the automotive industry.

Preliminary assessment results were presented during the summer of 1983. The general conclusion was that if battery developments continued along their present evolutionary path, few could hope to find application in a viable electric vehicle. The Jet Propulsion Laboratory subsequently issued a multitude of small contracts to the various battery developers requesting design flexibility information. That is, developers were asked to determine whether they had sufficient design flexibility to project a battery with more nearly the desired qualities. This atmosphere set the tone for a second system assessment seminar held in mid-December 1983 (Ref. 31). Following receipt of the contract deliverables, an independent panel of experts (under the direction of JPL) evaluated and interpreted the design projections. These were used as input in a refined system assessment methodology which evaluated the various advanced component technologies for electric and hybrid vehicle applications. Subsystem strengths and weaknesses were identified so that DOE funding could be more accurately targeted (Ref. 1).

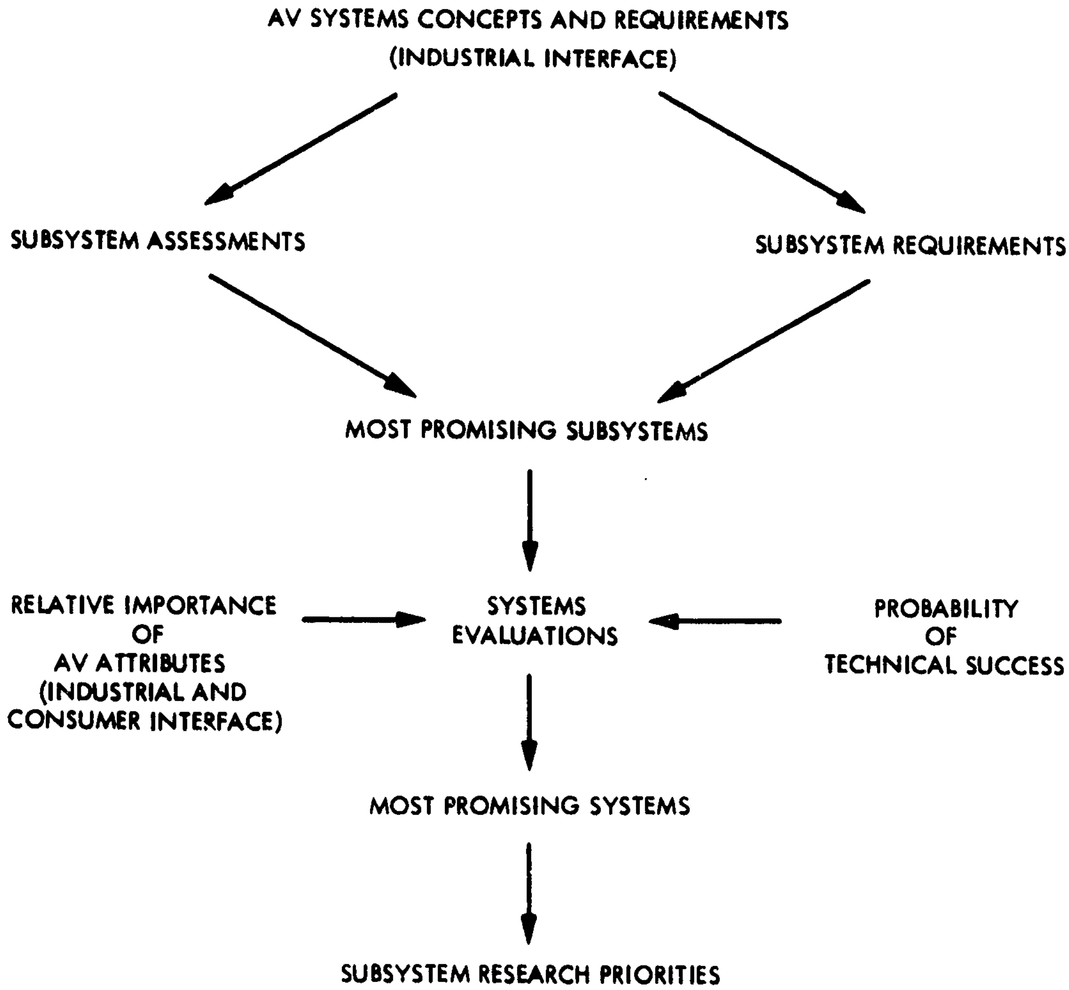

Figure 12. Advanced Vehicle Assessment Methodology (Ref. 5)

4. The Hybrid Vehicle Assessment

Hybrid vehicles are generally regarded by the automobile industry as promising high-risk concepts with insufficient near-term potential to stimulate significant private sector development initiatives. With the background of the hybrid vehicle potential assessment (1980), the development of the hybrid test vehicle and the assessment methodology of the advanced vehicle assessment, the hybrid vehicle assessment was launched. Although hybrids were included in the advanced vehicle assessment, only very simple configurations and strategies could be considered. The assessment was the first study to comprehensively identify and evaluate (for petroleum savings) the broad spectrum of reasonable physical configurations and energy management (power sharing) strategies. The extensive data base developed in support of the advanced vehicle assessment was also used for the hybrid vehicle assessment. Particular use was made of the mission definition methodology (development of 24-h and annual use patterns) and the projected characteristics of near-term and advanced batteries.[1] The overall hybrid vehicle assessment strategy that was adopted is shown schematically in Figure 13.

The analysis was based on the DOE Program objective to achieve national petroleum savings and included the following assumptions:

(1) Future petrochemical fuel shortages are likely, and substantial petroleum savings will be required.

(2) Performance, comfort and safety of any hybrid concept must be comparable to the characteristics of 1990 conventional vehicles

(3) Annual travel patterns in 1990 will be similar to those observed in 1978 (e.g., 1978 National Personal Transportation Study data are valid)

(4) Consumers will require at least the level of mobility presently enjoyed by a 50th percentile driver even in a petroleum-scarce scenario.

The hybrid vehicle design analysis techniques were used to develop alternate vehicle concepts, identify the major characteristics of each concept, select components, size the vehicle and evaluate energy management strategies. Alternative designs were developed with the requirement that passenger volume, cargo capacity and accessories be similar to those of a reference vehicle of identical performance (with respect to speed, acceleration and gradability). Computer simulations were performed to estimate the petroleum requirements of each conceptual vehicle. Petroleum savings potential was determined by comparing the hybrid vehicle consumption to that of a conventional

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[1]The advanced vehicle assessment completed in late 1984 actually used updated battery characteristics after developers responded to design flexibility issues.

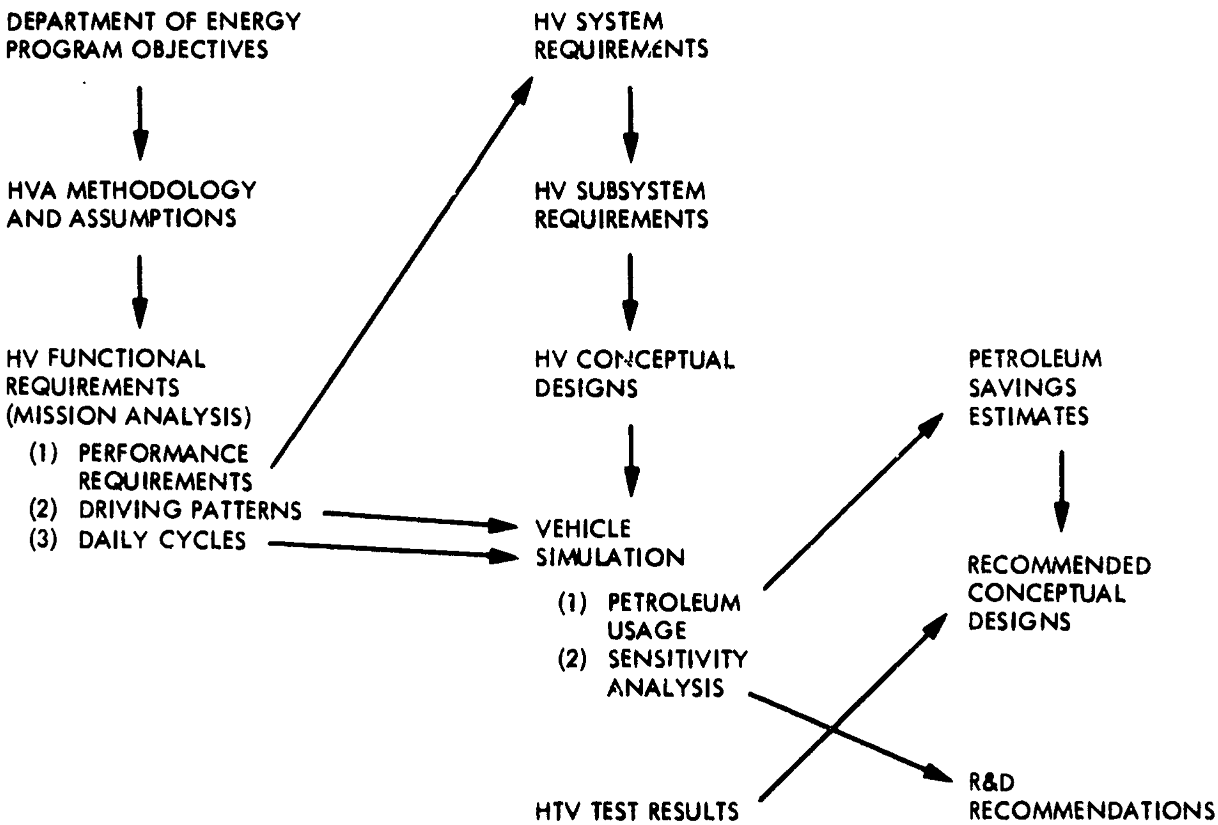

Figure 13. Hybrid Vehicle Assessment Methodology (Ref. 32)

reference vehicle having identical performance and driven in the same way. From this process, many hybrid vehicle designs promising significant fuel savings over their internal combustion engine counterparts were identified. These conceptual designs were not sufficiently detailed to justify the preparation of vehicle production cost estimates. Also excluded from the Phase I report (Ref. 32) are issues of environmental requirements, aftermarket and infrastructure requirements or electrical utility impacts.

5. Supporting Assessment Tools

The credibility of any assessment depends upon the methodology (or logic-flow process) and the specific tools employed (math models, data base, procedures, etc.). Many tools were created specifically for or adapted to, the needs of the various JPL assessment activities. These included:

(1) Vehicle simulation programs

(2) Component sizing routines

(3) Mission analysis (driving patterns)

(4) Multi-attribute decision analysis

a. Vehicle Simulation Programs

A comprehensive vehicle/component simulation tool is absolutely essential to evaluate conceptual designs in support of the assessment activities just described. Rather than building such a tool from scratch, JPL contracted with General Research Corporation in 1978 to modify and expand an existing program named ELVEC. ELVEC has been continuously expanded and enhanced since that time and has been available on the General Research Corporation timeshare network (Ref. 33). For all the power and detail in this user friendly 16,000 line program, there were some limitations due to its architecture. Design optimization in particular required a significant amount of data manipulation and off-line analysis. As a remedy, a contract was placed with the University of Florida to bring ELVEC (and HEAVY, a Boeing Co. developed electric and hybrid vehicle simulator) into Fortran 77 standards and to combine the best features of ELVEC and HEAVY with an "optimization driver". This task will be completed by December 1984 and will be available through a timeshare arrangement through the University of Florida.

Other simulation tools have also been used at JPL to support electric and hybrid vehicle activities on an ad hoc basis. The HYVEC program is a specialized, but generally undocumented, vehicle simulator which was originally conceived to analyze the Garrett flywheel-electric ETV-2 powertrain during its development. A modified version of HYVEC was taken and used by General Electric in the development of the hybrid test vehicle. The ease with which many physical configurations could be modeled made HYVEC the simulator of choice for the hybrid vehicle assessment.

b. Component Sizing Routines

To perform fair evaluations of competing alternative design concepts, it is necessary to abide by a rigid set of component sizing rules. The general guideline is that for any vehicle class, the operator would perceive identical performance, comfort and utility regardless of the componentry. The process is iterative in nature and is represented schematically in Figure 14. The performance requirements which drive the component sizing are acceleration, gradability and range. Acceleration requires a short burst of power but the grade requirement lasts for several minutes. Electric motors can provide up to 200% of their rated power for 30 s, but may be limited to about 110% for 3 to 5 min unless external cooling is provided. Transmissions and heat engines can be sized on the peak power (usually acceleration). For batteries, the peak power requirement of the cycle or acceleration determines the battery weight if the battery is power-limited (i.e., power capability becomes too low to meet the cycle before the battery runs out of energy). For an energy limited battery, the weight is governed by the requirements of the range parameter. It is also necessary to include a weight propagation factor due to the interactive weight growth of associated structures and dynamic components.

In the case of a hybrid vehicle, where power requirements may be shared between an electric drive and a heat-engine drive, the sizing methodology is far less specific; options can only be bracketed in terms of volume available, battery mass fraction, total vehicle weight, etc.

c. Mission Analysis

A measure of acceleration, gradability performance or energy economy at cruise conditions is important, to be sure, but since real vehicles switch continuously between all these modes, any single one cannot itself provide the measure of goodness. A driving cycle, or a series of cycles, approximating the type of duty cycle a vehicle might actually experience, must be the basis upon which alternative concept vehicles are compared. For many subsystems, and batteries in particular, the use pattern (trips per day, length of trips, etc.) may be as important as the cycle itself. Such attributes as thermal loss, self-discharge, charge time, etc. can only be evaluated by introducing the rigors of daily and annual use patterns. To support the various JPL assessment activities, a task was created to develop these missions.

The National Personal Transportation Study conducted by the U.S. Department of Transportation in 1977-1978 (Ref. 34) provided the basis for this effort. By applying standard statistical methods to this information, probability functions for daily travel were operated on by a Monte Carlo simulation to yield annual travel patterns. The result

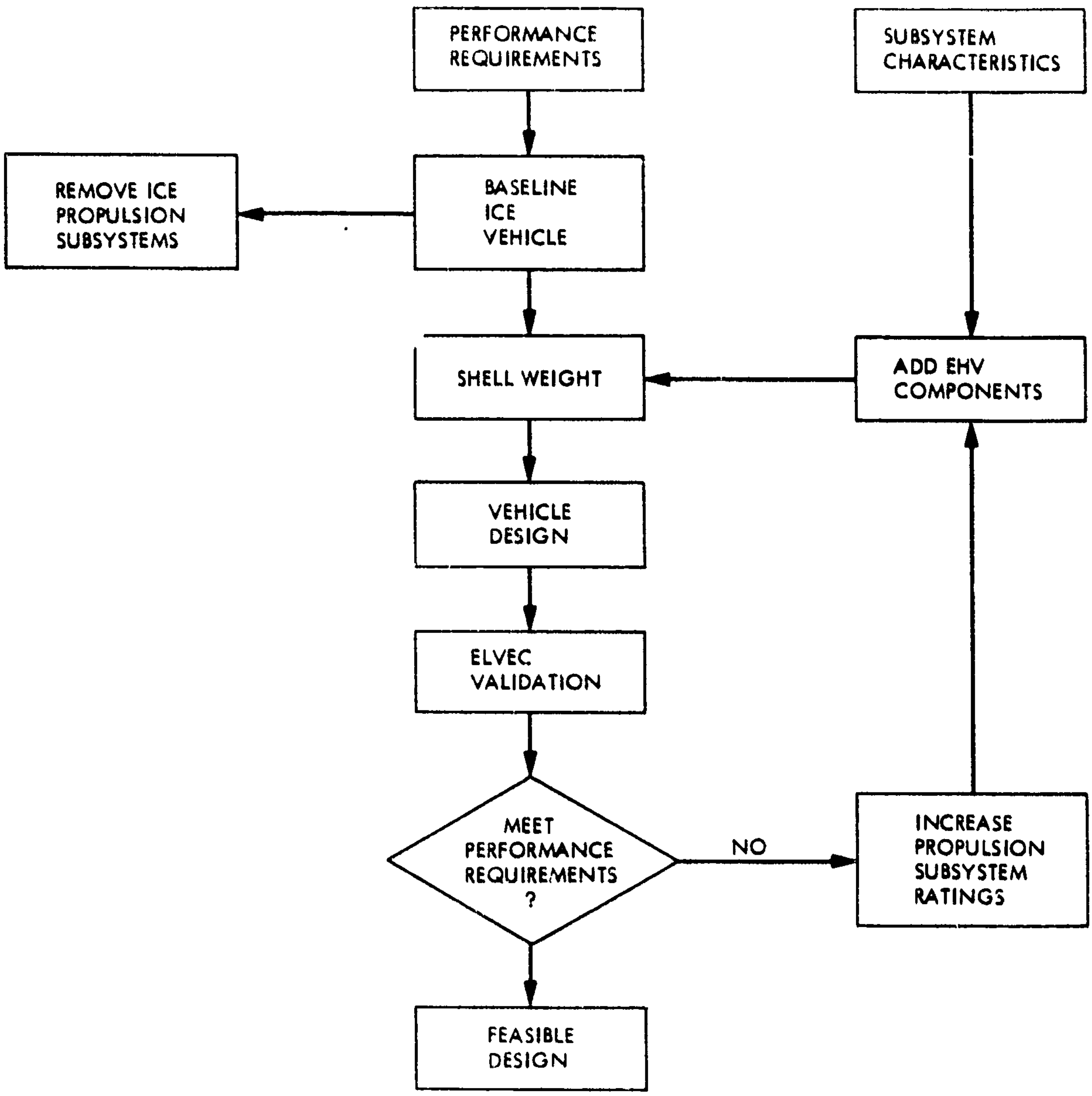

Figure 14. Alternate Vehicle Component Sizing Routine (Ref. 5)

for a 60th percentile vehicle traveling 16,000 km/yr is shown in Figure 15. Portions of the Environmental Protection Agency urban and highway cycles were used to define the various profiles associated with certain trip lengths. The specifics of this task are reported in Reference 35.

Each of the concept vehicles considered in either the advanced vehicle or hybrid vehicle assessments were evaluated under these annual use pattern conditions. Although several important time-dependent parameters were still ignored, this procedure identified many strengths and weaknesses of the competing subsystems which might otherwise have gone unnoticed.

d. Multi-Attribute Decision Analysis

In the course of conducting assessments, one must deal with a collection of uncertainties beyond the obvious uncertainty of projecting technological advances. This former group includes such matters as:

(1) What are the important issues or attributes which should be considered?

(2) How should these attributes be ordered or given a weighted ranking?

Multi-attribute decision analysis is a process which provides information to decision-makers for comparing and selecting from among complex alternative systems in the presence of uncertainty. The methodology of multi-attribute decision analysis is derived from the techniques of operations research, statistics, economics, mathematics, and psychology (Ref. 36).

Every analysis involving the preference ranking of alternative systems requires two kinds of models. A system model and a value model. The system model describes the alternative systems available to the decision-makers in terms of the risk and possible outcomes that could result from each. The value model assesses the outcomes in terms of the preferences of the decision-makers for the various alternatives. The output of the value model is a multiattribute utility function value for each outcome. These outcome utilities are entered back into the system model where an alternative system utility can be calculated for each alternative simply by taking the expected utility value of the outcomes associated with each alternative system. A schematic of this process is shown in Figure 16. This structured methodology involving personal interviews with 30 to 40 high-ranking decision makers, was an effective way to address those important market issues and forces otherwise ignored or misunderstood. This activity clearly identified that cost, maintenance and safety issues were the most significant factors in the choice of a vehicle.

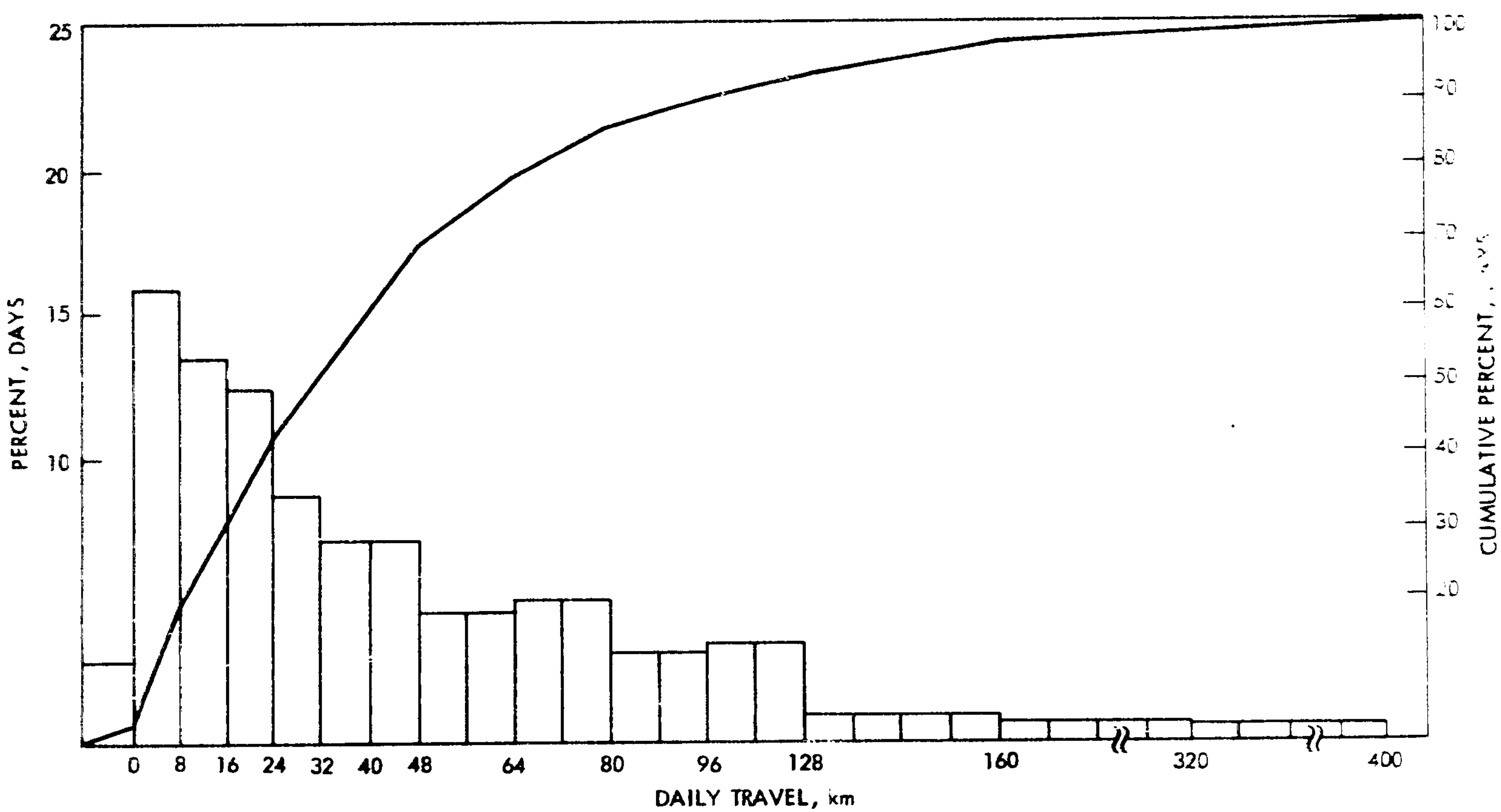

Figure 15. Annual Travel Pattern for the 60th Percentile Vehicle Traveling 16,000 km/yr (Ref. 35)

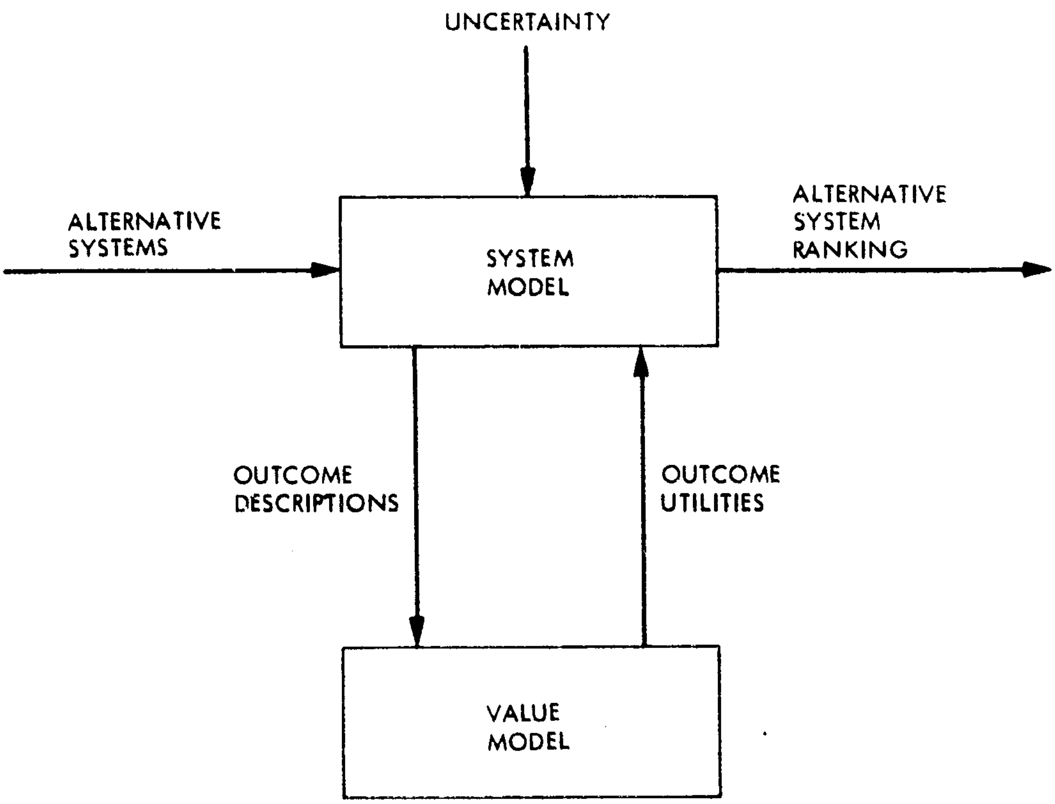

Figure 16. Multi-Attribute Decision Analysis Process (Ref. 35)

III. MAJOR FINDINGS

The previous section of this report briefly highlighted the major activities undertaken by the JPL Electric and Hybrid Vehicle Project since its inception. Each of those specific tasks resulted in informations useful to the Electric and Hybrid Vehicle Program and was conveyed through either deliverable reports to DOE or presentations in the open literature and other forums. It is not the purpose of this section to cull and restate the details of each activity's conclusions. That information is best gleaned from the context of each specific report which is either referenced or listed in the Bibliography. Rather, this section develops its perspective by moving back one level of abstraction in order to view the broader issues of major findings and lessons learned which cut across all the various technical disciplines.

A tremendous amount of excellent technical work has been accomplished during the 7 yr course of this Program. DOE, JPL and the other field centers can be justifiably proud of their accomplishments which are many. The real value of a review, however, is not to praise the successes but to draw wisdom from error. Hindsight is said to be 20/20; therefore, viewing activities from that perspective can yield valuable insights. Some of the following issues are raised, not to be critical, but to provide the context from which to consider the "lessons learned". Any activity can benefit from an honest evaluation of its strengths and weaknesses. It is in that spirit that the following comments are offered.

A. GOALS AND OBJECTIVES

The single most important element of any successful Program structure is its overall goal. It is the central driver which gives purpose to all the supporting activities. Conversely, all activities must find their justification in the fulfillment of this goal. Significant petroleum displacement through the introduction of electric and hybrid vehicles into the transportation fleet mix has been a primary goal of the DOE Electric and Hybrid Vehicle Program since its inception. Other objectives have found favor as well depending upon the economic or political climate; these include emergency preparedness and long-range R&D.

The petroleum displacement goal is at once easy to visualize and difficult to accomplish. This is because much of the strategic plan necessary to accomplish that goal is beyond the control of the DOE. To displace a significant amount of petroleum, hundreds of thousands of electric and hybrid vehicles must be produced, sold and used, thus requiring huge investments by industry in plants and equipment. External events such as synfuels coming on line or a plentiful gasoline supply (as now perceived) can prevent the necessary market acceptance of the vehicles. Most significantly, it requires a return to the type of activities characterized as "commercialization" where the DOE would necessarily assume some of the risks found unacceptable by industry. While there may be some support for this type of program by the public and in Congress, there appears to be no support for such a program in the present administration.

The Emergency Preparedness objective requires the development of a rapidly deployable, nonpetroleum vehicle option to be used in the event of a long-term petroleum disruption. The Program's main interest would be the establishment of plans, production demonstrations, mothballing of assembly lines and stockpiling of certain materials to allow the rapid startup of production of vehicles in an emergency period. This option could be compared to building a second strategic petroleum reserve. The cost of the R&D and planning for this program would be high, but the actual implementation costs in an emergency would be enormous. Again, while the public and certain members of Congress would have some interest, the current administration would not.

The Long-Range R&D thrust develops generic technology to support an eventual transition away from petroleum in personal transportation vehicles. It is basically a level-of-effort activity with few tangible or immediate objectives; thus providing the freedom to address all types of technology with little focus. This sort of program has complete autonomy and does not need cooperation from industry. It does not have to concern itself with any type of commercialization activity and thus cost goals need play no important role.

The latter is endorsed by the present administration. Unfortunately, this approach will not satisfy the primary DOE goal since a gap will always exist between the development of this technology and its readiness for production. The time constants are such (in our domestic automotive industry) that they cannot react at the rates necessary to take advantage of market force opportunities brought on by the inevitable economic swings unless production-level technology exists. Much of that gap cannot be addressed with a long-range, generic R&D charter; and the industry perceives development to be too high-risk or low-priority to be seriously pursued. Foreign manufacturers, however, enjoying complete governmental support and demonstrating a much shorter time constant, would likely be in a position to develop and take the market for themselves. While this may satisfy the primary DOE Program goal, it does so at great cost to the domestic auto industry.

The point of the previous discussion is this: social, political and economic forces have been changing dramatically over the 7-yr life of this program.

(1) The pervasive petroleum shortages of the seventies, which spawned the Electric and Hybrid Vehicle Program, have disappeared and the sense of urgency to provide alternatives has subsided as well.

(2) The philosophy held by the administration has moved from embracing government-sponsored commercialization programs to eradicating them altogether.

(3) The economy has been on a roller-coaster as inflation shot up in the late seventies followed by a period of deep recession and now cautious recovery.

In short, this has not been the sort of climate necessary to successfully bring about change. Orderly evolution requires periods of relative stability with external forces remaining constant or predictable. This has certainly not been the case in regards the Electric and Hybrid Vehicle Program. As a result, these mixed forces have worked to confuse the focus of not only the Program strategy but that of the various tasks and activities being performed by the field centers as well. Many tasks which had a clear purpose when conceived were of questionable value when completed. Some activities were modified, midstream, to reflect the changing environment while others were merely truncated. This is not to say that little of value was accomplished. On the contrary, the technology has made major advances in many areas. But, given the benefit of a more stable environment, and clearly defined goals resulting in a uniform strategy, far more could have been accomplished.

B. TECHNICAL PROGRESS

When the ERDA/DOE Electric and Hybrid Vehicle Program was launched in 1976, many argued that marketable electric vehicles were only awaiting significant improvements in the performance and cost of batteries. That statement is more true today than it was 8 yr ago. Major refinements in motors, controllers and vehicle system design have evolved to the point that the only significant technical hurdle remaining is the energy storage technology. These improvements have combined to reduce the performance requirements of a battery subsystem. The gap between what is asked of energy storage subsystems and what they can presently do has been narrowed, to be sure, but several nagging issues still remain. The reality is that improvements in battery technology have been slower than many had anticipated.

In any development activity, a set of goals provides the forcing function. If these goals are either nebulous, incomplete or off target, the success of the activity suffers. During the first few years of the Program, battery goals were rather nonspecific as befits a research-type activity. It was acknowledged that energy, power and cost parameters all needed improvement but no measurable or quantifiable targets were specifically generated or enforced (other than in support of the Near-Term Electric Vehicle Program, ETV-1 and ETV-2). This situation changed with the advent of the commercialization thrusts of late 1979 and 1980. At this point, the objectives of the battery R&D program became quite specific; to develop and provide: (1) viable near-term batteries capable of powering electric vehicles for 100 mi by 1986 and (2) advanced batteries capable of powering electric vehicles for 150 mi by 1990. The Jet Propulsion Laboratory and other field centers participated in analyses to convert these top-level goals into specific battery development targets. The intermediate requirements of range, acceleration, life and cost were subsequently translated into the now familiar near-term battery R&D goals of:

Specific Energy	56 Wh/kg at C/3
Specific Power	104 W/kg at 50% depth of discharge
Life	800 cycles at C/3
Cost	70 $/kWh (OEM)

Later review, coupled by the experience gained through in-vehicle test activities have shown that these development goals were incomplete and in some cases, inappropriate. That is, a battery subsystem could be designed to meet all of the above stated goals and still be wholly incapable of fulfilling the vehicle and Program goals. It turns out, in fact, that battery development goals are unique to each technology and must be revisited many times during the course of the activity. This issue was the subject of a JPL white paper presented to DOE in early 1982. It concluded that to properly direct (or assess) an electric vehicle battery development program, one must consider a multitude of system constraints far beyond the four limited goals currently being pursued. It went on to state that many of these constraints were interactive and therefore could not be viewed individually; rather that development should be integrated and directed from a system perspective. Obviously, basic research had to remain relatively unconstrained. However, the moment development efforts were directed toward an electric vehicle application, the full consequence of the system interface requirements must be addressed as completely and honestly as possible. Only then could development efforts be intelligently directed at the major technological barriers.

By ignoring these principles, many development activities have focused on the wrong issues, making design choices which actually ran counter to what was necessary. Specifying energy density and cycle-life goals under constant current conditions has proved to be unfortunate. While this may provide some useful information in electrochemical circles, it has little significance in terms of vehicle applications. It is entirely conceivable that two batteries could have reversed rankings when viewing data from constant current or vehicle duty-cycle tests. The ubiquitous C/3 constant current discharge requires a battery to be discharged at a rate such that it will be depleted in 3 h. Therefore, batteries with significantly different capacities were discharged under very different conditions making it impossible to draw conclusions from the data regarding vehicle applications. Some efforts to improve cycle-life have been ill-conceived. Electrolyte agitation for lead-acid batteries or vibrating nickel-zinc plates (to reduce dendrite growth) are solution paths which are probably unacceptable. Reliability, maintenance and safety issues have been all but ignored in most battery development activities. Although it has been argued that many of the current maladies visible in these development subsystems would be ironed out in a production version, some are inherent to the basic design approach. Safety issues can rarely be delt with during test and refinement; it must be designed in from the beginning.

Perhaps the number one concern of a manufacturer today is product liability. The Detroit OEMs are continually in the news concerning safety-related class-action suits and costly recall programs. They will not put electric vehicles on the streets until they are convinced that their reliability, maintenance and safety characteristics are at least as good as the present internal combustion engine fleet. Sealed battery technologies may be the only option acceptable to the automotive community. If that is indeed the case, the whole direction of some developments would have to be changed.

The point is this: the effort will likely end up off-target, unless component development is continually guided by a strong system role, which:

(1) Sets comprehensive, interactive requirements

(2) Evaluates progress

(3) Provides multiple feedback loops

C. SYSTEMS INTEGRATION

The DOE Electric and Hybrid Vehicle Program has been hampered by the lack of a strong system integration activity. The various projects and tasks conducted by JPL, Lewis Research Center, Argonne, Los Alamos, Lawrence Livermore, Aerospace and others were operated in a rather autonomous fashion. It is, of course, human and corporate nature to carefully define turf boundaries only to mount raids resulting in border disputes. Few natural urges exist, however which promote the coordination and integration of activities. The Congressional funding paths, reflected in the DOE organizational structure made coordination at the field center level difficult at best. In an effort to systematically coordinate the activities directed out of the two DOE Divisions (Electric and Hybrid Vehicles and Energy Storage) and the Electric, Hybrid and Advanced Vehicle Projects, JPL suggested the creation of a Lead Center role. This function, proposed in 1980, was envisioned to bring, under one management structure, the responsibility for integrating and directing (with DOE approval) the technical plans and accomplishments of the various field centers. While DOE Headquarters embraced the logic and value of such a role, the funding necessary to support such a task caused several, less effective alternatives to be considered. Ultimately, these efforts resulted in the creation of the Project Integration Office which was limited to providing little more than a monitoring function.

It was not until the advent of the advanced vehicle assessment study, launched in FY81, that the lack of coordination in the technology development process was clearly dramatized. Because this study involved a top-down system perspective of where the technologies were heading, various inconsistencies, holes and gaps in the program were easily discernable. Assembling the data necessary to support a system-level assessment of the various battery technologies proved to be a difficult task. The data standardization existing in the industry is not geared toward electric vehicle applications. As a result, information was gathered in various forms and had to be synthesized (accepting the attendant uncertainties) in order to perform evaluations. Simply stated, the data necessary to determine if battery technologies (being developed for electric vehicle applications) were suitable for that application, were largely unavailable.

In an effort to ameliorate that situation, JPL organized an unofficial task force in September 1982. Representatives from JPL, Argonne, Sandia and Aerospace were assembled to address the interface between battery development and vehicle system considerations. A development process philosophy was presented in order to provide the context for discussion of a strawman set of data requirements. These actions led to an official DOE headquarters sanction and charter for the Electric and Hybrid Vehicle Battery Test Working Task Force in January 1983. This group has been highly successful in building an interface between the vehicle system and battery development communities in the specific area of data requirements. From Figure 10, one can see that data requirements are a key element in an integrated approach to component development. The whole process, however, involving goal setting and evaluation feed-back loops, has not yet been officially endorsed. Until a process involving all these elements is understood, accepted, and implemented many opportunities will continue to exist for development activities to get off-track.

D. GENERAL OBSERVATIONS

Electric and hybrid vehicles have the potential for providing petroleum-free transportation (other than that used in the generation of electricity) for short trips comprising approximately 50 to 75% of total annual mileage driven in the U.S. Recognized limitations of electric vehicles (available range) and hybrid vehicles (perceived complexity) prevent their manufacture and use on a large scale at this time because petroleum is readily available at an acceptable cost and internal combustion engines are increasingly fuel efficient. However, with the long term outlook of a costly and uncertain fuel supply, the American public will, at some point, be willing to pay a premium for a transportation alternative which is not totally dependent on petroleum. Rather than giving up their accustomed mobility, the public will accept such vehicles, even at the expense of reduced performance and range, or for some reasonable cost premium. Therefore, the availability of a mature electric and hybrid vehicle technology, at an anticipated time of favorable market conditions, is in the national interest in order to enable a timely response by automobile manufacturers to public needs.

Electric and hybrid vehicle technology is not qualified for mass production. It is still quite primitive compared to its internal combustion engine counterpart, which is understandable when the total prior development activity is examined. Electric and hybrid vehicles must evolve through several generations of vehicles with successively higher performance capabilities and lower costs. Internal combustion engine vehicles enjoyed such an evolution over several decades with market forces stimulating improvement. This will not happen to the electric and hybrid vehicle. The very existence of the highly refined internal combustion ~~engine~~-almost guarantees that the electric and hybrid vehicle cannot compete for manufacturers' R&D funds or capital investment funds as long as the short-term liquid fuels outlook remains broadly tolerable.

Thus, the electric and hybrid vehicle dilemma! There are no current market forces to stimulate the needed technology improvement program by the industry. When market forces become favorable for electric and hybrid vehicles, years of technology development will be necessary, in addition to the normal 4- to 6-yr product development cycle heretofore required by our domestic industry. A clearly necessary Federal role, therefore, is to maintain the continuity of electric and hybrid vehicle evolution (bridging market fluctuations) to the point where major automobile manufacturers could respond in a favorable market.

An analysis of petroleum savings potential quickly results in the conclusion that the passenger-car market is the only sensible target. The petroleum consumed in commercial applications is insignificant by contrast. That wisdom has prevailed in the Program since its inception and is confirmed in the three DOE vehicle developments ETV-1, ETV-2 and hybrid test vehicle, which are all passenger cars. Unfortunately, as previously discussed, no viable passenger car market presently exists. There does exist, however, a small but enthusiastic group which is interested in purchasing and operating fleets of small commercial vans. The so-called Electric Vehicle Development Corporation (EVDC) is made up of representatives from General Telephone and Electronics, U.S. Postal Service and several power companies across the nation. This appears to be the only viable near-term market available in which to continue the evolution of electric vehicle technologies. The fleet structure is also better suited than private ownership, to handle the vagaries of reliability, maintenance and safety which are weaknesses in present battery technologies.

Any attempts to produce these vans on a marketable scale must involve the established automotive community. Their participation may not guarantee success but their absence will surely guarantee failure. This lesson was painfully learned in early Program attempts to create and vitalize a new grass roots electric vehicle industry with incentives. Such things as quality control, parts supply, repair and other support services will be absolutely essential. Grass roots competition can be successfully developed in the component supplier industry for such things as batteries, motors, controllers, etc. Chassis development, integration, production and consumer services, however, are best left to those currently in the business.

IV. RECOMMENDATIONS

It is reasonable to assume that the primary goal for the DOE Electric and Hybrid Vehicle Program will remain the reduction of foreign petroleum dependence in the United States. It can further be assumed that the preferred way of accomplishing this goal would minimize adverse effects on personal mobility, freedom of choice, and a free market system.

These assumptions imply that the continuation of the Electric and Hybrid Vehicle Program should involve implementation of activities which are focussed on technologies which will: (1) be acceptable to the general public, (2) perform competitively with appropriate internal combustion engine vehicle market segments, and (3) be manufacturable at a competitive initial and life-cycle cost.

Clearly, if one could identify the technologies which meet these requirements, the major continuing efforts needing DOE influence and support would be easy to justify. However, past experience has taught us that identifying these technologies is not only extremely difficult, it is time-dependent. Further, the time-dependency is due to factors both internal and external to electric and hybrid vehicle technology.

Consequently, it is vital for the Electric and Hybrid Vehicle Program to continue even through periods where none of the alternatives seem viable. In addition, there is a clear need for both short-range (1985-1990) first level and long range (1990-2000) second-level goals. Both sets of goals should include hardware and nonhardware activities, but the hardware activities should be distinctly different. The short range hardware should have a high probability of success and be development or application oriented. The long-range hardware should have a high potential payoff and be research or more generically oriented. The converse of these activities, short range low success probability and long-range low payoff potential must be avoided to maintain a viable program perceived positively by those outside the electric and hybrid vehicle mainstream.

It is important, even crucial, that continuing electric and hybrid vehicle activities make efficient use of lessons learned to date. Some of those lessons were learned under less restricted conditions which are not likely to be duplicated so they must not be "wasted". Perhaps the most important of these lessons is the necessity of using the system approach to integrate studies, hardware development, and goal setting activities.

A. SHORT-TERM RECOMMENDATIONS (1985-1990)

This period appears critical for maintaining electric and hybrid vehicle credibility since it is probable, barring a major military conflict, that petroleum will become neither unavailable nor excessively expensive. However, if the momentum is lost and the technology teams are disbanded it could be disastrous when the inevitable fuel shortage does occur. Therefore, short-term recommendations in the following areas are outlined below:

(1) Planning

(2) Coordination

(3) Evaluation

(4) Hardware support

(5) Analysis support

(6) Systems function support

1. Planning

Clearly, intelligent planning is, and has been, a part of the electric and hybrid vehicle effort from the beginning. However, due to the implications of several major efforts by JPL and others, it is appropriate to:

(1) Revisit short-range goals. In the context of the present plentiful fuel syndrome, greater emphasis should be given in planning to the evaluation of probability of success and to cost-risk-benefit tradeoffs. Primary short-range goals should now be directed more towards gaining sophistication in analysis testing and integrating activities. Priority should be given to maintaining a positive image through fostering of appropriate projects.

(2) Redefine component performance goals. Especially in the area of battery goals, system studies provide a new perspective on desirable electric vehicle and hybrid vehicle battery characteristics. In light of early system studies for example, battery energy goals based on C/3 discharge rates and power goals at 50% DOD are clearly inadequate. These should be expanded and redefined by DOE.

2. Coordination

One of the major problems of the early fragmented electric and hybrid vehicle activities was the coordination of various efforts. This problem decreased markedly with time and is continuing to decrease. However, there are three important areas where high level coordination effort are still needed:

(1) Standardization

(2) Joint ventures

(3) Meetings and seminars

a. Standardization

Standardization has already had a dramatic posi a effect on the credibility of both analytical and experimental electric and hybrid vehicle activities. For example, the acceptance of the SAE J227a driving cycles provided the possibility of a consistent definition of range. Similarly, it has been possible to establish comparable battery performance specifications (albeit not yet adequate).

Additional near-term standardization efforts are needed in the areas of:

(1) Cycle-oriented battery evaluation

(2) Definition of time-dependent cycles for various missions

(3) Definition of common missions

(4) Appropriate economic comparisons

(5) Data collecting and reporting format

(6) A method of quantifying probability of success

(7) Commonly used technical terms

While there has been some progress in standardization, much of it is de facto standardization, within certain groups, and not consistently accepted across the electric and hybrid vehicle community. DOE can play a vital role by fostering formal standardization procedures.

(1) Cycle-oriented battery evaluation. It is clear that current goals and evaluation procedures are inadequate. From a performance standpoint, the most important question for a battery is how well it performs in a system environment. More specifically, how much useful energy can it deliver while meeting time-dependent vehicle power requirements, including self-discharge effects and including all ancillary requirements for self-protection and unattended operation.

The evaluations, both experimental and analytical should therefore incorporate discharge patterns representative of those expected in typical applications. While it is obvious that these discharge patterns cannot be as detailed or as inclusive as annual driving cycle/patterns, they can be sufficiently representative for a good indication of battery viability. DOE should actively work towards the establishment of the new battery evaluation standards.

(2) Definition of time-dependent cycles for various missions using computer simulation. Recent computer simulation work at JPL on 24-h cycles has used portions of previously accepted driving cycles in conjunction with "rest" times to make up the total daily cycles. A number of different daily cycles have been further combined to make the model annual driving patterns. This technique appears to be quite workable and has provided valuable insight, especially for a system with high self-discharge batteries or significant heat loss.

This concept should be continued and expanded to provide annual cycles for each mission which appears of interest. Specifically, mission capabilities similar to those considered in the advanced vehicle study should be considered and standardized.

(3) Definition of common missions. The missions included in the advanced vehicle study were:

(a) The 80-mi two-passenger commute vehicle

(b) The 100-mi, five-passenger electric vehicle

(c) The 150-mi, five-passenger electric vehicle

(d) The 250-mi, five-passenger electric vehicle

(e) The five-passenger hybrid vehicle

This group, along with a class I and a class II electric van, would include a good representative cross section of vehicle missions which fall within the electric and hybrid vehicle potential capability. However, since the recommendation is to standardize these missions, including the detailed breakdown of the driving cycle segments, a careful consideration should be made by all segments of the prospective user groups of the standard missions.

(4) Appropriate economic comparisons. There have been, and will continue to be, major misunderstandings on economic comparisons, unless standardizations are made. These problems are magnified when projections are made for alternative technologies 10 yr, or even 20 yr, in the future. Obviously no one can accurately predict interest rates or inflation that far in the

future. However, many electric and hybrid vehicle researchers are forced to make assumptions of that type (along with many others) since so much of the electric and hybrid vehicle effort is directed to future events. Also, the definitions of commonly used terms such as "OEM cost" and the basis for dollar values are often quite different with various groups.

Since many technical decisions are based on economic considerations, it is vital that everyone is speaking the same economic language. The DOE should prepare (or have prepared) a "white paper" on economic comparison to distribute to all interested parties.

(5) Date collecting and reporting format. All too often a great deal of time, effort, and money are used in collecting data that has limited usefulness for any other group. This is due to a combination of incomplete and/or inaccurate collecting of data, and incomplete or improper reporting of the results. To a great extent this problem could be alleviated through the standardization of at least a minimum set of guidelines. This should not be done unilaterally, but through a consensus of the typical groups involved in the activities. The data summary notebooks prepared by JPL and Argonne National Laboratory, and coordinated by the Battery Test Task Force are examples of how this issue could be addressed.

(6) A method of quantifying probability of success. Although a few attempts have been made to put technology projections into their proper perspective, it still remains a major problem to compare technologies in various stages of development. For example, projections relating to cost and performance of a well-established technology can be made with near 100% certainty. However, similar projections on a brand new technology where the complete system has never even been designed, much less thoroughly tested, may have a near-zero certainty of being valid. Intelligent choices, then, are not likely to be made.

An effort needs to be made to include in the technical evaluations, a standardized measure of the probability of success that technology can perform as claimed in the time period promised, and the economics projected are realistic.

This is an elusive goal with no obvious solution. However, the apparent success of using a battery evaluation panel suggests the possibility of semipermanent groups of experts to be impaneled for that purpose. A panel of this type could use an accepted evaluation procedure in a consistent, repeatable manner to provide the needed standardization.

(7) Commonly used technical terms. This may be more of an inconvenience than a serious problem. However, it is one that could be dealt with and resolved in a fairly direct manner. A list of commonly used technical terms (with potentially ambiguous meanings) should be prepared. This list should be circulated among interested groups for their additions or comments and ultimately published for distribution throughout the electric and hybrid vehicle community.

b. Joint Development Ventures

It is clear that while the individual researcher and small company can make important contributions to the electric and hybrid vehicle technology, it is extremely important to encourage the involvement of the potential manufacturers. This applies not only to the basic vehicle manufactures, but also those of critical components such as batteries, motors, controllers, etc.

One way of accomplishing this goal is through the use of joint development ventures. The nurturing and coordination becomes an important activity which may well determine the success or failure of the venture. All types of joint ventures should be explored if they show promise of leading to an advancement in electric and hybrid vehicle state-of-the-art. It should also be noted that involving the manufacturing community will provide the additional benefit of causing many previously ignored electric and hybrid vehicle development issues to be addressed.

c. Meetings and Seminars

With decreased emphasis on R&D for electric and hybrid vehicle related projects, there will be fewer publications and technical meetings for communication among interested groups. Thus, it is more important than ever to coordinate a "core" of meetings and seminars to keep the information flowing.

With the departure of JPL, the meeting most likely to be lost is the continuation of the Seminar series which was begun in December of 1980. The second meeting was December 1983, and based on the response and caliber of presentations, it should be held at least every 2 yr beginning in 1985. In addition to the real-time exchange of information, the seminars result in a Proceedings which contains the most up-to-date material from the most significant projects.

3. Evaluation

The following evaluation procedures need to be continued and in most cases, expanded:

(1) Analysis procedures

(2) Test procedures

(3) Components in a system environment

(4) Proposed new technology

(5) Probability of success

a. Analysis Procedure

Every analysis of real-world materials or events has limitations. There are no perfect models (although some come close) so the results obtained through analysis are not perfect. The usefulness then, of an analysis, depends to a great extent on the compromises made to simplify the approach.

Some of the compromises made in the name of simplicity or expediency have been too extensive, thus making the results suspect. And since the next generation of analyses should move to a higher level of sophistication, a means of evaluating the analysis procedures should be established.

There are two elements to be considered in analysis evaluations: assumptions and mathematical techniques. Assumptions should be clearly identified, even if they appear to be insignificant relative to the results. Mathematical techniques also play an important role and must be chosen carefully. For example, some curves may be approximated by straight lines with little loss in generality in some cases, but if the local slope of the curve is important it would be missed. Likewise while a polynomial might appear to more nearly match a curve shape, it might be totally wrong if an extrapolation is made to slightly outside the original "fit" region.

The best way to review the analysis would be with a panel of 2 or 3 qualified people who specialize in analysis techniques.

b. Test Procedures

Whether by accident or design, a significant number of tests have been remarkably undocumented (outside of results). Undoubtedly, most of these test were accompanied by competent, carefully considered procedures. However, under these undocumented circumstances, the results may carry with them an air of uncertainty. Furthermore, the documentation will be much more meaningful if documented in a manner consistent with similar work.

Consequently, it is not unreasonable to ask researchers to supply sufficient consistent documentation with experimental work that the procedures can be evaluated. At the least, this will provide a means of communicating an appropriate credibility with an experimental project. The Battery Test Task Force recommendation of a standardized test for all electric vehicle battery tests funded by DOE is a good example of addressing this issue.

c. Components in a System Environment

Enough experience has been gained in electric and hybrid vehicle activities to demonstrate that a seemingly successful component is often spectacularly unsuccessful in a system environment. The reason is that when designing, testing, and evaluating an isolated component, the effects of system interactions are missing. Often these system interactions play major roles in such things as efficiency, stability, durability, maintainability, etc.

Therefore, every effort should be made to address system interactions early in the development process. If this cannot be done experimentally, then the best system models should be used to make analytical evaluations.

d. Proposed New Technology

There have been and will continue to be new technologies proposed in connections with electric and hybrid vehicles. Some of these proposals will have merit, others not, and it is often difficult to tell which is which.

JPL and other labs have played an important role in helping to separate those ideas with merit from the others. This has been possible, at least in part, due to the vast reservoir of technical expertise available to the Electric and Hybrid Vehicle Project.

Since it will be necessary to continue this function, at the least on an ad-hoc basis, DOE should identify the specific areas of expertise likely needed and whether they can be supplied internally or if external sources will be needed. Suggested areas include, but are not limited to, electrochemistry, turbomachinery, pumps and compressors, structures, electric machinery, electronics, microprocessors, internal combustion engines, gear boxes and transmissions, vehicle dynamics, and system engineering.

4. Technology Development Support

There are at least two classifications of technology development which might be considered for DOE support:

(1) Those highly visible outside the electric and hybrid vehicle community (e.g., a new vehicle)

(2) Those of low visibility outside the electric and hybrid vehicle community (e.g., a new electrode material).

Those highly visible can do much toward generating positive feelings about electric and hybrid vehicles if the demonstrations are successful. They can do considerable damage, by generating negative feelings, if the demonstrations are not successful.

The almost invisible technology developments are much more benign and as such are subject to less pressure for successful demonstrations. Thus, higher risk (with potentially higher-payoffs) developments can and should be undertaken in this category, if they support the success of relatively short range technology goals.

a. High Visibility Projects

In the first category are several vehicle projects which seem to have a good probability of success, both technically and from the standpoint of enhancing the electric and hybrid vehicle image. They are:

(1) The Ford ETX effort

(2) The EPRI/DOE van effort

(3) The Eaton van effort

While vans do not represent the best opportunity for conserving petroleum, they seem to be best suited for utilizing near-term components. Specifically, vans have the volume and load capacity to carry the available batteries needed for reasonable range and performance. Further, in a fleet situation, first indications are that the economics can be fairly attractive. These ventures are clearly important to positive electric and hybrid vehicle reactions and thus should be supported accordingly.

b. Low Visibility Projects

Among the developments falling into this classifications are:

(1) Battery

(2) Motor

(3) Inverter

(4) Controller

(5) Transmission (transaxle)

(6) Chargers/state of charge indicator

(7) Passenger comfort hardware

(8) Safety considerations

This list is little different than a corresponding list would have been 10 yr ago. That is not to say that there has not been progress, there has. And, the progress has been significant in every category, even impressive in some. However, none of the items have been developed to the point where improvement (either technical or economic) would not significantly improve the electric vehicle.

1) Battery. As would have been the case 10 yr ago, the battery need overshadows every other item on the list. Battery improvements simply have not been nearly enough to make passenger electric vehicles competitive with their internal combustion engine counterparts. This is partly due to the massive improvements in the internal combustion engine vehicle in the last 10 yr, but also partly due to inadequate battery goals and inadequate attainment of those goals. Both experimental work and system studies have shown the importance of many other parameters having major significance in the system environment such as time-dependent factors like heat loss and self-discharge.

Another important result from system studies is that the desirable battery characteristics are clearly different for different electric vehicle missions, and much different yet for hybrid vehicles. Consequently, vehicle mission priorities should be established and battery developments aimed at providing the most favorable characteristics for those missions.

Therefore, for the short-term development support of batteries, the following is recommended:

(1) Use continually updated system studies based on the latest battery information to establish desired battery characteristics for several electric vehicle and hybrid vehicle missions. The advanced vehicle assessment results should be used until such time as the need for updating with new information is indicated. Establish priorities for these missions based on potential petroleum displacement, and the likelihood of obtaining an acceptable battery.

(2) Based on the mission priorities, establish realistic battery performance goals (far beyond the classic four).

(3) Investigate the feasibility of overcoming potential show stoppers of an otherwise acceptable battery couple. These issues may include self-discharge, short cycle life, poor performance at partial discharge, low energy efficiency, high initial cost, possible safety problems, high maintenance requirements, excessive volume requirements, etc.

(4) Encourage the development of any remaining candidates. Note that the advanced vehicle assessment

provides the first generation of this support, but it is assumed that new information will be generated as a result of the advanced vehicle assessment input.

2) Motor. The biggest concern with electric and hybrid vehicle motors continues to be weight and cost. From these standpoints the AC motor seems to have a clear advantage over its DC counterpart. Unfortunately, the success of the AC motor for electric vehicle applications is unmistakenly tied to the inverter needed to provide the alternating current. Therefore it is recommended that the development of the AC motor continue but be biased by the concurrent effort on an acceptable inverter system.

It is also too early to determine the ultimate potential of some of the more experimental motors such as the variable reluctance motor. These exploratory efforts should continue, especially while there is still some questions about an acceptable AC motor-inverter system.

3) Inverter. The development of an acceptable inverter has already been mentioned as crucial to the AC motor. At the present time, however, the inverter seems to be within reach, primarily based on three separate efforts: General Electric/Ford, the Eaton AC-3 work, and the JPL 40-kW inverter. While none of these is necessarily the final answer, the Eaton inverter has been constructed and has had appreciable experimental evaluation and the General Electric/Ford system will soon undergo evaluation. The JPL inverter, on the other hand, appears to have some very attractive features but has had very little experimental verification. All of these development efforts should continue until the final potential is more clear. Unresolved problems include combinations of weight, cost, stability, and efficiency although they do not appear insurmountable.

4) Controller. This item is becoming less of a concern as industry experience and capability with microprocessors grows. In addition to rapidly increasing usage, there is a corresponding decrease in cost and size of the required electronic hardware. Thus, while the controller is not a trivial problem, neither is it the major concern presented by the battery or inverter.

Again, presupposing a successful inverter development, a significant portion of controller development effort should be directed towards AC subsystems. In addition, with regard to hybrid systems, the whole issue of energy management is still in very early stages, and has thus far been based on the assumption that the controller could supply whatever functions are necessary. This clearly needs to be verified with hardware and software designs.

5) Transmissions. Even though there are thousands of transmissions and transaxles available, few if any, seem particularly well suited for electric and hybrid vehicle use. This is not really very surprising considering the difference in speed-torque characteristics and peak power requirements for electric and hybrid vehicles versus internal combustion engine vehicles. Consequently,

there is still a strong need for transmissions (or transaxles) with the proper characteristics.

Probably the best choice from a performance (not cost) standpoint is a high-efficiency continuously variable transmission. However, several studies including those by Eaton have indicated that a lightweight, high-efficiency two-speed gearbox can be very effective; a high-efficiency continuously variable transmission is also quite elusive. Due to the torque-speed characteristics of the typical drive motor, the electric vehicle gearbox should be capable of running continuously and efficiently in any gear. Further, even though it is clearly desirable to have an automatic shift, it has also become clear that a manual override of some type is needed. This latter function would certainly have to be compatible with protection of the machinery, but apparently could be fairly easily accomplished though the microcomputer functions and software which will already be integrated in the system.

6) Charger/state-of-charge indicator. Especially where commercial applications are envisioned, it is essential to have a reliable state-of-change indicator and a reliable efficient means of recharging the battery daily. It is not clear that an onboard charger is critical for commercial applications, but it apparently is a necessity for private noncommercial use.

Therefore, since the most immediate application (which might result in a volume production) is the electric van, the highest short-range priorities should be:

(1) Reliable state-of-charge indicator. Note this will likely be battery dependent and as such should be tied to batteries selected for further development.

(2) Reliable, efficient offboard charger (or onboard if the projected characteristics would allow).

7) Passenger comfort hardware. Again the priorities for short-term development should probably be directed towards the commercial van application. Thus the following are expected to be the most important items:

(1) Heater and defroster

(2) Power brakes

(3) Power steering

Technically these items are simpler and require less power than air conditioning. However, air conditioning is near the top of the priority list for noncommercial applications and as such should be continued if resources permit.

The heater and defroster represent the lower end of the concern scale, not because they are not important but because off-the-shelf hardware is essentially available. Power brakes and power steering are virtually necessities, since for the van and most car applications, "base" vehicles will come equipped with both power accessories and the electric vehicle conversion will definitely increase the operating gross weight.

8) Safety considerations. While almost all electric and hybrid vehicle work to date has addressed safety issues to some extent, there has been little in the way of an organized effort. Since many new concepts in batteries and drive systems are being pursued, a safety program should be initiated. Certain questions should be posed and reasonable answers should be expected with regard to every technology. It seems possible that several of the technologies now being considered will be eliminated, at least for certain applications, when the safety issues are really pressed. DOE should pursue these safety considerations actively.

5. Analysis and Simulation Support

There has been a trend of increasing sophistication in analyses and simulation which needs to be continued. Partially, this trend has come about as a result of vastly improved and more accessible computer facilities, and partly because many earlier results were simply shown to be invalid. There are three areas where it is especially important to continue improving analysis capabilities:

(1) System assessments

(2) Battery and component models

(3) Vehicle use models

a. System Assessments

No single activity has done as much to put technologies in perspective as the system assessments. In addition to showing the overall effects of inherent strengths and weaknesses, the system assessments showed the importance of optimization. Optimization in this sense means that the technologies are optimized for the application as opposed to a vehicle. Application includes use (e.g. taxi or family car), environment (unprotected in Chicago vs garaged in Miami), load factors (one or two persons vs carpool), etc.

The interrelationships between subsystem and system optimization are clearly evident with system studies. Energy management concepts and subtle differences in component arrangements make significant differences in energy efficiency and life cycle costs.

One could conclude that the important system assessment work has really only begun. This is especially true for hybrids and advanced vehicles. The first generation of these studies initially used rather rigid and very limited envelopes of battery and component capabilities. Those studies showed glaring deficiencies which would have made many of the technologies totally noncompetitive. The technology researchers reacted by expanding the envelopes and emphasizing the flexibilities of the various technologies.

Even though some results have been obtained taking into account the larger envelopes, much remains to be done in this area. For example, no attempts have been made to optimize energy managements, choice of technology, and component performance simultaneously. It is very important that this work continue so as to provide direction for continued developments. The present JPL/University of Florida efforts to develop a simulation/optimization code is a move in this direction.

b. Battery and Component Models

As a group, battery and other component models are in rather sad shape. Since system assessments have shown the importance of accurately portraying component capabilities, this is rapidly being recognized as a major problem area.

For example, none of the commonly used battery models include the effects of aging, environmental factors (such as ambient temperature), depth of discharge or level of recharge, the time distribution of "rest" periods, maximum discharge rates, etc. While many of these factors and others could be considered "second order" effects, they are not negligible and there is no reason to ignore them. The availability of computers and elegant software to assist the researcher makes it unreasonable not to update and improve the various models. Other examples where models are needed are drivetrain dynamics (to help isolate the cause and cures of AC subsystem low-speed instabilities), the time-dependent behavior of flow systems and batteries with significant self-discharge, realistic behavior of clutches, behavior of power steering and brakes, air-conditioning subsystems, and many others.

This is critical if simulation is ever to go to the next level of sophistication, therefore, it might be an appropriate theme of a near-term national seminar (similar to the JPL 1980 and 1983 seminars). Everyone would benefit from the dissemination of such information and it would clearly show where priorities exist for improving modeling capabilities.

c. Vehicle Use Models

Use models are needed for each type of vehicle application where there is a potential for displacing significant quantities of petroleum. This would include the company car use, commuter car, and both single and dual car family use. In addition, taxis, postal service vans, nonpursuit police cars, utility vans, and various delivery vans should be considered. Use patterns in this context mean far more than driving cycles. It would include other important factors such as chronological distributions of driving cycles, rest periods,

periods available for recharge, facilities available, environmental factors, typical load factors, and other factors deemed important. This concept, while very important in internal combustion engine vehicle applications is paramount for electric and hybrid vehicles. Put simply, if the final capabilities of the vehicle are inadequate for the final vehicle use, the vehicle will be viewed in a very negative sense. On the other hand, if the design goals are for capabilities beyond those required for the end use, either the vehicle will be excessively heavy and/or expensive, or it will never be built because of being beyond the range of the technology.

Undoubtedly much of the information needed for these models is available. Other parts would have to be estimated or obtained from some type of inquiry. Even so, it is evident that there is a far better chance of having an acceptable electric or hybrid vehicle if it has a bit of "real world" built into it. This can only be done through judicious modeling, or, an extensive period of "cut and try". The "cut and try" approach not only seems unworkable, it seems to be the most direct route to the total demise of electric and hybrid vehicles. DOE should actively pursue the development of a complete set of vehicle use patterns for the range of vehicles of interest.

6. System Function Support

The previous five recommendation categories are not independent of each other and must not be considered as such. Therefore, this last recommendation category is presented primarily as a means of connecting in a coherent manner all of the simultaneous activities. The system function is simultaneously the glue that holds everything together, the pattern which gives the individual threads direction and meaning, the rejuvenator for replacing tired ideas, and the interpreter for giving meaning to abstract and seemingly unrelated inputs. The system function is always present when goal-setting, planning, and development activities are occurring within a single identifiable group activity. However, unless this function is formally instituted and receives appropriate attention, the results will be compromised. The point is that this is an extremely important function in maximizing the worth of the output from all efforts. Yet at the same time it is less tangible and, as such, often conveys a lower sense of priority than other activities.

a. Integration

The system integration effort should not be confused with coordination. Integration in the system sense means establishing a rational connection among planning, goal-setting, and development activities. The alternative to proper integration is a set of more or less autonomous efforts which may or may not be additive in the accomplishment of some common goal.

Integration is not easy since many R&D groups prefer the more or less autonomous activity concentrating on their subset goals which they perceive (usually) to be compatible with and necessary to program goals. Unfortunately, this approach strongly ties program accomplishment to the perception of individuals well removed from the program.

Thus the need for a program system integration function is clear. What is not clear is the most effective way for DOE to implement it. The alternatives are: (1) totally within DOE, (2) within DOE with outside assistance, or (3) outside DOE with continuous input to DOE. The choice of implementation alternatives will depend on several factors including budget and/or manpower restrictions, political considerations, and the availability of suitable system-oriented people.

b. Feedback

The feedback function is of course not truly separable from the integration function just described. However, several recent activities have served to demonstrate the necessity of an active feedback loop connecting development to planning, goal setting and other portions of the program. Without the feedback loop, at least two undesirable events can occur:

(1) The developers acquire myopia and do not consider the possibility that their goals are inappropriate or incomplete.

(2) The users of a developing technology acquire an unwillingness to interfere and do not press the developers for more flexibility.

The consequences of these two events are that both program and technology fall short and are viewed in a more negative light. Consequently, DOE needs to be constantly seeking feedback at all levels and feeding it into the integration function. Only in this way, with all important functions integrated and tied together with appropriate feedback loops (e.g., refer to Figure 10), will the progress of the effort be maximized.

B. LONG-TERM RECOMMENDATIONS (1990-2000)

Obviously, the uncertainties of the short range (1985-1990) are magnified when considering the longer range course of action. However, of the many possibilities, the answer to these two major questions will dictate the future projections:

(1) Is the Electric and Hybrid Vehicle Program still viable in 1990?

(2) Is petroleum still relatively abundant at a reasonable price?

Only if the answer to both is yes will long-term recommendations be meaningful. Even under those circumstances, there will be biases, unknown at present, due to successes and failures, budget and manpower limitations, political and economic factors, etc which will directly affect program decisions. However, it is possible to project two areas of generalization where long-range recommendations are appropriate:

(1) The development of a critical base for a self-sustaining technology

(2) The nurturing of appropriate high-risk technologies

This does not mean to imply that all of the short-term activities will cease. Clearly they will continue, but they will be subject to an updated set of short term recommendations in about 1990. The long range recommendations, however, refer to activities that are already underway (to some extent) and should be continued and modified as appropriate to bear fruit in the 1990-2000 time period.

1. The Development of a Critical Base for A Self-Sustaining Technology

The electric and hybrid vehicle community at present (and most likely through the short range period) is fragmented and in a somewhat precarious position. This is due to the lack of a competitive market for their electric and hybrid vehicle-related products and/or services. In other words, they are not associated with a self-sustaining technology.

The desired methods for the technology to become self-sustaining is through a combination of market "pull" and technology "push". To a great extent the "pull" is associated with a lack of petroleum availability and/or a high price. But this recommendation precludes the influence of scarce petroleum. The push, on the other hand, is largely associated with the ability to offer an electric or hybrid vehicle which is attractive to buyers without scarce petroleum. Unfortunately, developing the technical base for the "push" is very expensive and time-consuming.

The challenge, then, is to massage the electric and hybrid vehicle community and their individual activities to the point where even without the type of pull and push referred to, their progress will be self-sustaining. The most likely way of accomplishing this formidable task is to find applications for the technologies outside electric and hybrid vehicles, and conversely to look for electric and hybrid vehicle adaptations of otherwise developing technologies.

Examples of electric vehicle technologies which already appear to be approaching the self-sustaining state are the AC inverter/controller and bipolar lead/acid batteries. There are others which could reach this state with a combination of technical successes and moderate support from DOE. Examples are high-efficiency continuously variable transmission, improved electric motors (both DC and AC), low-power environmental control subsystems, and improved charger/state of charge indicators. Equally important, but more difficult for which to find co-support, are other battery couples and nonconventional power sources.

Clearly, since a self-sustaining technology is highly desirable, DOE should provide support to those which could combine to form a technical base for future electric and hybrid vehicle support, and have the promise of becoming self-sustaining in this time period. Among those with high support priority are:

(1) Improved continuously variable transmission

(2) Improved drive motors

(3) High efficiency environmental control

(4) Improved charger/state-of-charge indicators

(5) Promising battery couples (for both electric and hybrid vehicle and other applications)

2. The Nurturing of Appropriate High-Risk Technologies

Into this category fall those technologies which offer high potential payoffs for electric and hybrid vehicles (if successful), but have relatively low probability of success and few apparent applications outside electric and hybrid vehicles. These technologies have the common characteristics of being long-range, expensive, and high risk. They are unlikely to find appreciable support outside DOE and thus will probably compete enthusiastically for DOE funding.

Without a doubt, some of these infant technologies should receive long-term support from DOE. However, it is just as certain that not all which desire support can (or should) receive it. Unless resources are unlimited (highly unlikely), then attempting to support too many high risk activities will dilute each effort to the point that it might be meaningless.

Therefore, the main query for DOE is to determine what are "appropriate" high-risk technologies and how to prioritize them. Part of the answer lies in results of studies like the advanced vehicle assessment since that represents an effective method making of intelligent comparisons. That this is only part of the answer is due to the fact that even carefully conducted studies like the advanced vehicle assessment are limited by the scarcity of input data. Since the technologies are in their infancy, many of the performance parameters and possibly most of the economic parameters are based on speculation. And all speculations are not created equal. The advanced vehicle assessment also showed that while this is the correct approach, one study is not sufficient. It was found that apparent glaring deficiencies in various technologies could be overcome with relatively minor design changes and that apparent "winners" had major problems previously unnoticed. Thus, the advanced vehicle assessment study needs to be "updated" periodically as new information is made available, and conversely the results of the studies need to be used to "improve" the technologies. Note that perhaps it is also time to reconsider the assumed missions of the advanced vehicles, based on a more realistic appraisal of the capabilities of all-electrics and hybrids. While the missions must be competitive with a segment of internal combustion engine applications, they must also be realistic from a design standpoint.

In summary, DOE should support, (at a level compatible with available resources but above a "critical" level), one or more high-risk, potentially high-payoff technologies which would otherwise fold. The technologies to be supported should be compared with alternative technologies from both a performance and economic standpoint using periodically updated system assessment studies as guides.

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