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STUDY OF ADVANCED ELECTRIC PROPULSION SYSTEM CONCEPT USING A FLYWHEEL FOR ELECTRIC VEHICLES

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
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U.S. DEPARTMENT OF ENERGY
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NOTICE

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PREFACE

The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 (Public Law 94-413) authorized a Federal program of research and development designed to promote electric and hybrid vehicle technologies. The Energy Research and Development Administration, now the Department of Energy (DOE), which was given the responsibility for implementing the Act, established the Electric and Hybrid Vehicle Research, Development, and Demonstration Project within the Division of Transportation Energy Conservation to manage the activities required by Public Law 94-413.

The National Aeronautics and Space Administration under an Interagency Agreement (Number EC-77-A-31-1044) was requested by ERDA (DOE) to undertake research and development of propulsion systems for electric and hybrid vehicles. The Lewis Research Center was made the responsible NASA Center for this project. The study presented in this report is an early part of the Lewis Research Center program for propulsion system research and development for electric vehicles.

The research described in this report was conducted under Contract DEN3-78 with the National Aeronautics and Space Administration (NASA) and sponsored by the Department of Energy through an agreement with NASA.

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1. ABSTRACT

A study for evaluation of advanced electric propulsion system concepts with flywheels for electric vehicles predicts that advanced systems can provide considerable performance improvement over existing electric propulsion systems with little or no cost penalty. Using components specifically designed for an integrated electric propulsion system avoids the compromises that frequently lead to a loss of efficiency and to inefficient utilization of space and weight. A propulsion system using a flywheel energy storage device can provide excellent acceleration under adverse conditions of battery degradation due either to very low temperatures or high degrees of discharge. Both electrical and mechanical means of transfer of energy to and from the flywheel appear attractive; however, development work is required to establish the safe limits of speed and energy storage for advanced flywheel designs and to achieve the optimum efficiency of energy transfer. Brushless traction motor designs using either electronic commutation schemes or dc-to-ac inverters appear to provide a practical approach to a mass producible motor, with excellent efficiency and light weight. No comparisons were made with advanced system concepts which do not incorporate a flywheel.

2. INTRODUCTION

This study is intended to identify and evaluate advanced propulsion system concepts for on-the-road electric vehicles. Electric vehicles are of interest because their use will reduce petroleum consumption and pollution. Today about one half of the petroleum consumed in the United States is used for transportation. The introduction of electric vehicles could significantly shift the transportation energy base to other sources such as coal, nuclear, and solar.

Most electric passenger cars built in recent years have been conversions of conventional automobiles using available dc motors with various control schemes.

The availability of vehicles, motors and control devices rather than optimum energy efficiency and performance often dictated the nature of the propulsion system design. With the evolution of a new generation of electric vehicles for passenger use, specially-design components will presumably be used. If a new generation of electric vehicles is to be mass produced for a potentially large market, the components for these vehicles should be tailored to meet the specific requirements of an automotive market. The criteria for weight and efficiency would not necessarily be those for the industrial motor and controller nor for aircraft motors, but would aim to meet the vehicular needs of light weight, low cost and high efficiency.

The study was to select from several proposed concepts, two concepts that have a range of 100 miles over the J227a D cycle (ref. 1) and also meet performance standards set by NASA using battery characteristics given by NASA. Conceptual designs of these two concepts were then to be prepared.

3. OBJECTIVE

The objective of the study is to identify attractive concepts for advanced propulsion systems that offer considerable performance improvement over existing propulsion systems with little or no potential cost penalty.

4. TASK DESCRIPTIONS

The program effort was organized into four main tasks as shown in Table 1. In the first task, Preliminary Analysis, a variety of candidate propulsion systems were evaluated using the performance requirements for a four passenger vehicle assuming the use of an improved state-of-the-art (ISOA) lead-acid battery. It was also assumed that advanced components would be available for an engineering model by 1983. Components assumed available in this time frame include high-speed light-weight traction motors designed specifically for electric vehicles, advanced semiconductor controllers for these motors, high-specific-energy flywheels, and light-weight continuously-variable-transmissions (CVT). Task 1 also includes an assessment of the technology advancements required to yield the components and system integrations for the advanced propulsion systems.

In the second task, Design Trade-Off Studies, the most attractive candidates are subjected to a more detailed analysis to determine optimum sizes and ratings of system components, optimum operating points and operating modes to achieve the required performance considering energy consumption, battery life and life cycle cost.

In the third task, Conceptual Design, layout drawings for the two most attractive concepts are to be prepared showing the location of all components within possible vehicle configurations. Consideration is to be given to cost, effective component operation, maintainability, reliability, and passenger safety and comfort. Performance and life cycle costs of these conceptual designs are to be estimated.

In the fourth major task, Development Plan, the required effort for development of the conceptual designs will be assessed. This task is to identify all major developmental efforts for each new technology requirement. The plan is to cover the effort required up to and including fabrication and laboratory testing of an engineering model of the advanced propulsion system. Work on this task was submitted as a preliminary draft.

Table 1. Task Descriptions

Task No.	Description
1	Preliminary Analysis Evaluate general concepts and recommend five for Task 2
2	Design Trade-Off Studies Optimize and evaluate specific concepts
3	Conceptual Design Prepare conceptual designs of two concepts
4	Development Plan Identify major activity areas and estimate required effort

5. REQUIREMENTS

Advanced concepts for evaluation are envisioned as propulsion systems which can be developed in about five years using advanced technologies that are projected to produce components with lower weight and higher efficiency than current state-of-the-art components. These systems are expected to include flywheel energy storage devices not presently available to boost the peak power to give improved performance of electric vehicles.

The purpose of the study is the conceptual design of two advanced electric propulsion systems with the objective of meeting the cost and performance requirements listed in Table 2, when the propulsion system is installed in an electric vehicle with characteristics as listed in Table 3 using a battery with characteristics as listed in Table 4.

The requirements are taken to apply at the test weight of the vehicle at an ambient temperature of 27°C and for a new traction battery. The test weight is taken as the curb weight of the vehicle plus 300 pounds (136 kg).

In addition to the requirements given in Table 1, effort to minimize the effect on performance and operation due to battery degradation and operating temperature extremes of -29°C to +52°C. The propulsion system is to be designed to optimize the battery available energy and battery life.

The driving cycles for evaluating electric vehicles are those specified by SAE J227a which lists four different test schedules. The characteristics of these schedules are summarized in Figure 1. Different schedules are used for different types of vehicles. The schedule "D" is the one to be used for evaluating advanced electric vehicles. The range for an electric vehicle operating repeatedly over the SAE J227a cycles is determined by the point where the vehicle can no longer satisfy the acceleration at the start of the cycle.

Table 2. Advanced Electric Vehicle
Performance Requirements and Cost Goals

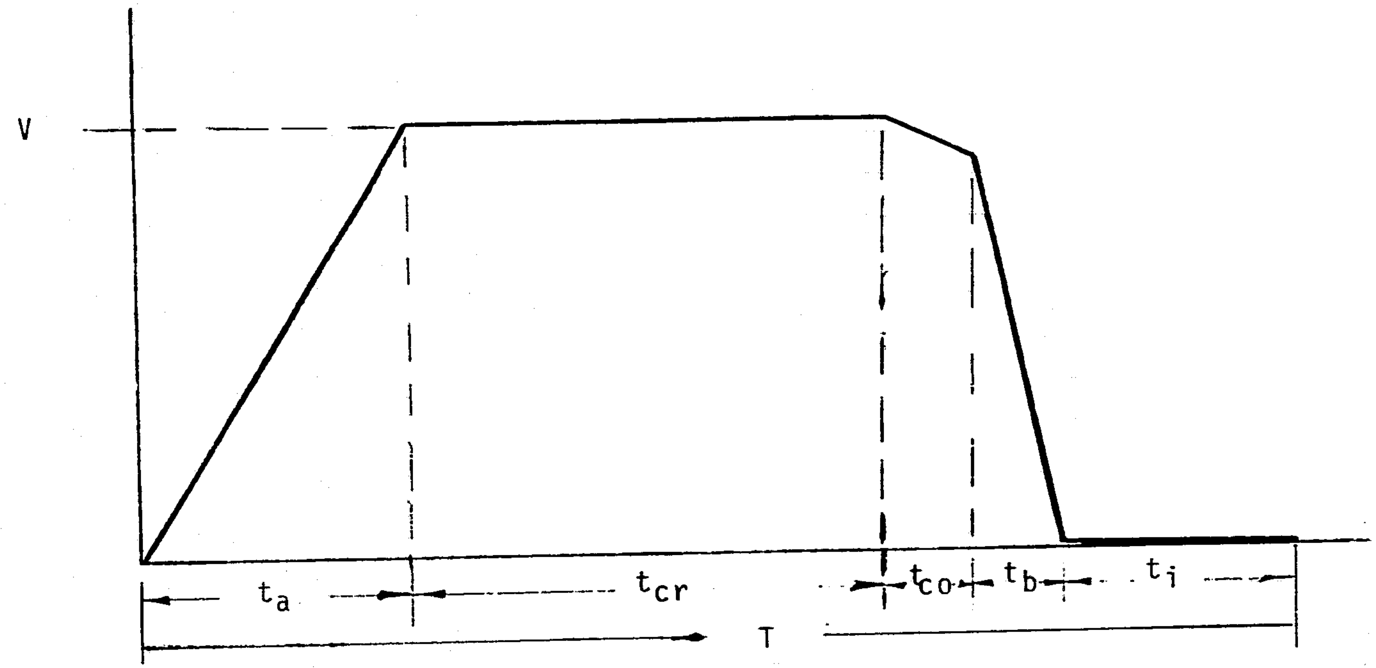
Min. Range, SAE J227a Schedule D, km (mi)	161 (100)
Min. Range at constant 72 km/h (45 mi/h), km (mi)	209 (130)
Max. acceleration time 0-89 km/h (0-55 mi/h), seconds	15
Max. merging time, 40-89 km/h (25-55 mi/h), seconds	10
Min. passing speed, km/h (mi/h)	105 (65)
Sustained speed on an uphill 4% grade, km/h (mi/h)	89 (55)
Ramp speed. Min. attainable from a stop on an uphill 6% grade in 305 m (1000 ft), km/h (mi/h)	65 (40)
Maximum wall plug energy for SAE J227a, Schedule D	559 kJ/km (250 W-H/mi)
Minimum life	161,000 km (100,000/mi)
Maximum life cycle cost (propulsion system plus battery only)	$.05/km ($.08/mi)

Table 3. Electric Vehicle Characteristics

Base weight, kg (lbs)	326 (718)
Maximum payload, kg (lbs)	272 (600)
Test load, kg (lbs)	136 (300)
Weight propagation factor	1.299
Tire radius, mm (in)	292.1 (11.5)
Aero drag coefficient times Area, C_dA, m^2 (ft^2)	.56 (6)
Air density, $(\frac{kg}{m^3})$ $(\frac{sec^2 lbs}{ft^4})$	1.26 (2.38×10^{-3})
Rolling resistance coefficients	
C_o Non-dimensional	8×10^{-3}
C_1 $\frac{sec}{m}$ $(\frac{sec}{ft})$	3.599×10^{-5} (1.097×10^{-5})
C_2 $\frac{sec^2}{m^2}$ $(\frac{sec^2}{ft^2})$	1.036×10^{-6} (9.63×10^{-8})
Rotational inertia factor non-dimensional	1.04

Table 4. Battery Characteristics

	Lead Acid	Nickel-Zinc
Specific energy wh/kg	40	80
Specific power w/kg	100	150
Cycle life (80% discharge)	800	500
Cost $/kWh	50	75
Efficiency %	60	70



TEST SCHEDULE - Time in Seconds

	A km/h	A mi/h	B km/h	B mi/h	C km/h	C mi/h	D km/h	D mi/h
V	16.1	10	32.2	20	48.3	30	72.4	45
t_a		4		19		18		28
t_{cr}		0		19		20		50
t_{co}		2		4		8		10
t_b		3		5		9		9
t_i		30		25		25		25

Figure 1. SAE Electric Vehicle Driving Cycles SAE J227a

6. PRELIMINARY ANALYSIS

The characteristics and performance of 28 candidate propulsion systems were analyzed. These candidates covered a variety of component types and arrangements and included ac and dc traction motors with and without multi-speed transmissions. All candidates included a flywheel storage system to provide load levelling for the battery and to give a power boost for acceleration and an energy sink for use in regenerative braking. Single and dual axle drives were considered.

A computer program which calculates the energy consumption of electric vehicles in any driving cycle was used to help evaluate the candidate systems. Preliminary studies of component types were made to establish the characteristics and data which were input to the computer program. Special subroutines were prepared to generate performance characteristics of various components. CVTs and electrical controllers were modeled on the basis of known losses. Motor types were modeled using equivalent circuit concepts and theoretical relationships for known losses.

6.1 Methodology

The method for analysis of propulsion system candidates was iterative in nature using a computer simulation of the specific driving cycles. Specifications of components were set initially at values believed to be adequate to satisfy performance requirements. These were then used as input for the computer with the various driving cycles set to simulate all the required performance goals. Component sizes and ratings were altered as required to satisfy all the power requirements. Battery weight was varied to meet the range requirements. Resulting vehicle weights, energy consumption and range were used as figures of merit for assessing the relative attractiveness of each of the candidates. In addition to the computer analysis, preliminary evaluations of technology risks and other factors were made. The most attractive concepts without excessive risks were identified for further study in design trade-off studies.

The computer program, Appendix E, calculates all of the energy losses for the driving cycle on a second-by-second basis. The subroutines for the various motor types permits a direct calculation of copper and iron losses, bearing friction and windage. The motor subroutine for ac induction motors uses the equivalent circuit for induction motor and calculates the air gap magnetic flux required to produce the necessary counter emf. The dc motor subroutine calculates the required field coil excitation current and magnetic flux using a typical reluctance circuit and the magnetic saturation characteristics of a laminated iron used in motor construction.

Losses in the motor controller were separately calculated at each time step to find the efficiency of these units.

Axle and transmission losses due to gear friction, bearing friction and windage were also calculated at each time step rather than using a fixed efficiency for these units. The losses for multi-speed transmissions varied with the gear ratio.

Run-down losses for the flywheel were included in the calculation. The in-and-out efficiency of the flywheel storage system with its controller losses were also included.

6.2 General Concepts

The propulsion system for an electric vehicle can be very simple. An electric motor can be mechanically coupled to the drive wheels and the battery can be electrically connected to the motor by a simple control circuit. The electric motor draws current from the battery to provide propulsion power to drive the vehicle. Some means of controlling the power to the drive wheels is necessary to control the vehicle speed. A variety of different types of motors and their control is possible. Varying degrees of complication evolve around the control schemes for different types of motors and driveline components. High efficiency, light weight and easy handling are obviously desirable. Separately excited dc motors can be controlled by field weakening over a large speed range. The use of a transmission extends the vehicle speed range without a corresponding increase in motor speed range. Some vehicles also use chopper control of armature current to extend the range of motor controlability.

For the envisioned automotive market the nature of the design would be such as to favor those designs more susceptible to mass production and low maintenance. Mechanically commutated dc motors would appear to be less attractive than squirrel cage induction motors or electronically commutated dc motors. However, the controller for such motors could have complications, weights and costs that would more than offset any savings due to the simpler motor construction. The trade-off between cost and efficiency would not merely be judged in terms of the cost of energy saved but would rather consider the increase in range and increase in battery life.

Various general concepts using a variety of motor types and drive configurations have been proposed for preliminary analysis. All of these use a flywheel for a power booster to provide a power boost for acceleration and to maintain acceptable performance even on a nearly discharged battery or under adverse temperature conditions. The arrangement of the driveline components are shown in Figures 2, 3, 4, and 5.

These four general configurations represent different driveline power flow paths using different elements.

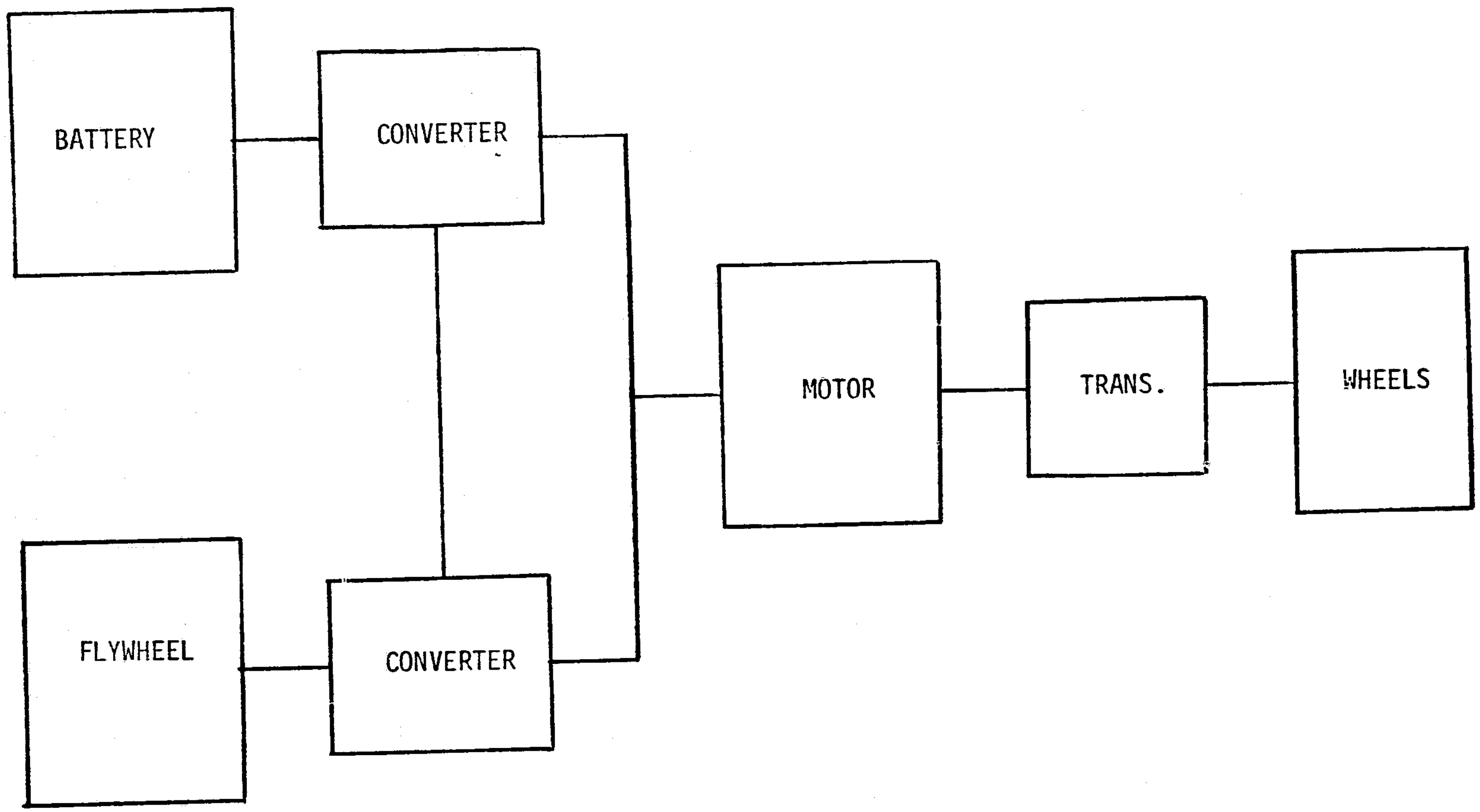


Figure 2. General Concept "A"

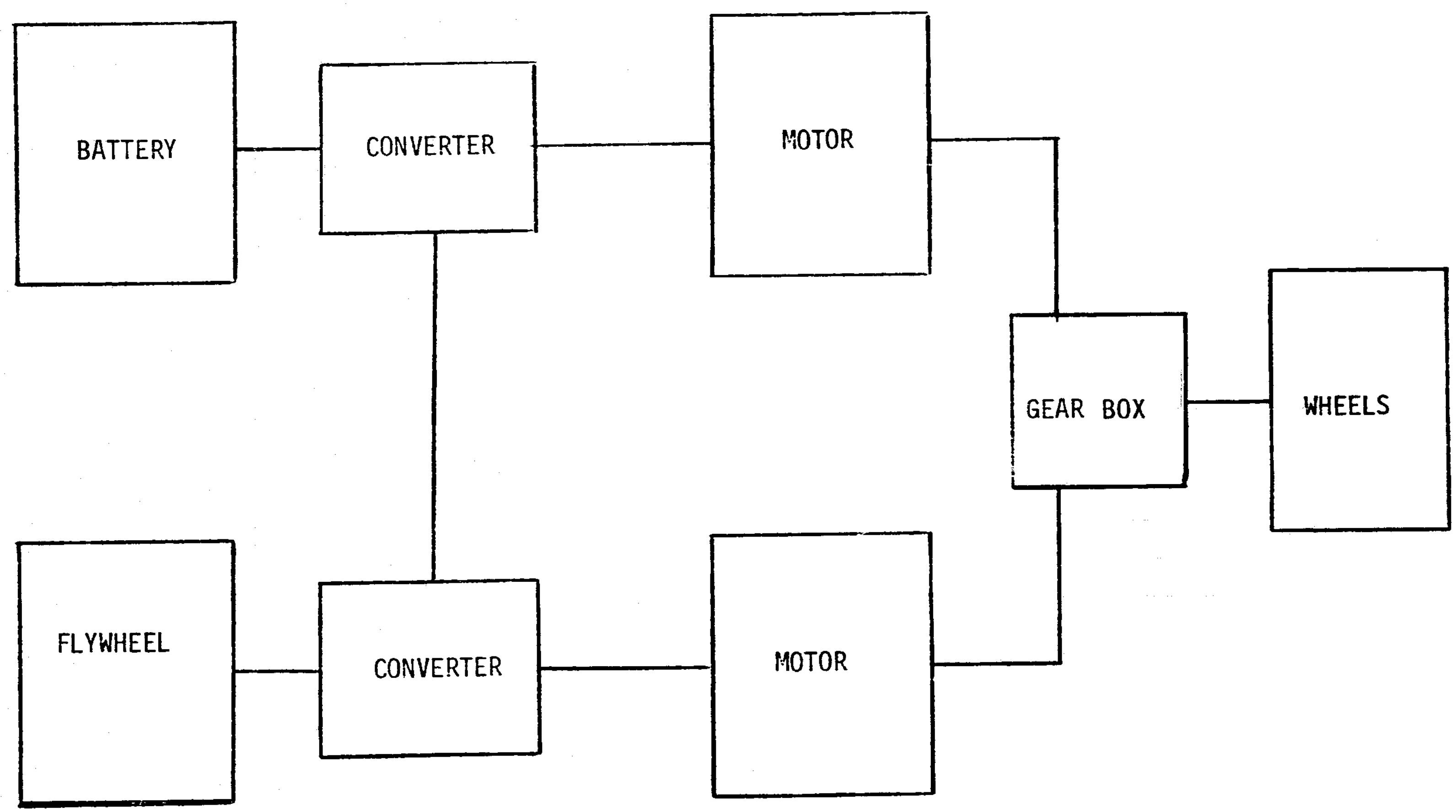


Figure 3. General Concept B

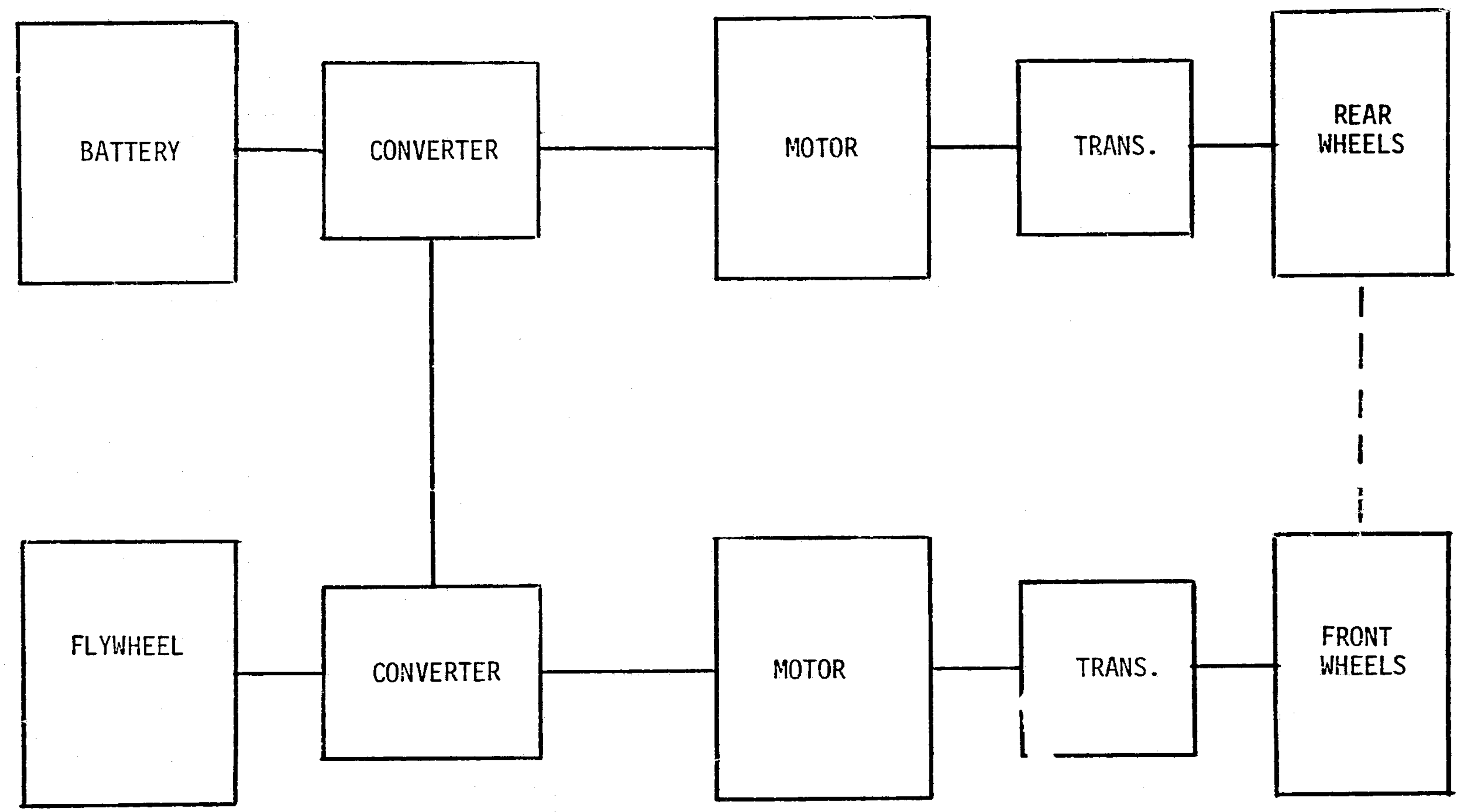


Figure 4. General Concept C

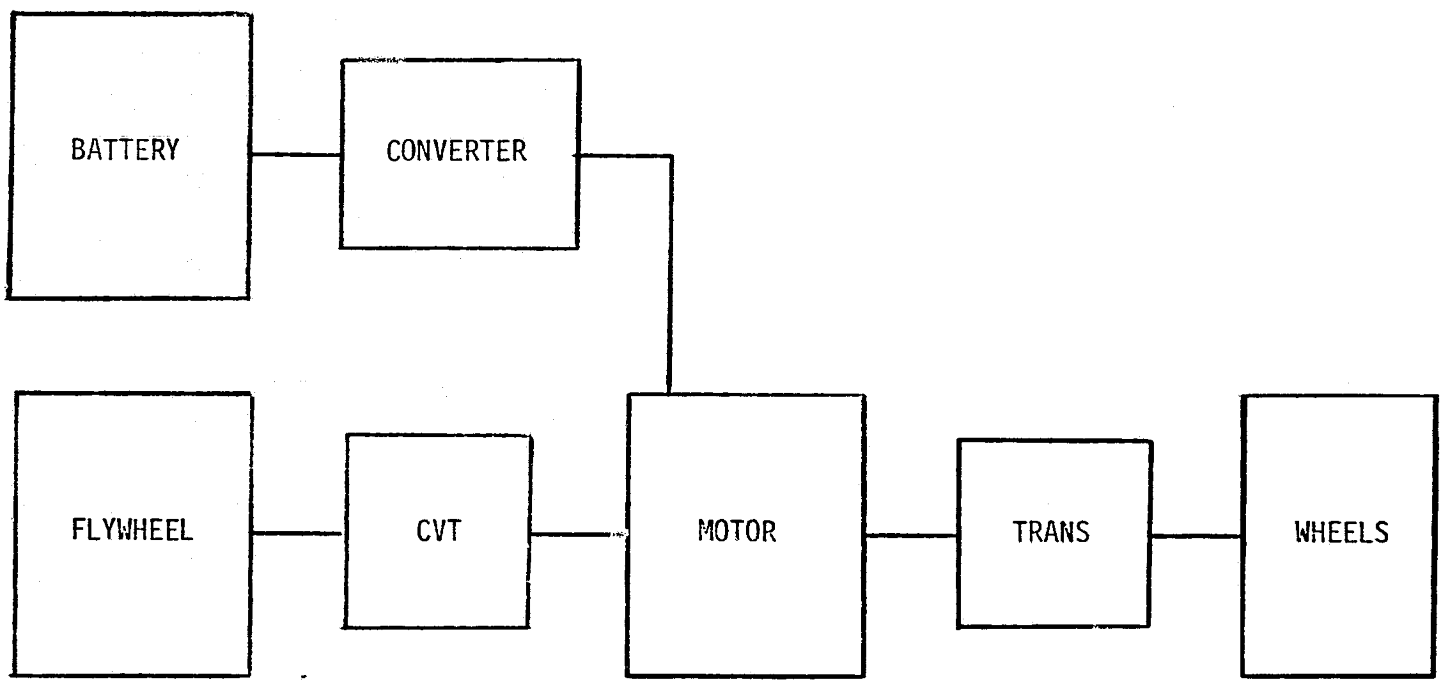


Figure 5. General Concept D

In general Concept A a single traction motor drives the vehicle with or without a transmission. Electrical energy for the traction motor comes from two sources, the battery and the flywheel storage system. The nature of the energy converters depends upon the type of traction motor used. The motor types considered for this general concept are three-phase ac induction motors and electronically commutated dc motors. The flywheel energy buffer consists of a flywheel coupled to a generator which converts the flywheel kinetic energy to electrical energy. To recharge the flywheel, the generator must run as a motor, thus, suitable motor types for coupling to the flywheel are those which can function both as a generator and as a motor over a wide speed range. Electronically commutated dc motors with field control appear to be most suitable for this purpose. The high speed of the flywheel drive motor requires a brushless design to minimize friction and run-down losses. Two types are considered for the preliminary analysis; one with permanent magnets for the field and the other with wound field coils. Permanent magnet motors are somewhat simpler than wound field machines and require no excitation current; however, the absence of controllable field coils limits the means of voltage control. The inability to weaken the field prevents the desirable reduction of eddy current and hysteresis losses during cruising and coasting periods where flywheel power is not required.

General Concept B differs from General Concept A primarily in having two traction motors. It seemed possible that two smaller electric motors could give better efficiency than a single larger motor because one could be turned off to eliminate some of the losses which lead to reduced efficiency at light loads. Two motors would be used for acceleration and braking and a single motor used during cruise and other light load conditions. As with General Concept A this general concept covers variations having different motor types, with and without multi-speed transmissions.

General Concept C employs two traction motors as does General Concept B, but uses two drive axles on the grounds that better recovery of energy via regenerative braking may be possible with this arrangement. This general concept also covers a range of motor types, with and without multi-speed transmissions.

General Concept D is similar to General Concept A in having a single traction motor, but instead of using an electrical conversion of flywheel kinetic energy a mechanical conversion utilizing a continuously variable transmission (CVT) is used. Torque output of the flywheel is directly related to the rate of change of the flywheel's angular momentum which can be controlled by the rate of change of the CVT speed ratio. For this concept to be practical requires a light-weight CVT with high efficiency. It is believed that such a device can be developed.

6.3 Characteristics of Traction Motors

The evaluation of the performance of any motor in a propulsion system is made in terms of its torque/speed characteristics and its losses.

Many different types of motors can be considered as possible traction motors for advanced electric propulsion systems. For such an application the motor should have high efficiency and be light weight and inexpensive. It should be easily controlled when used with batteries as the main source of energy.

Over the years, there has been a steady growth in the improvement of the design of electric motors to take advantage of technological advancements in high temperature insulation, precision bearings, improved lubricants and precision reduction gearing. The invention of commutating poles and improved brush materials has permitted the design of dc motors to nearly keep pace with other technological advancements; however, at the present time commutation problems limit the output of dc machines. The brushes and commutator bars can be an economic obstacle to development of a mass produced electric vehicle using dc motors. Electronic commutation of dc motors could be economical and could provide a breakthrough for higher speed and higher power-to-weight ratio.

Because of its ease of control the conventional shunt motor with field weakening is a popular choice for electric vehicles. It can be controlled over a fairly wide speed range using a chopper-type field current regulator to control the magnetic field. Weakening the field reduces the counter emf at a given speed to permit a greater armature current. The motor operates in essentially two regions as shown in Figure 6. At high speed (above the base speed), full voltage is applied to the armature windings, and power is controlled by regulating the field current. This is the field weakening region. At speeds below the base speed, the motor is incapable of generating adequate counter emf to permit operation with full voltage across the armature. In this region, armature current control is required. Armature current can be regulated by a semiconductor chopper switch which controls the on-off ratio. Figure 7 shows a simplified chopper circuit for control of armature current.(ref. 2) For field current control, the power levels are lower and a transistorized chopper would be used in the first analysis.

The torque/speed characteristics of the separately excited dc motor are calculated in the computer program using the basic relationships for the force on a conductor in a magnetic field and the voltage induced in a conductor moving through a magnetic field. Thus, the torque is directly proportional to the product of the armature current and the air gap flux. The air gap flux is that required to produce a counter emf equal to the applied voltage less the IR drop across the armature. This counter emf is directly proportional to the product of the motor speed and air gap flux.

A relationship is built into the program to calculate the air gap flux as a function of the field current using a typical reluctance circuit for a dc motor and a typical magnetic saturation curve for electrical grade iron. At motor speeds less than the base speed the field current is held at its maximum value which is set to give a magnetic flux high enough to slightly saturate the iron between the coil slots. At speeds above the base speed the field current is reduced and the flux falls along the curve calculated for the air gap, leakage flux and the magnetic properties of the iron.

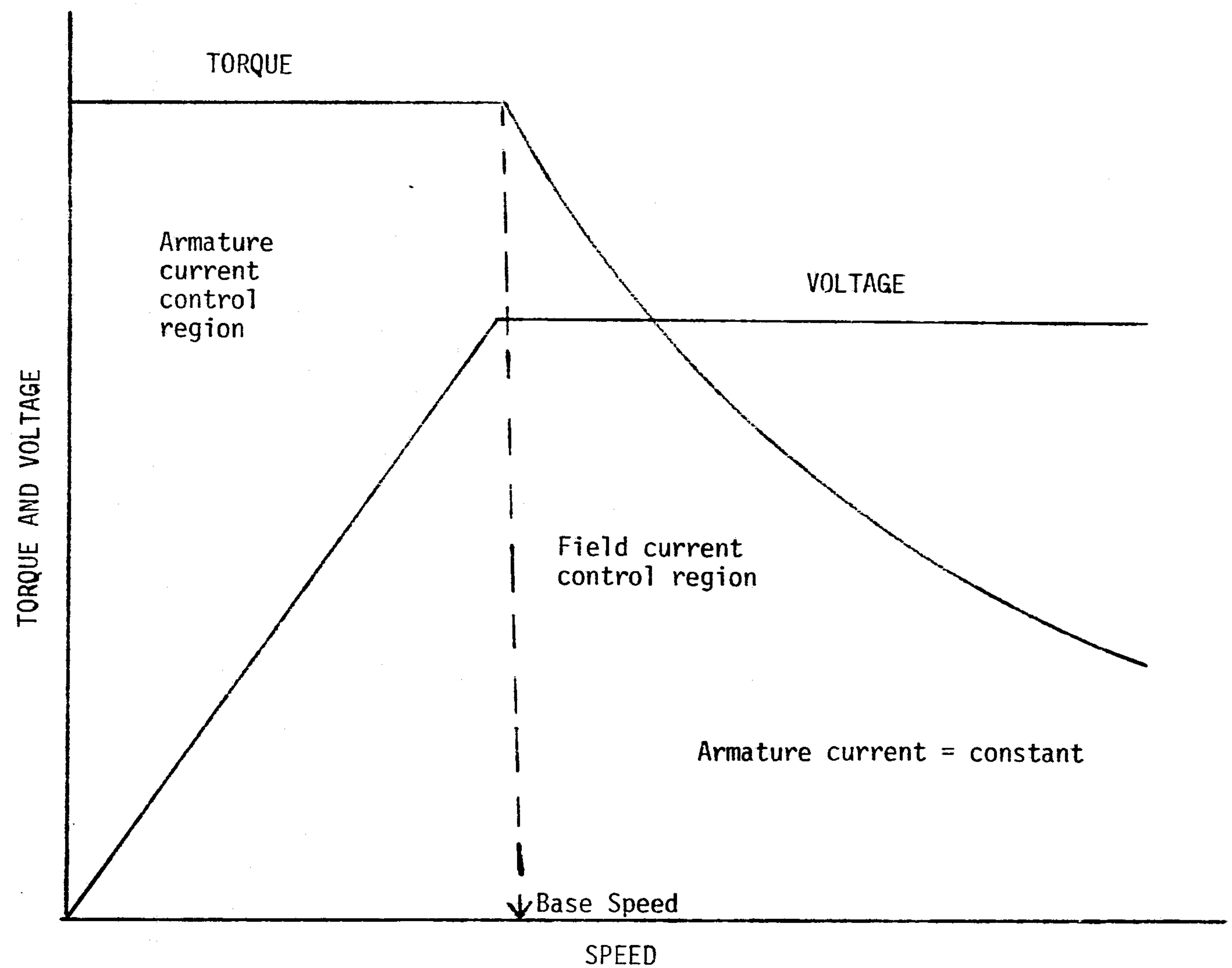
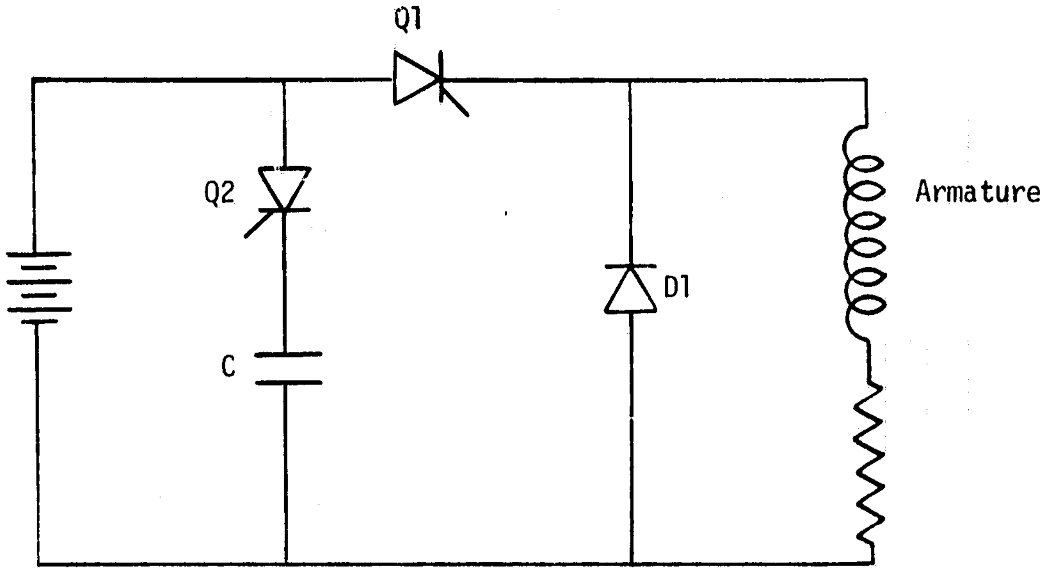


Figure 6. Torque-Speed Characteristics of Electric Motors



Q2 = commutating SCR
D1 = freewheeling diode
Q1 = main power switch
C = capacitor(is charged by external circuit not shown)

Figure 7. Chopper Circuit for DC Motors

The motor speed is determined from the vehicle speed and driveline gear ratios and tire size. Then the flux required for the counter emf is found as a first approximation ignoring the (IR) voltage drop across the armature. Then the required armature current to produce the desired motor torque with the set value of air gap flux is found. Using this armature current, an IR voltage drop is calculated to find a new counter emf and air gap flux. An iteration procedure converges very rapidly to the correct current and flux.

The identifiable losses used in the analysis are the following:

I^2R loss for the field
I^2R loss for the armature
Windage losses
Bearing friction
Eddy current losses
Hysteresis losses

These losses are set initially at percentages of the total losses at a design point and the appropriate values of resistances, drag coefficients, other loss coefficients are calculated from this point to permit subsequent calculation of losses at all other operating points. Using the specific rating of the motor at its design point, power and efficiencies over a wide range of operating points have been calculated. Figure 8 shows characteristics of a dc motor calculated by the program listed in Appendix E. Motor efficiency and current are shown as functions of motor output power with speed as a parameter. At speeds over 2200 rpm, field weakening is used to control power output.

The usual alternative to the dc traction motor is the three-phase ac induction motor. Using the squirrel cage construction, this is a rugged motor capable of mass production with relatively low cost, light weight and high efficiency. Operation of an ac motor from a dc energy source such as a battery requires a dc to ac inverter which can be an expensive item. Achieving regeneration with an induction motor can be difficult with a dc to ac conversion system as it must be a two-way converter (i.e. a rectifier as well as an inverter) and it must maintain the ac current to sustain the air gap magnetic flux.

In terms of the air gap magnetic flux the induction motor and separately excited dc motor are quite similar and thus the torque/speed characteristics are much alike. At speeds below the base speed both motors operate with maximum magnetic flux and above the base speed the flux is steadily reduced. In the case of the dc motor above its base speed, the field current regulator achieved the function. For the induction motor, the inductance of the magnetizing circuit is such that varying the voltage to the motor in proportion to the frequency when operating below the base speed achieves the desired maximum flux. Keeping the voltage constant with respect to frequency when operating above the base speed achieves the steady reduction in flux.

Because the two motor types are magnetically quite similar, the torque capacity and weights are potentially the same. The efficiencies are also potentially the same. The main differences are power factor, torque angle, controllability and operating ease as a generator.

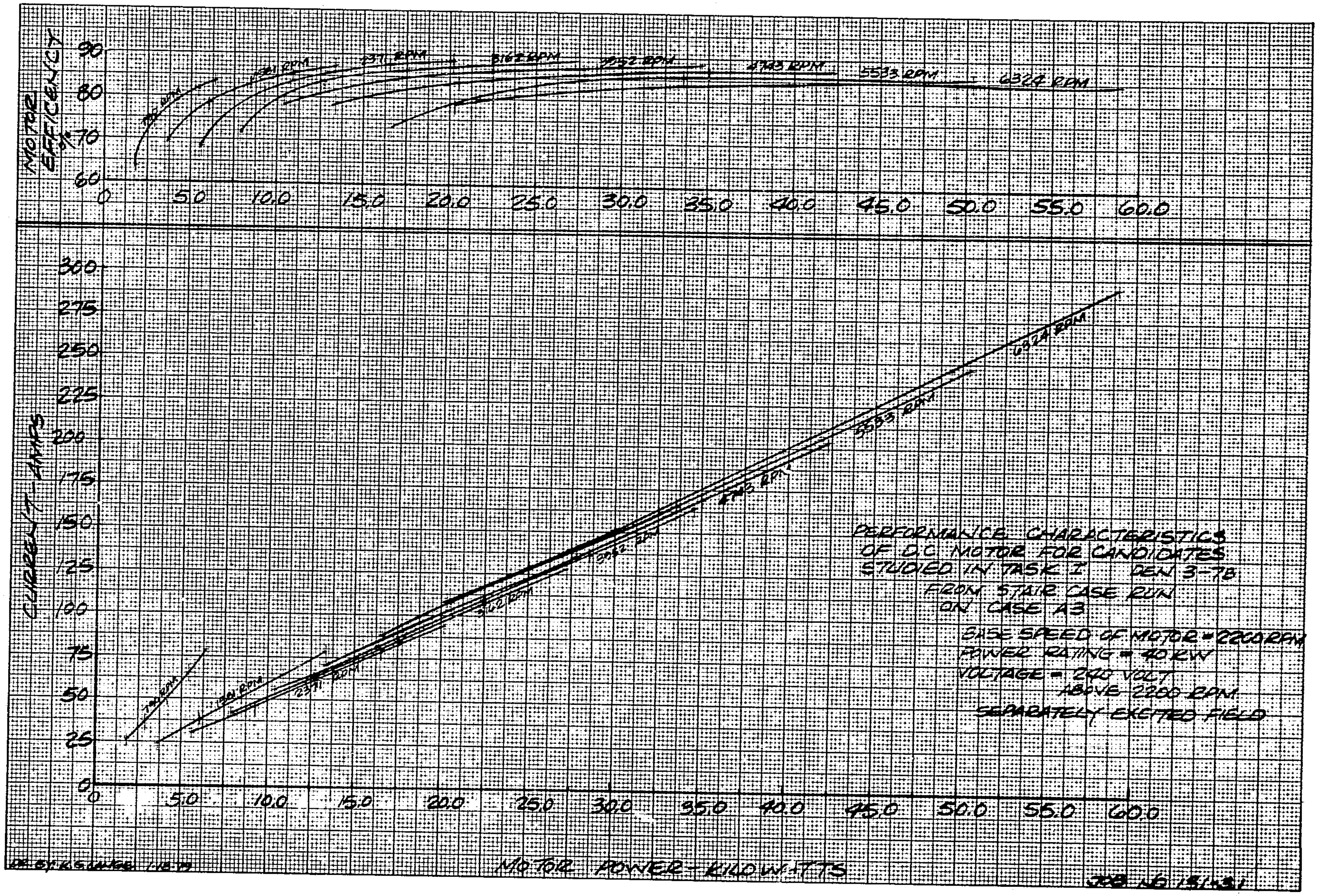


Figure 8. Performance Characteristics of DC Motor

The torque/speed characteristics of the three-phase induction motor are calculated in the computer program using the equivalent circuit (ref. 3) shown in Figure 9. The circuit is for one leg of a three phase motor. The value E_1 is the voltage across one leg and is equal to the line-to-line voltage for a delta connection or to $\frac{1}{\sqrt{3}}$ times the line to line voltage for a wye connection. The value R_1 is the resistance of the stator windings. The value R_2 is the rotor resistance referred to the stator and R_3 is an equivalent resistance associated with core losses. The values for the inductances and resistances are calculated for hypothetical motor using the desired motor characteristics at a design point. At this design point, the motor rated power, speed, slip, efficiency and power factor are used in conjunction with a hypothetical distribution of identifiable losses to permit the calculation of the circle diagram (ref. 3) of Figure 10 and all the circuit constants for the equivalent circuit.

The value of the resistance R_1 is set to give the I^2R losses of the stator at rated power. The value for R_2 is set for the I^2R losses of the rotor and the value for R_3 to give the total eddy current and hysteresis losses.

The inductances X_1 and X_2 are the leakage reactances and combined with the magnetizing (transformer) reactance X_3 to satisfy the specified power factor. An arbitrary power factor may be specified; however, excessively high power factor (say over 88 percent) will give leakage reactances which are unrealistically low. With reasonable air gap dimension leakage reactances less than four percent of X_3 will be unlikely.

A very low value of R_2 will result in a motor with low slip and good efficiency; however, very low values of R_2 yield motor designs with excessive starting current. For an industrial motor operated at a fixed frequency, good starting is very important. For an automotive motor operated from a variable frequency inverter, good starting torque is much less important and the higher efficiency of a low slip motor is very desirable.

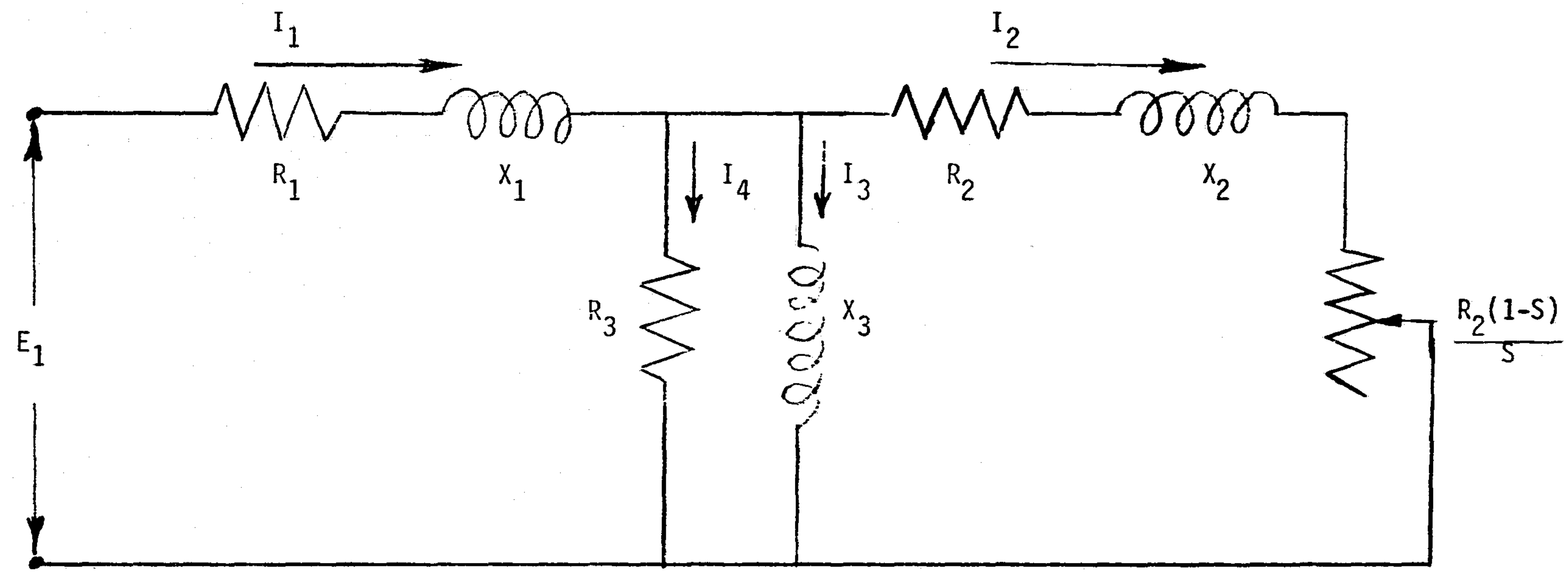
The torque of an induction motor is dependent upon slip and voltage and can be found from the values of the equivalent circuit elements as follows:

$$T = \frac{K\,E_1^2 R_2}{S\left[\left(R_1 + \frac{R_2}{S}\right)^2 + (X_1 + X_2)^2\right]}$$

where K is a constant if saturation of the core is neglected.

A plot of torque as a function of slip is shown in Figure 11.

A special subroutine was written to calculate the characteristics of three-phase induction motors based on design parameters at rated power and speed. The design parameters included slip at rated power, power factor, efficiency and the distribution of losses. The characteristics of a typical motor calculated by this subroutine is shown in Figure 12.



S	=	Slip	
E_1	=	Phase voltage	V/phase
I_1	=	Stator current	A/phase
I_2	=	Rotor current	A/phase
I_M	=	$I_4 + I_3$ = Exciting current	A/phase
R_1	=	Stator resistance	Ω/phase
R_2	=	Rotor resistance	Ω/phase
R_3	=	Iron loss equivalent resistance	Ω/phase
X_1	=	Stator leakage reactance	Ω/phase
X_2	=	Rotor leakage reactance	Ω/phase
X_3	=	Magnetizing reactance	Ω/phase

Figure 9. Equivalent Circuit of Induction Motor

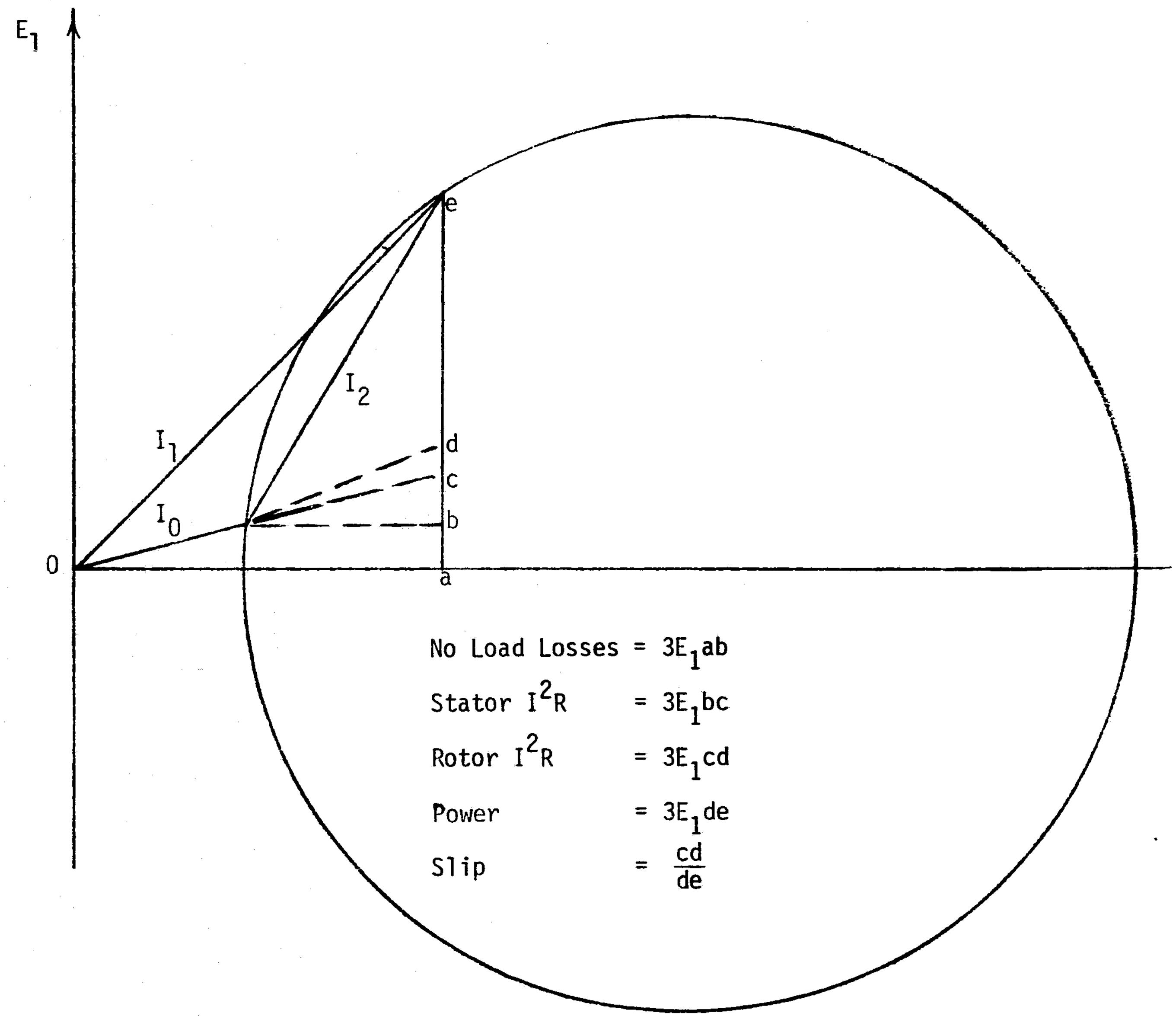


Figure 10. Circle Diagram for Induction Motor

Data for this plot was generated by computer program listed in Appendix E. Slip = 4.0%

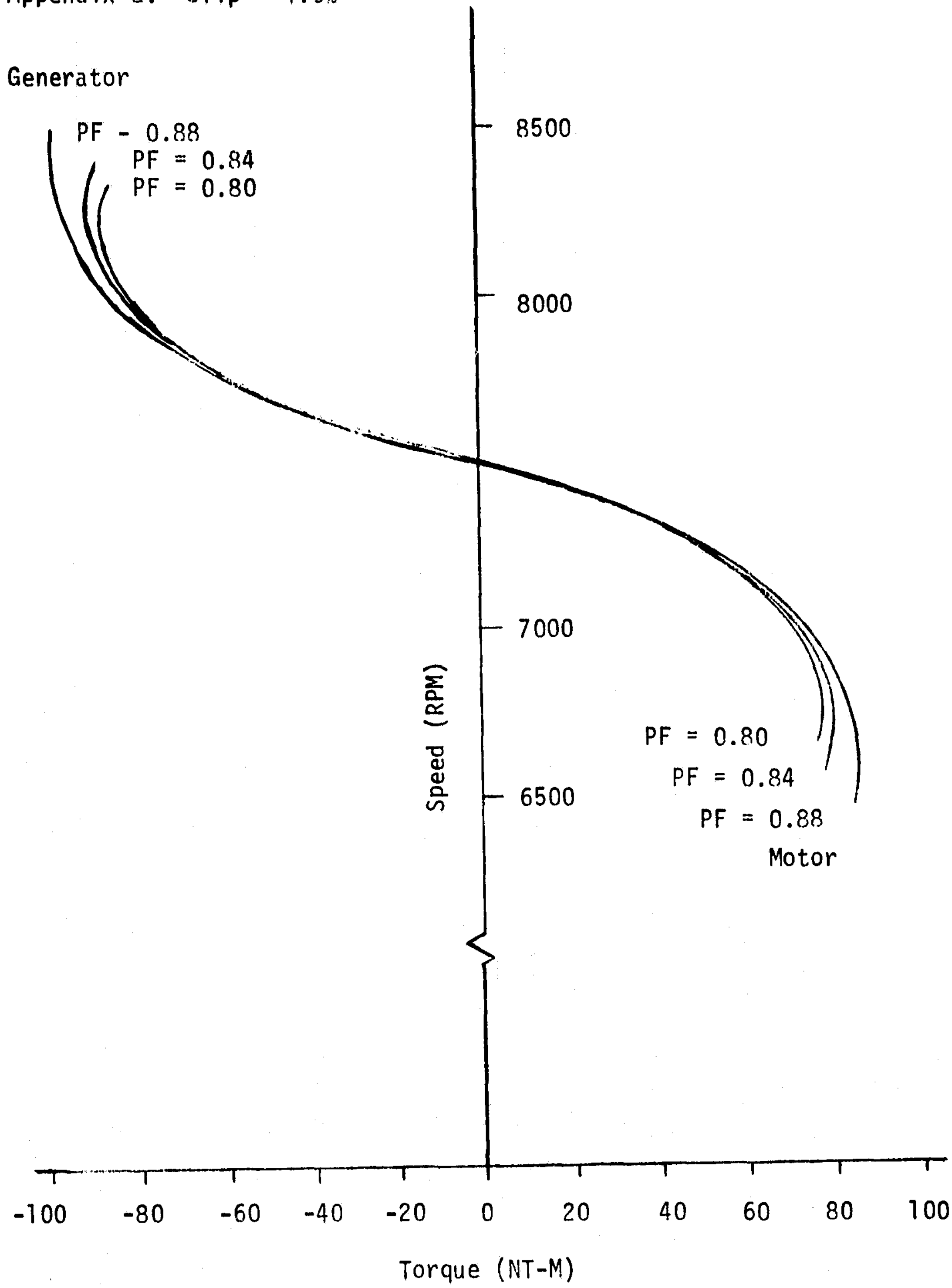


Figure 11. Torque vs. Speed at Various Power Factors

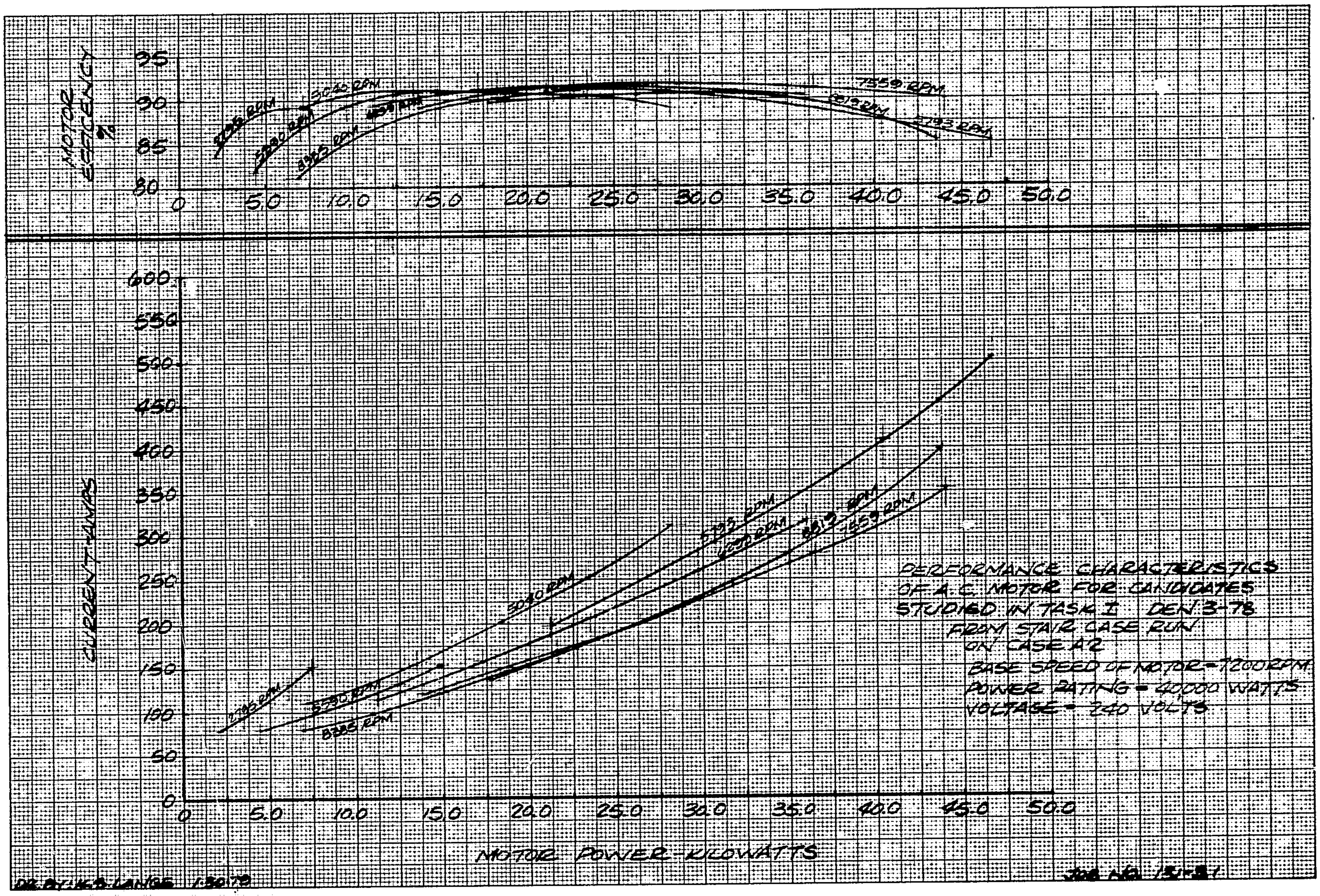


Figure 12. Performance Characteristics of AC Motor

6.4 Characteristics of Controllers

The most appropriate controller for a given motor type depends not only upon the motor type but also upon the operating conditions for the motor. For an advanced propulsion system it seems obvious that regenerative braking is necessary. When the motor is operated below its base speed, it will not be able to generate a counter emf greater than the battery voltage. Effective regeneration will require some means of voltage boosting unless the motor speed can be kept above its base speed either by using a motor with a low base speed or by continuously shifting gears to keep the motor speed high. The continual shifting of gears is awkward and is an undesirable way to achieve regeneration. Reducing the base speed of the motor may result in an unnecessarily large and heavy motor.

Voltage boosting can be accomplished with a dc motor by use of a suitable chopper controlled voltage booster in the armature circuit. Figure 13 shows such a chopper controlled booster. Armature current flowing when chopper switch Q2 is closed builds up a flux in the inductance of the armature circuit. The decay of this flux when Q2 is turned off forces the current to flow to the battery through the diode D2. The inductance of the circuit must be high enough to sustain the current through D2 and to prevent excessive current through Q2. The amount of inductance required depends upon the chopper frequency. The higher the frequency the smaller the inductance. The chopper switch Q2 can be a SCR for a chopper frequency of 400 Hertz or less. Frequencies over 1 kHz will require transistor switches.

For an electronically commutated dc motor, an electronic switching circuit is required. This circuit must switch the polarity of the armature coils in phase with the rotor and at a frequency dependent upon the rotor speed times the number of poles. The number of armature circuits to be switched can be selected to give smooth motor torque and low current ripple. Three armature circuits would require a switching circuit similar to a three-phase inverter except that the turn-on and turn-off times are tied to the rotor shaft position. Increasing the armature circuits to more than three would increase the number of semiconductor switches required while at the same time decreasing the current carried per switch. The choice of how many circuits would depend upon the current ratings and costs of transistor switches.

A simplified commutation circuit for an electronically commutated motor with seven armature circuits is shown in Figure 14. In this circuit, the switching elements are shown as SCRs. If high chopping frequencies for current control and voltage boosting are superimposed upon the switching for commutation, the SCRs would probably have to be replaced by transistors.

For a three-phase induction motor, a dc to three-phase ac inverter is required. The output frequency must vary as the motor speeds up or slows down in order to maintain a desired amount of slip. The power factor of the load can vary substantially so the inverter must be capable of driving a highly inductive load.

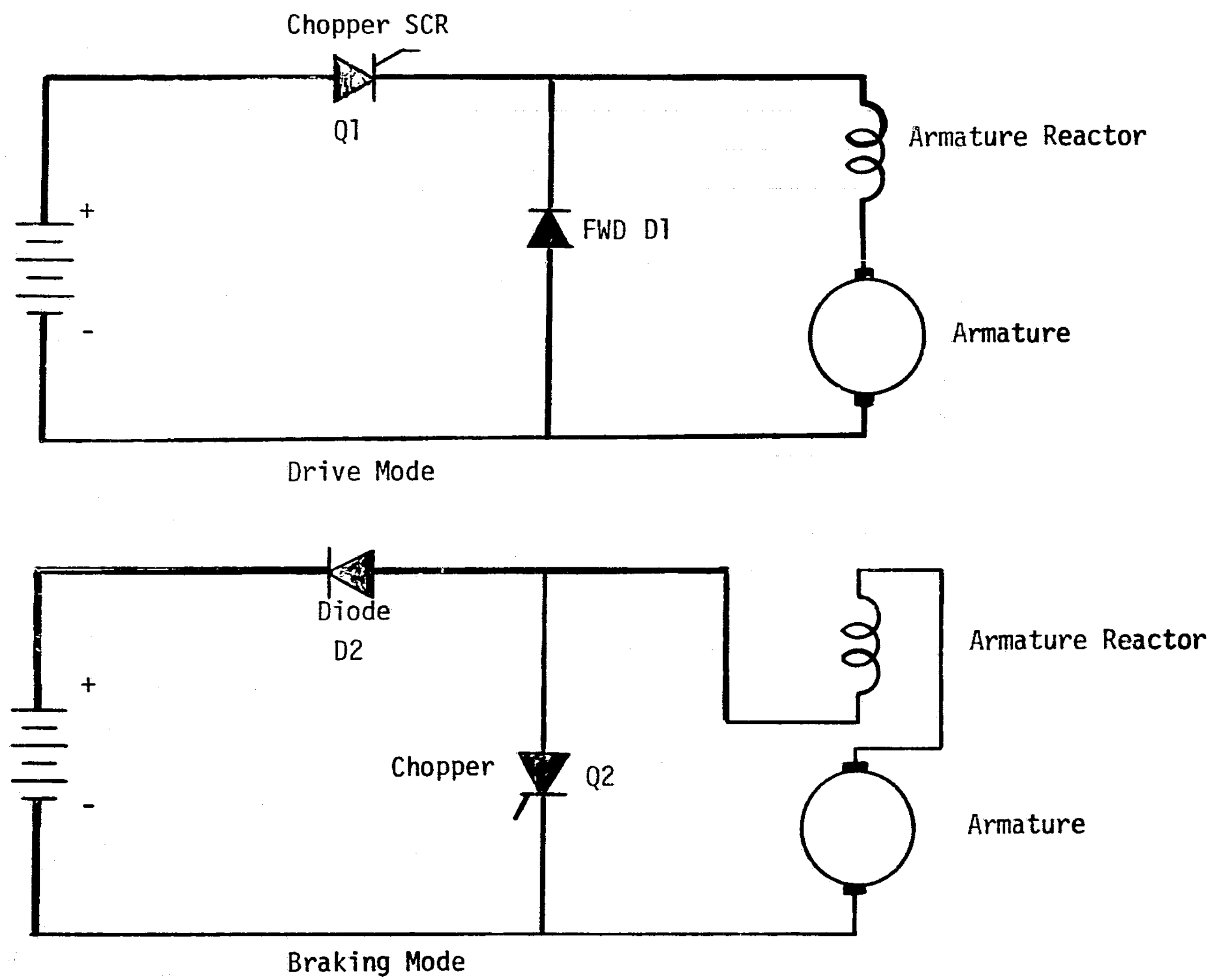


Figure 13. Simplified Chopper Circuit for dc Motor with Regeneration Capability

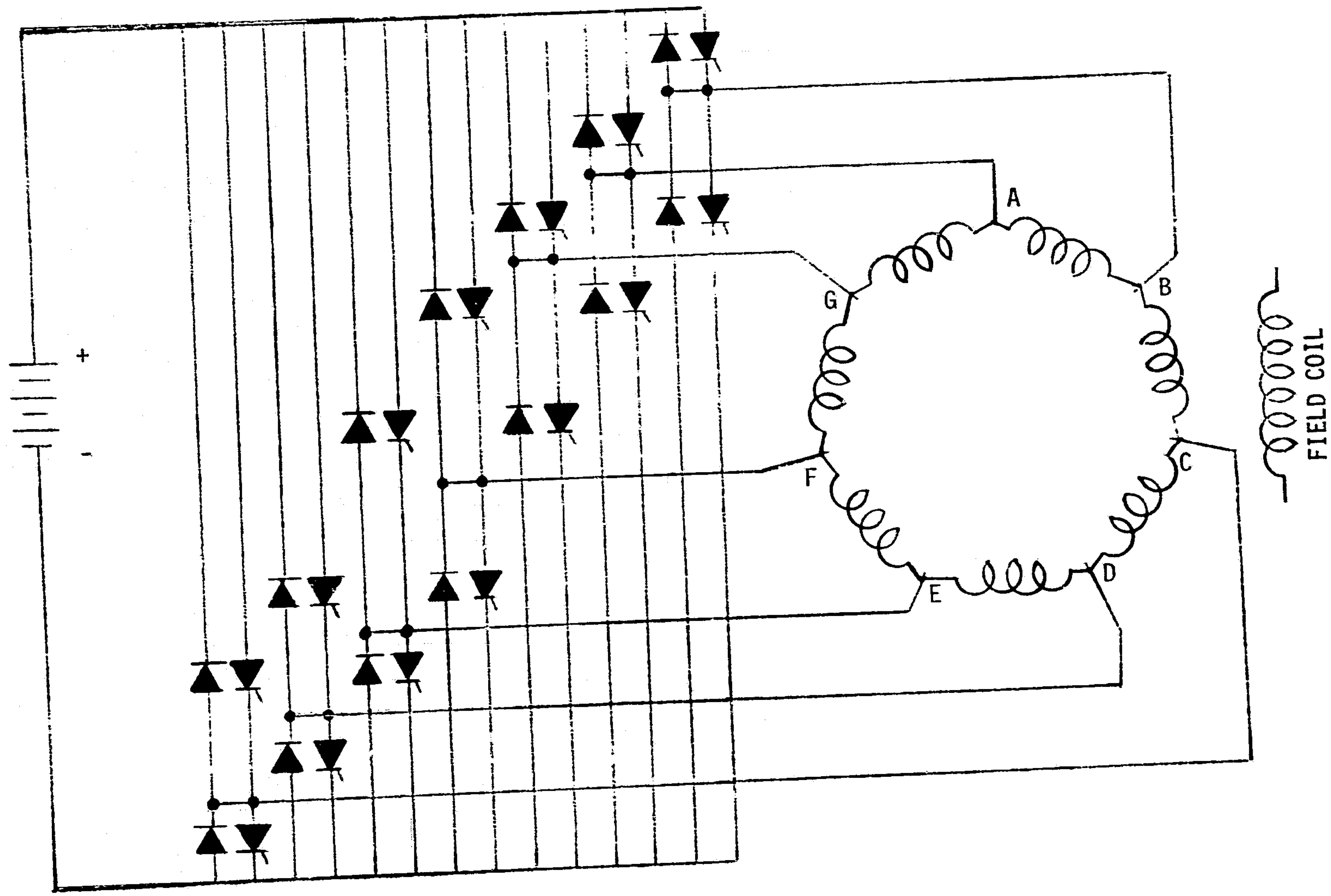


Figure 14. Electronically Commutated DC Motor
Seven Coils Per Pole Pair - 14 Thyristors and 14 Diodes

Above the base speed of the motor, the inverter output voltage is limited by battery voltage. At speeds less than the base speed, the voltage should increase linearly with frequency to insure maximum air gap flux. A chopper switch for the armature current used with a voltage feedback loop can provide voltage control.

Voltage boost for regeneration can be achieved with difficulty in a similar way to that used with a dc motor providing that the current required for air gap flux can be maintained and the frequency for a desired negative slip can also be maintained.

The control circuits for the electronically commutated dc motor and the three-phase induction motor shown in Figure 15 are very similar in terms of the number and types of semiconductor elements used. The main difference is the manner of maintaining rotor current and its effect on air gap flux and motor control. For the electronically commutated dc motor, rotor current is directly controlled to assure air gap flux. A separate field excitation control unit is used to maintain and control the rotor current. Slip rings may be used or a brushless inductor design may be used. For the induction motor the rotor current is produced by transformer action due to the ac current in the stator inducing an ac voltage in the rotor. The induced rotor voltage goes to zero for zero slip or for zero current in the stator. The condition of zero voltage at zero current for the induction motor is similar to the condition encountered in a series wound dc motor. For the series motor to maintain stability as a generator, it is common to use a diverting chopper circuit to control the field current independent of the current returned to the battery. A similar mode of separating the current for field magnetization from that returned to the battery is required when operating the induction motor as a generator. One way of viewing the control of the induction motor is to consider the out-of-phase current component as the magnetizing (or field current) and the in-phase component as the power producing current. Then essentially the controller by use of slip control and current control endeavors to control both the in-phase and out-of-phase current. The total current in the semiconductor elements for a given power is thus somewhat higher for an induction motor than for an electronically commutated motor as it must handle both the in-phase and the out-of-phase current.

The computer modeling for the controller characterizes the losses in terms of three parameters. There is a fixed loss. A loss associated with a fixed voltage drop across the semiconductors and there is a loss proportional to the square of the current. The loss factors for these parameters are adjusted for the type of controller to be consistent with the rating of the semiconductor elements and normalized in terms of input current.

6.5 Characteristics of CVTs

The use of a CVT to extract energy from a flywheel in a smooth controlled manner requires a smooth and continuous variation in the speed ratio of the CVT. A variety of CVT types can provide such continuous changes in speed ratio, but additional constraints on the CVT for use in an advanced

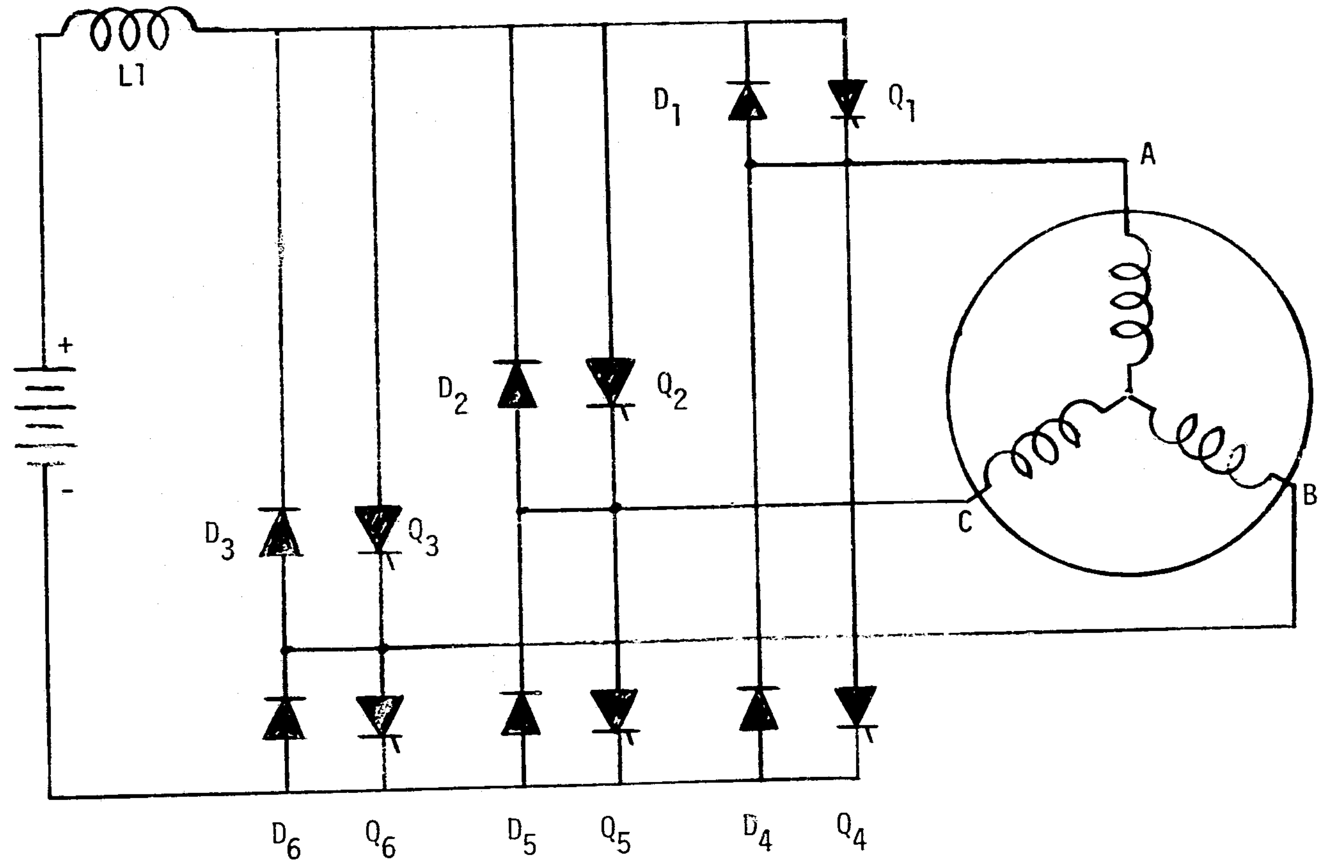


Figure 15. Inverter for 3-phase Induction Motor

propulsion system are light weight and high efficiency. (refs. 4,5) Hydraulic type CVTs appear to have poor efficiencies at light load although they can have very acceptable efficiencies at high loads. Conventional belt type units appear to have inadequate power capacity, poor life and excessive losses (ref. 6). New (refs. 7,8,9) traction type devices seem to hold promise; however, much development work will be required to perfect a unit for use with a high speed flywheel. If the unit were developed for the high speed and low torque at the flywheel shaft it could be fairly small.

For the preliminary analysis it was assumed that a light-weight high-speed traction-type device could be developed. If such a unit were developed it would have to have good efficiency in order to also have good durability. Traction devices with poor efficiency have excessive wear. Good efficiency and good life go hand-in-hand.

It was assumed that the losses for a traction type CVT could be expressed in terms of slippage, windage drag and spin torque. The slippage results in a loss of speed so that the output speed is slightly less than the theoretical or ideal output speed. The difference in speed is expressed as a percent creep and is believed to be a function of transmitted torque as shown in Figure 16.

The actual torque transmitted will be less than the ideal torque because of losses due to the nature of the traction geometry. The ideal geometry for the traction contact will be pure rolling (ignoring the slip mentioned above); however, the actual contact zone in a traction device is an area that is enlarged by elastic deformation of the material in contact. Within this zone there may be a variation from pure rolling which may be termed spinning, and thus the loss is called spin torque. An example of high spin torque is a front tire with excessive toe-in. A good design is one which minimizes spin torque. Figure 17 shows the relationship of torque loss due to spin torque.

The windage drag used in the analysis is essentially a viscous drag torque. This torque loss is a linear function of speed.

The values of spin torque, creep and viscous drag were chosen to give a CVT efficiency similar to values measured by others. (ref. 10)

6.6 Characteristics of Flywheels

The flywheel for use in an energy storage unit should be light weight, have low losses, low volume and minimum adverse effects upon vehicle performance. Recent development in high-specific energy flywheels (ref. 11) using high-strength fiber-composite material indicate that such materials have good promise, and moreover indicate that suitable flywheels can be developed in the desired time frame. (ref. 12)

For a given amount of available energy a high-specific strength fiber-composite flywheel will be lighter weight and less expensive than high-strength steel flywheels. (refs. 13,14)

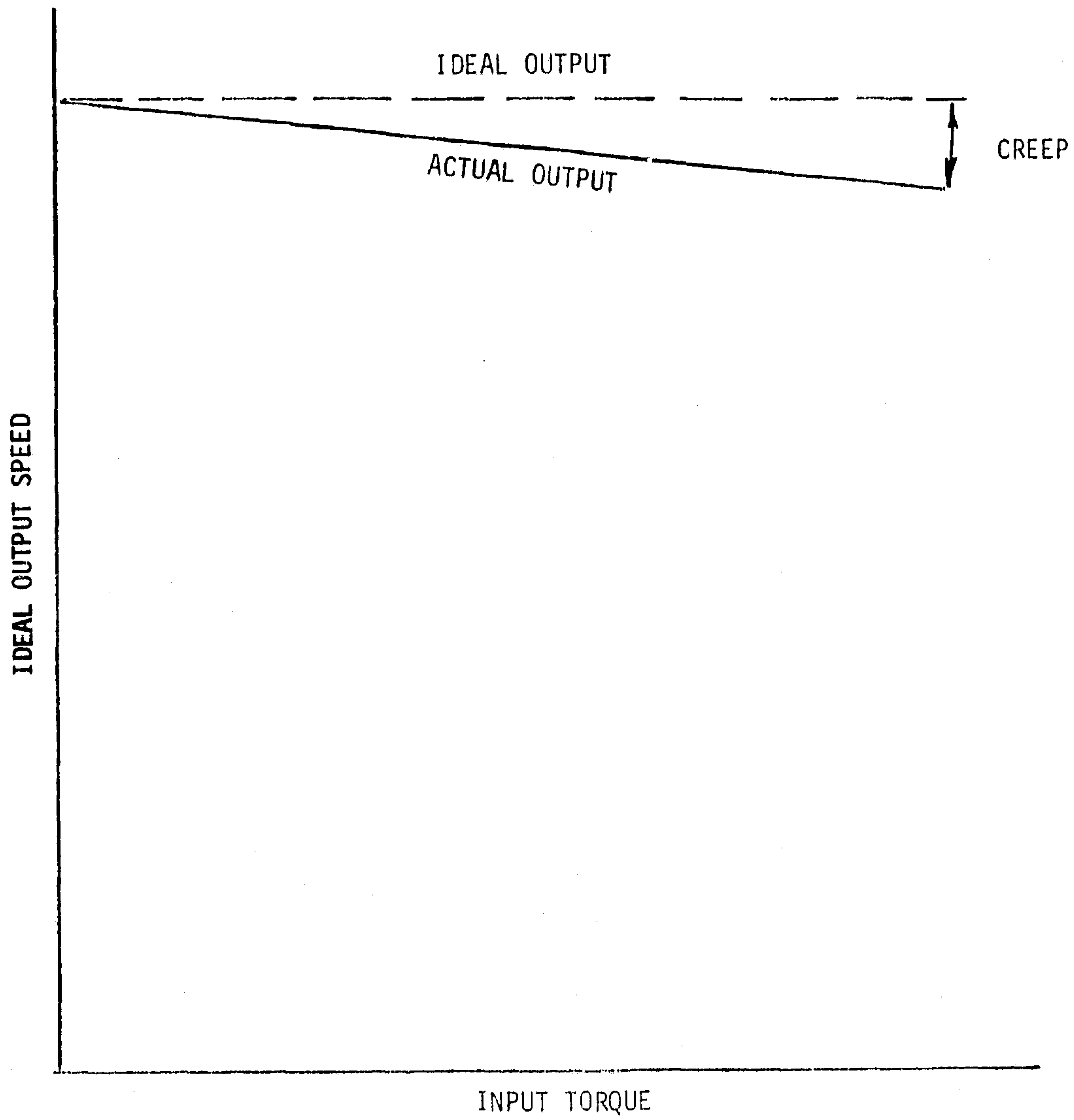


Figure 16. Velocity Loss Due to Creep

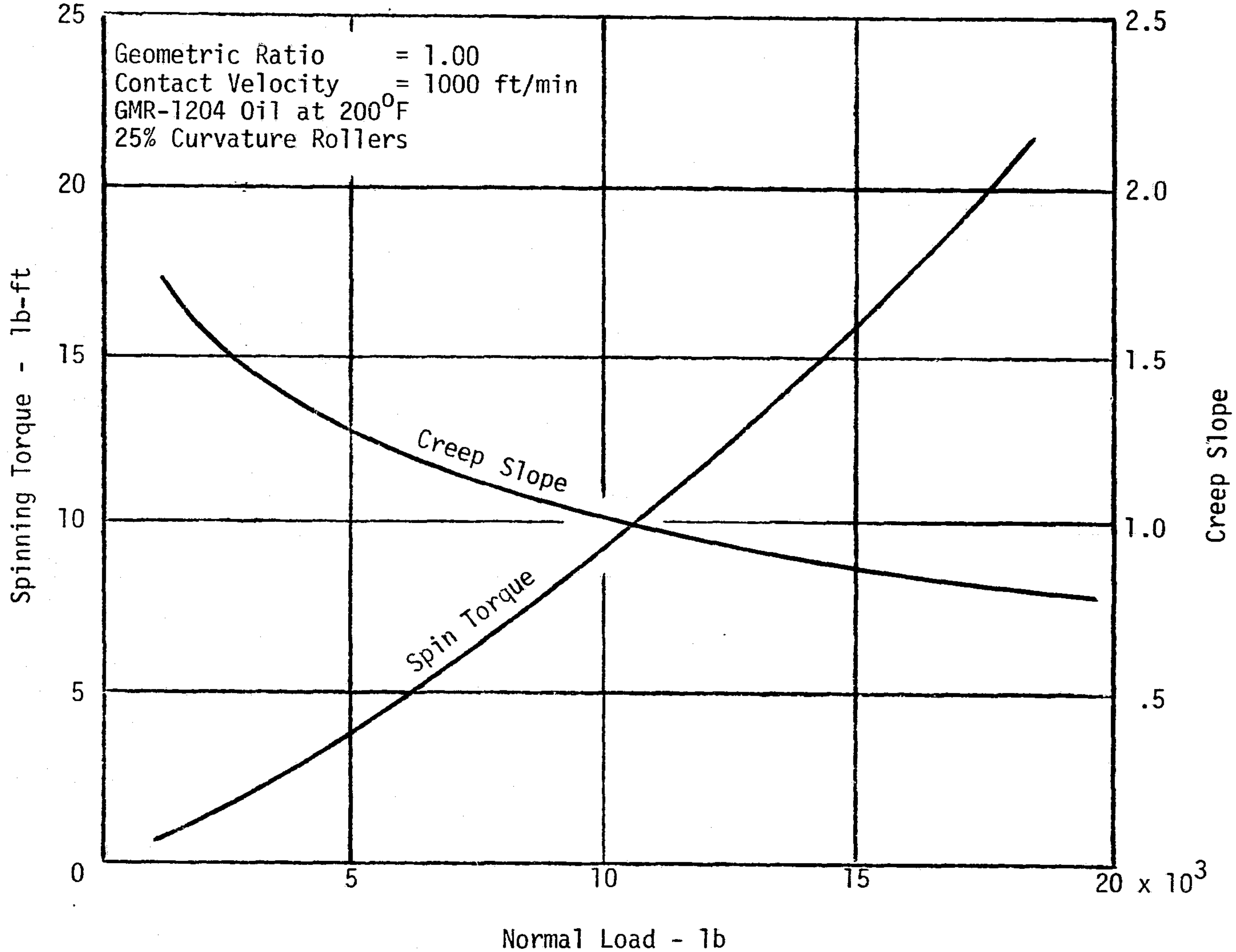


Figure 17. Effect of Normal Load on Spinning Torque and Creep Slope (ref. 10)

The specific energy is proportional to the strength-to-weight ratio of the material. Thus, high-strength and low-weight materials can yield high-specific strength. The relationship for kinetic energy-to-weight ratio is as follows:

$$\frac{KE}{WT} = K \frac{\sigma}{\rho}$$

where KE = Kinetic Energy
WT = Weight
K = Constant; depends upon shape
σ = Stress
ρ = Density

Less obvious but very important is the fact that the fiber-composite flywheel has much less angular momentum and is thus safer and has less gyroscopic moment than a steel flywheel.*

The stored energy in a flywheel is given as follows:

$$KE = \frac{1}{2} I \omega^2$$

where I = Moment of inertia
ω = Angular velocity

And the momentum is given as follows:

$$M = I\omega$$

Thus in terms of maximum rated energy the maximum momentum* may be expressed as:

$$M = \frac{2(KE)_{rated}}{\omega}$$

The total amount of energy required for the flywheel depends upon the driving conditions to be satisfied. If the vehicle is to be driven over the SAE J227a Schedule D exclusively and always over a level course, a minimum amount of energy could be approximated by examining the maximum kinetic energy of the vehicle. However, any practical vehicle must be able to drive a multitude of courses and operate on upgrades and downgrades.

A way of analyzing the energy storage requirement is to consider the vehicle operating at a point where it has a set value of flywheel energy which permits the vehicle to either accelerate or decelerate. The vehicle should be able to either go up a grade with some acceleration capability or to go down a grade with some regenerative braking capacity. Figure 18 shows an example of a set point for the flywheel and shows the energy capacity

*The angular momentum and gyroscopic moment of a fiber composite-flywheel is about 25% of that for a steel flywheel of the same energy.

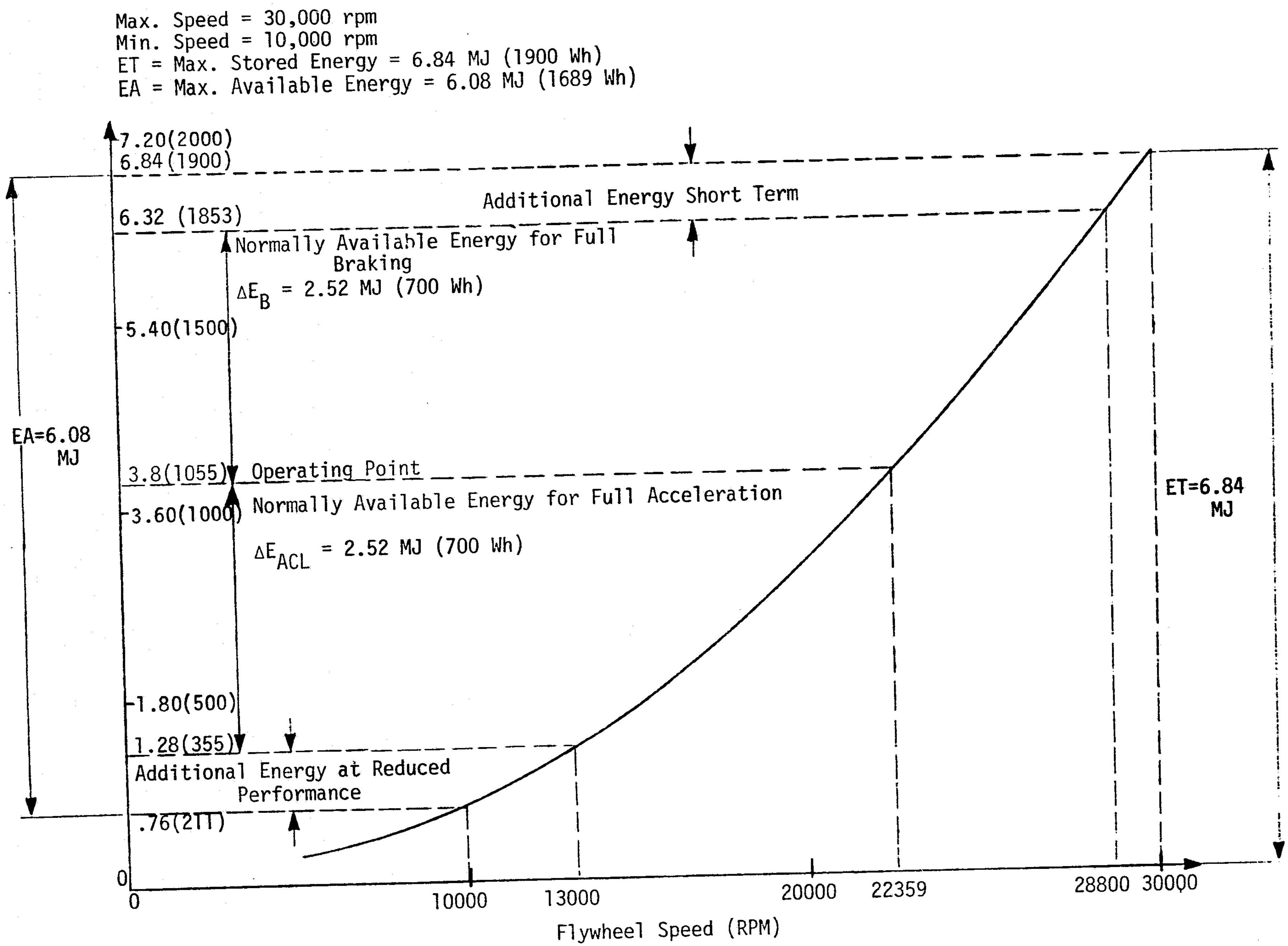


Figure 18. Flywheel Stored Energy vs. Flywheel Speed

for braking and for acceleration. The total available energy is approximately six times the minimum energy required for the SAE J227a Schedule D.

For the preliminary analysis, a uniform rate energy loss due to aerodynamic drag and bearing friction was assumed.

6.7 Characteristics of the Drivetrain Components

The drivetrain components of concern are the final drive gears (axle) and the multi-speed transmission. It was assumed that each of these units could be characterized by their gear ratios and by certain types of energy loss coefficients. Three types of energy losses were used for each unit. These losses were expressed as torque losses which were then calculated as energy losses by multiplying by rotational speed. The three torque losses were as follows:

a. Constant torque (example: bearing preload)
b. Loss proportional to applied torque (example: gear friction)
c. Loss proportional to speed (viscous drag)

The values of the coefficients for these losses were adjusted to give a reasonable loss at rated power. (ref. 6)

6.8 Performance Comparisons

The candidate propulsion systems are all compared on the basis of the same base weight and payload. Aerodynamic drag and tire rolling resistance coefficients are the same for each vehicle. The basic loss coefficients for the motors and controllers are also the same for the same type of device. The differences in configurations and motor types do lead to difference in the propulsion system weight and effective efficiencies. Differences in gear ratios are also required. The costs of different candidates will increase as weight and complications increase. The likelihood of successful development is different for the various candidates.

Table 5 lists some of the basic characteristics of the candidate propulsion systems. Candidates A1 through A8 have a single drive axle and a single traction motor. Candidates B1 through B8 have single drive axle and two traction motors. Candidates C1 through C8 have two drive axles and two traction motors. Candidates D1 through D4 have a single drive axle and a single traction motor.

Two types of flywheel drive motors are represented. The PM types have permanent magnets for field flux and the WF types have separately excited wound fields. The WF types use field control and the field can be shut off to reduce standby losses associated with eddy currents and hysteresis. Two traction motor types are represented in the candidates. The AC1 and AC2 types are three-phase induction motors specially designed for use in electric vehicles. The DC1 and DC2 types are separately-excited electronically-commutated dc motors specially designed for electric vehicles. The dc motors have a lower base speed than the ac motors so the axle gear ratios are different as shown in Table 5.

Table 5. CHARACTERISTICS OF CANDIATE PROPULSION SYSTEMS

CODE NO.	SYSTEM TYPE: TYPE	SYSTEM TYPE: MOTOR TYPE	SYSTEM TYPE: TRANS. TYPE	SYSTEM TYPE: MOTOR NO.	SYSTEM TYPE: AXLE NO.	VEHICLE PARAMETERS: BASE WT.	VEHICLE PARAMETERS: MAXIUM PAYLOAD	VEHICLE PARAMETERS: TEST LOAD	VEHICLE PARAMETERS: WEIGHT PROP. F.	VEHICLE PARAMETERS: AIR DR. C_dA	VEHICLE PARAMETERS: AIR DENS.	VEHICLE PARAMETERS: ROT. INER. F	TIRE FACTORS: RADIUS	TIRE FACTORS: ROLLING RESIST. COEF. a_0	TIRE FACTORS: ROLLING RESIST. COEF. a_1	TIRE FACTORS: ROLLING RESIST. COEF. a_2	DRIVE AXLE FACTORS: RATIO	DRIVE AXLE FACTORS: WEIGHT	DRIVE AXLE FACTORS: TORQUE	DRIVE AXLE FACTORS: COST FACTOR	DRIVE AXLE FACTORS: LOSS COEFFICIENT a_0	DRIVE AXLE FACTORS: LOSS COEFFICIENT a_1	DRIVE AXLE FACTORS: LOSS COEFFICIENT a_2
A1	PM	AC1	DIRECT	1	1	718.67	600	300	1.299	6.0	.00238	1.04	11.5	.008	1.097E-05	9.63E-08	7.933	96	250	1.50	.50	1.0E-04	.020
A2	PM	AC1	TRANS	1	1												7.266						
A3	PM	DC1	DIRECT	1	1												7.933						
A4	PM	DC1	TRANS	1	1												5.444						
A5	WF	AC1	DIRECT	1	1												7.933						
A6	WF	AC1	TRANS	1	1												7.266						
A7	WF	DC1	DIRECT	1	1												7.933						
A8	WF	DC1	TRANS	1	1												5.444						
B1	PM	AC2	DIRECT	2	1												7.933						
B2	PM	AC2	TRANS	2	1												7.266						
B3	PM	DC2	DIRECT	2	1												7.933						
B4	PM	DC2	TRANS	2	1												5.444						
B5	WF	AC2	DIRECT	2	1												7.933						
B6	WF	AC2	TRANS	2	1												7.266						
B7	WF	DC2	DIRECT	2	1												7.933						
B8	WF	DC2	TRANS	2	1												5.444	96					
C1	PM	AC2	DIRECT	2	2												7.933	144					
C2	PM	AC2	TRANS	2	2												7.266						
C3	PM	DC2	TRANS	2	2												5.444						
C4	PM	DC2	DIRECT	2	2												7.933						
C5	WF	AC2	DIRECT	2	2												7.933						
C6	WF	AC2	TRANS	2	2												7.266						
C7	WF	DC2	DIRECT	2	2												7.933						
C8	WF	DC2	TRANS	2	2												5.444	144					
D1	CVT	DC1	DIRECT	1	1												7.933	96					
D2	CVT	DC1	TRANS	1	1												5.444						
D3	CVT	AC1	DIRECT	1	1												7.933						
D4	CVT	AC1	TRANS	1	1	718.67	600	300	1.299	6.0	.00238	1.04	11.5	.008	1.097E-05	9.63E-08	7.266	96	250	1.50	.50	1.0E-04	.020

The traction motors and motor controller characteristics are summarized in Table 6. All motors and controllers were rated for a 240 volt dc system. The rated power is in watts. The specific weight is normalized to a base speed of 3600 rpm.

All motors were initially selected to give a total rated power of 40 kW. The main difference in the motors for the various candidates are the base speeds and resultant torque. The slower speed motors would have higher torque and greater weight. The motors for candidates without transmissions require greater torque to achieve acceptable performance.

The flywheel generator controller, battery, flywheel, and CVT characteristics and transmission factors are summarized in Tables 7 and 8. The three main characteristics for the preliminary analysis of the CVT for D1 through D4 are the loss factors. The spin torque is taken as four percent of rated torque and the creep is set at three percent at maximum torque. The viscous drag is set at two percent of rated torque at maximum speed. With these values the efficiency at rated torque and speed is about 91 percent.

The calculated performance of the candidates is summarized in Table 9. The test weight of the various candidates ranges from a low of 4097 pounds for D4 to a high of 4559 for C4. All candidates have adequate power to satisfy all the driving requirements. All would meet the range requirement of 100 miles if some small adjustment were made in battery weights. The range in the repeated SAE J227a Schedule D using 1600 pounds of batteries varied from a low of 91.8 miles to a high of 120.3 miles. Part of the difference in range is due to differences in energy consumed per mile and part is due to greater available energy from the battery as a consequence of load leveling the battery to permit greater energy extraction. The energy per mile* varied from a low of .55 MJ/km (248 Wh/mile) to a high of .68 MJ/km (304 Wh/mile). The range for a steady 72 km/h (45 mph) cruise varies from a low of 191 km (118.7 miles) to a high of 250.5 km (155.7 miles). Changing gear ratios and shift points can improve the range at 72 km/h (45 mph) but may have an adverse effect upon the performance and upon the range in a variable speed driving cycle.

6.9 Other Factors

This section is prepared to comply with clauses (2) and (3) of the contract requirements which read as follows:

> "The contractor's recommendation shall include supporting information that provides: (1) a summary of the physical and operating characteristics of the candidate systems (2) an appraisal of the advantages of one versus the other and (3) a summary of component and system technology advancements required."

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*This is energy from the battery. To obtain wall plug energy, the recharger efficiency and battery efficiency must be considered.

Table 6. CHARACTERISTICS OF CANDIDATE PROPULSION SYSTEMS

CODE NO.	DRIVE MOTOR FACTORS: RATED POWER	BASE SPEED	MAX SPEED	OVERLOAD %	RATED VOLTS	RATED AMPS.	SPEC. WEIGHT	FL LOAD EFF.	I^2R %	HYST. %	EDDY %	FRICT. %	WINDAGE %	FREQ	COST FACT.	POWER FACT.	MOTOR CONTROLLER: POWER	VOLT	AMPS	WEIGHT	MOTOR CONTROLLER a_0	a_1	a_2
A 1	40,000	2200	7800	200	238	203	.005	91	67	5	10	9	9	110	4	.84	45,000	238	406	.54	82	2.5	.004
A 2		7200	9000			194	.005	91			10	9	9	240	4	.84			388		82		.004
A 3		2200	7800			212	.0055	90.4			8	13	7	110	4.5	—			424		60		.003
A 4		5400	7800			207	.0055	90.4			8	13	7	180	4.5	—			414		60		.003
A 5		2200	7800			203	.005	91			10	9	9	110	4	.84			406		82		.004
A 6		7200	9000			194	.005	91			10	9	9	240	4	.84			388		82		.004
A 7		2200	7800			212	.0055	90.4			8	13	7	110	4.5	—			424		60		.003
A 8		5400	7800			207	.0055	90.4			8	13	7	180	4.5	—			414		60		.003
B 1		2200	7800			203	.0063	90.4			10	9	9	110	4	.84			406		82		.004
B 2		7200	9000			194	.0063	91			10	9	9	240	4	.84			388		82		.004
B 3		2200	7800			212	.0069	90.4			8	13	7	110	4.5	—			424		60		.003
B 4		5400	7600			207	.0069	90.4			8	13	7	180	4.5	—			414		60		.003
B5		2200	7800			203	.0063	91			10	9	9	110	4	.84			406		82		.004
B6		7200	9000			194	.0063	91			10	9	9	240	4	.84			388		82		.004
B7		2200	7800			212	.0069	90.4			8	13	7	110	4.5	—			424		60		.003
B8		5400	7800			207	.0069	90.4			8	13	7	180	4.5	—			414		60		.003
C1		2200	7800			203	.0063	91			10	9	9	110	4	.84			406		82		.004
C2		7200	9000			194	.0063	91			10	9	9	240	4	.84			388		82		.004
C3		5400	7800			207	.0069	90.4			8	13	7	180	4.5	—			424		60		.003
C4		2200	7800			212	.0069	90.4			8	13	7	110	4.5	—			414		60		.003
C5		2200	7800			203	.0063	91			10	9	9	110	4	.84			406		82		.004
C6		7200	9000			194	.0063	91			10	9	9	240	4	.84			388		82		.004
C7		2200	7800			212	.0069	90.4			8	13	7	110	4.5	—			424		60		.003
C8		5400	7800			207	.0069	90.4			8	13	7	180	4.5	—			414		60		.003
D1		2200	7800			212	.0055	90.4			8	13	7	110	4.5	—			424		60		.003
D2		5400	7800			207	.0055	90.4			8	13	7	180	4.5	—			414		60		.003
D3		2200	7800			203	.005	91			10	9	9	110	4	.84			406		82		.004
D4	40,000	7200	9000	200	238	194	.005	91	67	5	10	9	9	240	4	.84	45,000	238	388	.54	82	2.5	.004

Table 7. CHARACTERISTICS OF CANDIDATE PROPULSION SYSTEMS

CODE NO	BUFFER CONTROLLER POWER	VOLTS	AMPS	SPEC. WEIGHT	LOSS COEF. a_1	a_2	a_3	BATTERY CHARACTERISTICS VOLTS	SPEC. ENERGY	SPEC. POWER	WEIGHT	COST FACT	EFF.	FLYWHEEL CHARACTERISTICS SPEC. ENERGY	WEIGHT	MAX SPEED	RUNDOWN %	COST	GENERATOR OR CVT FACTORS RATED POWER	BASE SPEED	MAX SPEED	OVERLOAD %	RATED VOLTS
A1	40,000	241.	406.	.0015	123.	3.75	.006	240	15	20	1600	2.5	65	38	50	30,000	8.	500	40,000	20,000	30,000	200	241
A2			388														8.						
A3			425														8.						
A4			414														8.						
A5			406														4.						
A6			388														4.						
A7			425														4.						
A8			414														4.						
B1			406														8.						
B2			386														8.						
B3			425														8.						
B4			414														8.						
B5			406														4.						
B6			388														4.						
B7			425														4.						
B8			414														4.						
C1			406														8.						
C2			388														8.						
C3			425														8.						
C4			414														8.						
C5			406														4.						
C6			388														4.						
C7			425														4.						
C8	40,000	241	414	.0015	123.	375	.006										4.						
D1																	4.			20,000	30,000	200	241
D2																	4.						
D3																	4.						
D4								240	15	20	1600	2.5	65	38	50	30,000	4.	500	40,000				

Table 8. CHARACTERISTICS OF CANDIDATE PROPULSION SYSTEMS

CODE NO.	GENERATOR OR CVT FACTORS (CONTINUED)											TRANSMISSION FACTORS							
	RATED AMPS	SPEC. WEIGHT	FULL LD EFF.	I^2R %	HYST[1] %	EDDY[2] %	FRIC[3] %	WINDAGE %	FREQ	COST FACT.	POWER FACT.	RATIO H GEAR	RATIO 2nd. GR.	RATIO L GEAR	LOSS COEF a0	a1	a2	WEIGHT	COST FACT
A1	196	.0075	85	40	8.	8.	5.	39	666.6	6		1.0	1.0	1.0	1.0E-09	1.0E-12	1.0E-10	1.05	15
A2	196	↑	↑	↑	↑	↑	↑	↑	↑	↑		1.0	1.74	3.87	.1667	33.3E-07	.06667	65	275
A3	196	↓	↓	↓	↓	↓	↓	↓		↓		LIKE	A1						
A4	196	.0075	85	40	8.	8.	5.	39		6		LIKE	A2						
A5	205	.0055	87	45	5.	5.	5.	40		5.5		LIKE	A1						
A6	205	↑	↑	↑	↑	↑	↑	↑		↑		LIKE	A2						
A7	205	↓	↓	↓	↓	↓	↓	↓		↓		LIKE	A1						
A8	205	.0055	87	45	5.	5.	5.	40		5.5		LIKE	A2						
B1	196	.0075	85	40	8.	8.	8.	39		6		1.0	1.0	1.0	1.0E-09	1.0E-12	1.0E-10	50	150
B2	196	↑	↑	↑	↑	↑	↑	↑		↑		1.0	1.74	3.86	.1667	33.3E-07	.06667	115	400
B3	196	↓	↓	↓	↓	↓	↓	↓		↓		LIKE	B1						
B4	196	.0075	85	40	8.	8.	8.	39		6		LIKE	B2						
B5	205	.0055	87	45	5.	5.	5.	40		5.5		LIKE	B1						
B6	205	↑	↑	↑	↑	↑	↑	↑		↑		LIKE	B2						
B7	205	↓	↓	↓	↓	↓	↓	↓		↓		LIKE	B1						
B8	205	.0055	87	45	5.	5.	5.	40		5.5		LIKE	B2						
C1	196	.0075	85	40	8.	8.	8.	39		6		1.0	1.0	1.0	1.0E-09	1.0E-12	1.0E-10	1.05	15
C2	196	↑	↑	↑	↑	↑	↑	↑		↑		1.0	1.74	3.86	.1667	33.3E-07	.06667	100	325
C3	196	↓	↓	↓	↓	↓	↓	↓		↓		LIKE	C2						
C4	196	.0075	85	40	8.	8.	8.	39		6		LIKE	C1						
C5	205	.0055	87	45	5.	5.	5.	40		5.5		LIKE	C1						
C6	205	↑	↑	↑	↑	↑	↑	↑		↑		LIKE	C2						
C7	205	↓	↓	↓	↓	↓	↓	↓	↓	↓		LIKE	C1						
C8	205	.0055	87	45	5.	5.	5.	40	666.6	5.5		LIKE	C2						
D1					4.	3.	2.					LIKE	A1						
D2					4.	3.	2.					LIKE	A2						
D3					4.	3.	2.					LIKE	A1						
D4					4.	3.	2.					LIKE	A2						

(1) Spin torque as % of rated torque (2) Creep % at max torque (3) Viscous torque as % of rated torque at max speed

Table 9. PERFORMANCE OF CANDIDATE PROPULSION SYSTEMS

CASE NO.	GEN.	MOTOR	TRANS.	NO. OF MOTORS	NO. OF AXLES	TEST WT. lbs.	ACCEL. 0–55	TIMES 25–55	MINIMUM SPEED PASSING	ST. 4% G	M.P.H. 6% RAMP	BATTERY WT. LB.	SAE J227a Sch. D P BAR	E BAR	PERFORM W-H/MILE	RANGE	STEADY 45 MPH P BAR	E BAR	PERFORM W-H/MILE	RANGE
A1	PM	AC	NONE	1	1	4335	LT 15	LT 10	65	55	40	1600	8.08	17.51	299	93.8	6.78	18.41	241	122.3
A2	PM	AC	YES	1	1	4123							7.62	17.83	296	96.2	6.02	18.95	214	141.5
A3	PM	DC	NONE	1	1	4368							8.17	17.45	304	91.8	6.94	18.30	247	118.7
A4	PM	DC	YES	1	1	4174							7.62	17.82	301	94.7	6.11	18.89	217	139.2
A5	WF	AC	NONE	1	1	4307							8.01	17.56	289	97.1	6.76	18.43	240	122.7
A6	WF	AC	YES	1	1	4095							7.52	17.89	287	99.8	6.01	18.96	214	142.0
A7	WF	DC	NONE	1	1	4350							8.10	17.50	295	94.9	6.93	18.31	246	118.9
A8	WF	DC	YES	1	1	4155							7.54	17.88	292	98.1	6.10	18.90	217	139.5
B1	PM	AC	NONE	2	1	4517														
B2	PM	AC	YES	2	1	4236														
B3	PM	DC	NONE	2	1	4551							7.59	17.85	285	100.2	6.08	18.91	216	140.1
B4	PM	DC	YES	2	1	4288							7.34	18.02	287	100.5	5.57	19.27	196	155.7
B5	WF	AC	NONE	2	1	4487														
B6	WF	AC	YES	2	1	4207														
B7	WF	DC	NONE	2	1	4532							7.50	17.91	275	104.1	6.07	18.92	216	140.3
B8	WF	DC	YES	2	1	4263							7.24	18.09	277	104.3	5.56	19.28	198	156.1
C1	PM	AC	NONE	2	2	4524														
C2	PM	AC	YES	2	2	4287														
C3	PM	DC	YES	2	2	4340							7.38	17.99	289	99.6	5.60	19.25	199	154.8
C4	PM	DC	NONE	2	2	4559							7.60	17.84	285	100.1	6.08	18.91	216	139.9
C5	WF	AC	NONE	2	2	4496														
C6	WF	AC	YES	2	2	4260														
C7	WF	DC	NONE	2	2	4541							7.51	17.90	276	103.9	6.07	18.92	216	140.2
C8	WF	DC	YES	2	2	4322							7.28	18.06	280	103.4	5.59	19.26	199	155.1
D1	CVT	DC	NONE	1	1	4378							7.08	18.20	273	106.8	6.83	18.38	243	121.0
D2	CVT	DC	YES	1	1	4198							6.60	18.54	253	117.1	6.06	18.92	216	140.4
D3	CVT	AC	NONE	1	1	4338							6.96	18.28	265	110.4	6.67	18.49	237	124.7
D4	CVT	AC	YES	1	1	4097	LT 15	LT 10	65	55	40	1600	6.49	18.61	248	120.3	5.96	18.99	212	143.4

Clause (2) above is understood to be a qualitative comparison of the 28 alternates studied under Clause (1). In order to make a consistent comparison, values of "goodness" were assigned to the "qualitities" considered significant. These goodness values were multiplied by a weighing factor assigned according to the importance placed on the particular quality to the overall goodness of the power system. Then for each alternate the products were added together to give a number that indicated the overall desirability of the alternate. Finally the desirabilities were divided into low, medium and high and presented in Table 10.

The comparison was based on subjective appraisals of goodness and importance. The numbers were not used as the basis of comparison but only to keep track of the comparison process. For example, if the alternates had the same or nearly the same desirability the reasons why they came out that way were reexamined and the numbers changed if necessary to agree with the overall appraisal.

The summary of the technology advances required for the various alternates requested by Clause (3) of the contract is provided by the following discussion. These advances are discussed under the headings of the components or parts of the system to which they apply. The comparison of the alternates with respect to the extent of such advances required is summarized in Table 11.

With the possible exception of the CVT, none of the alternates require breakthroughs on the scale typified by high temperature storage batteries for example. The type of advances required are reduction in size, weight, cost, and increase in durability.

Generators and Motors

The properties of the electrical machines depend basically on physical laws and the properties of iron, copper, and magnetic and insulating materials. The improvements in these machines that can be expected are in their design for higher speeds and higher short time overload capacities. Higher speeds will reduce weight but increase eddy current and hysteresis losses. Reduction of losses can be accomplished by the use of higher grade iron, thinner laminations, and finer subdivision of the conductors. (Refs. 15,16) All of these approaches are understood. The extent of their application is set by manufacturing cost which can be greatley reduced by production engineering effort.

Improved insulating materials together with design for forced cooling by either air or liquid coolants can greatly increase overload capacity as required to obtain the short-time performance expected of passenger cars.

Table 10

ADVANTAGES AND DISADVANTAGES OF POWER SYSTEMS

○ POOREST ◐ AVERAGE ● BEST

CASE	GEN.	MOTOR	TRANS.	NO. OF MOTORS	NO. OF AXLES	SIMPLICITY	LOW FIRST COST	ABSENCE OF CRITICAL MAT.	LOW STAND-BY LOSS	EASE OF PRODUCTION	EASE OF CONTROL	LIGHTNESS	COMPACTNESS	EFFICIENCY
A1	PM	AC	NO	1	1	BEST	BEST	POOREST	POOREST	BEST	AVERAGE	AVERAGE	BEST	POOREST
A2	PM	AC	YES	1	1	AVERAGE	AVERAGE	POOREST	POOREST	BEST	POOREST	BEST	BEST	AVERAGE
A3	PM	DC	NO	1	1	AVERAGE	AVERAGE	POOREST	POOREST	BEST	AVERAGE	AVERAGE	BEST	POOREST
A4	PM	DC	YES	1	1	POOREST	POOREST	POOREST	POOREST	AVERAGE	AVERAGE	BEST	BEST	AVERAGE
A5	WF	AC	NO	1	1	AVERAGE	BEST	AVERAGE	BEST	BEST	BEST	AVERAGE	BEST	POOREST
A6	WF	AC	YES	1	1	AVERAGE	BEST	AVERAGE	BEST	BEST	AVERAGE	BEST	BEST	AVERAGE
A7	WF	DC	NO	1	1	POOREST	AVERAGE	AVERAGE	BEST	BEST	BEST	AVERAGE	BEST	POOREST
A8	WF	DC	YES	1	1	POOREST	POOREST	AVERAGE	BEST	AVERAGE	BEST	BEST	BEST	AVERAGE
B1	PM	AC	NO	2	1	AVERAGE	AVERAGE	POOREST	POOREST	BEST	POOREST	POOREST	BEST	BEST
B2	PM	AC	YES	2	1	AVERAGE	POOREST	POOREST	POOREST	BEST	POOREST	AVERAGE	AVERAGE	BEST
B3	PM	DC	NO	2	1	POOREST	POOREST	POOREST	POOREST	BEST	POOREST	POOREST	BEST	AVERAGE
B4	PM	DC	YES	2	1	POOREST	POOREST	POOREST	POOREST	AVERAGE	AVERAGE	AVERAGE	AVERAGE	BEST
B5	WF	AC	NO	2	1	POOREST	BEST	AVERAGE	BEST	BEST	AVERAGE	POOREST	BEST	BEST
B6	WF	AC	YES	2	1	POOREST	AVERAGE	AVERAGE	BEST	BEST	AVERAGE	AVERAGE	AVERAGE	BEST
B7	WF	DC	NO	2	1	POOREST	AVERAGE	AVERAGE	BEST	BEST	BEST	POOREST	BEST	AVERAGE
B8	WF	DC	YES	2	1	POOREST	POOREST	AVERAGE	BEST	AVERAGE	BEST	AVERAGE	AVERAGE	BEST
C1	PM	AC	NO	2	2	POOREST	AVERAGE	POOREST	POOREST	BEST	POOREST	POOREST	AVERAGE	BEST
C2	PM	AC	YES	2	2	POOREST	POOREST	POOREST	POOREST	AVERAGE	POOREST	AVERAGE	POOREST	AVERAGE
C3	PM	DC	NO	2	2	POOREST	POOREST	POOREST	POOREST	BEST	POOREST	AVERAGE	POOREST	BEST
C4	PM	DC	YES	2	2	POOREST	POOREST	POOREST	POOREST	AVERAGE	POOREST	POOREST	AVERAGE	AVERAGE
C5	WF	AC	NO	2	2	POOREST	AVERAGE	AVERAGE	BEST	BEST	AVERAGE	BEST	AVERAGE	BEST
C6	WF	AC	YES	2	2	POOREST	AVERAGE	AVERAGE	BEST	BEST	AVERAGE	AVERAGE	POOREST	BEST
C7	WF	DC	NO	2	2	POOREST	POOREST	AVERAGE	BEST	AVERAGE	BEST	BEST	AVERAGE	AVERAGE
C8	WF	DC	YES	2	2	POOREST	POOREST	AVERAGE	BEST	AVERAGE	AVERAGE	AVERAGE	POOREST	BEST
D1	CVT	AC	NO	1	1	BEST	AVERAGE	BEST	POOREST	BEST	AVERAGE	AVERAGE	BEST	AVERAGE
D2	CVT	AC	YES	1	1	AVERAGE	POOREST	BEST	POOREST	AVERAGE	AVERAGE	BEST	BEST	BEST
D3	CVT	DC	NO	1	1	POOREST	BEST	BEST	POOREST	BEST	BEST	AVERAGE	BEST	AVERAGE
D4	CVT	DC	YES	1	1	POOREST	BEST	BEST	POOREST	AVERAGE	BEST	BEST	BEST	BEST

Table 11. TECHNOLOGY ADVANCES REQUIRED

○ LARGE EFFORT ◒ MEDIUM EFFORT ● SMALL EFFORT

CASE	GEN	MOTOR	TRANS	NO. OF MOTORS	NO. OF AXLES	GENERATOR	MOTOR	TRANSMISSION	CONVERTER	CONTROL	C.V.T.	OVERALL SYSTEM
A 1	PM	AC	NO	1	1	◒	●	●	◒	◒		◒
A 2	PM	AC	YES	1	1	◒	●	●	◒	○		○
A 3	PM	DC	NO	1	1	◒	◒	●	◒	◒		◒
A 4	PM	DC	YES	1	1	◒	◒	●	◒	◒		◒
A 5	WF	AC	NO	1	1	◒	●	●	◒	●		●
A 6	WF	AC	YES	1	1	◒	●	●	◒	◒		◒
A 7	WF	DC	NO	1	1	◒	◒	●	◒	●		●
A 8	WF	DC	YES	1	1	◒	◒	●	◒	●		◒
B 1	PM	AC	NO	2	1	◒	●	●	◒	○		○
B 2	PM	AC	YES	2	1	◒	●	●	◒	○		○
B 3	PM	DC	NO	2	1	◒	◒	●	◒	○		○
B 4	PM	DC	YES	2	1	◒	◒	●	◒	◒		[illegible]
B 5	WF	AC	NO	2	1	◒	●	●	◒	◒		●
B 6	WF	AC	YES	2	1	◒	●	●	◒	◒		◒
B 7	WF	DC	NO	2	1	◒	◒	●	◒	●		●
B 8	WF	DC	YES	2	1	◒	◒	●	◒	●		◒
C 1	PM	AC	NO	2	2	◒	●	●	◒	○		○
C 2	PM	AC	YES	2	2	◒	●	●	◒	○		○
C 3	PM	DC	NO	2	2	◒	◒	●	◒	○		○
C 4	PM	DC	YES	2	2	◒	◒	●	◒	○		○
C 5	WF	AC	NO	2	2	◒	●	●	◒	◒		●
C 6	WF	AC	YES	2	2	◒	●	●	◒	◒		◒
C 7	WF	DC	NO	2	2	◒	◒	●	◒	●		●
C 8	WF	DC	YES	2	2	◒	◒	●	◒	◒		◒
D 1	CVT	DC	NO	1	1		◒	●	●	◒	○	○
D 2	CVT	DC	YES	1	1		◒	●	●	◒	○	○
D 3	CVT	AC	NO	1	1		●	●	●	●	○	○
D 4	CVT	AC	YES	1	1		●	●	●	●	○	○

Controls

Electrical and many non-electrical systems today take advantage of the breakthrough in control technology of the microcomputer. The microcomputer is well suited to process and generate the various signals needed for the control of an electric vehicle. There also may be simpler approaches to the problem like specialized LSI chips. In any case, the only advances required are those already available for application to the electric car.

Step Transmissions

No basic advances appear to be necessary to multi-ratio transmissions. These devices have been perfected for internal combustion-engined cars to the point where they are as small and light as necessary for electric automobile applications.

Reduction of losses through better bearings, reduction or elimination of oil churning loss, reduction of control power and clutch or brake drag should take place through redesign of the present relative lossy transmissions and drive systems for electric vehicle application.

Continuously Variable Transmissions

These devices have never been successfully applied to automobiles on any significant scale. They may very well require an advance in traction coefficient or contact fatigue strength beyond the values currently being obtained. Transmissions designed following ball bearing practice are large, heavy, and expensive. Whether or not they are too large, heavy, and expensive is not definite but it is possible that their characteristics put them outside the range of practicality for vehicle application unless a significant technological advance can be made.

Power Converters

Most of the alternates employ semiconductor power converters between dc and ac devices. The technology of these converters is so new that significant improvements would not be surprising. The power handling devices, thyristors, or transistors now available have the capability required although increase in the frequency capability of thyristors and the current capability of transistors is very desirable. The advances which are necessary and can be expected are in simplifying and packaging their auxiliary equipment, such as the firing and protective circuitry, and in reducing the filtering required. One advance, the development of high-power transistors, appears to have already occurred. Of course, prices must be reduced drastically but this can be expected to result from production for a large competitive market.

Other Problems

The foregoing discussion considered the elements which differed between the alternates and is summarized in Table 11. In addition there are advances necessary or desirable in the elements used in all alternates.

The flywheel is probably the most important component from the standpoint of development required. Vehicle flywheels (ref. 5), while extremely promising, are in an early state of development. Only a few vehicles are in operation today with flywheels in their power systems and in many of these the flywheel energy-to-weight ratio is too low for passenger road vehicles. Laboratory demonstrations (refs. 14,17), however, have shown energy-to-weight ratios considerably better than lead-acid batteries. The application of these wheels as power boosters for road vehicles has only barely begun. (ref. 11)

Specifically, durability and accident hazard must be determined for a flywheel design having the characteristics postulated for the power systems studied.

Advances are necessary and will certainly occur in the "packaging" and interconnection of automotive electrical equipment. The present style is set by industrial lift trucks and similar equipment where weight is less important and space restraints less demanding than in a passenger car. Even in the latest electric vehicles, electric equipment connecting parts and equipment layout is more typical of industrial than of passenger vehicle practice.

6.10 Recommended Candidates for Task II

The candidates recommended for further examination in the design trade-off studies were candidates D4, D2, A6, A8 and B5. The two candidates, D4 and D2, represented the best two candidates in terms of range, but have some obvious developmental problems in that no suitable CVT is currently available.

Candidates A6 and A8 are the most attractive of the non-CVT candidates. Their ranges are just slightly less than those for the best multi-motored candidates, but their relative simplicity and lighter weight will probably make them more cost effective than any of the multi-motored candidates. The most attractive of the multi-motored candidates is B5 and it is kept for further examination to determine if the expected difference in cost effectiveness is born out when the candidates are optimized.

Recommended Candidates for Task II Studies

A6	AC Induction Motor With Flywheel/Generator
A8	DC Brushless Motor With Flywheel/Generator
B5	Two AC Motors Without Transmission, With Flywheel/Generator
D2	DC Brushless Motor with Flywheel/CVT
D4	AC Induction Motor With Flywheel/CVT

7. DESIGN TRADE-OFF STUDIES

The characteristics and design of the five recommended candidates were examined in more detail during the design trade-off studies. In the preliminary analysis, all candidates had the same total weight of batteries and same total installed power. However, during the trade-off studies, the design and performance factors for each candidate are examined to achieve a more optimum design and various differences in weight and power requirement emerge. As the details of the design become more specific, the estimates of life-cycle cost become more meaningful.

The candidates A6, A8, D2, D4 and B5 are shown in more detail in Figures 19, 20, 21, 22, and 23.

7.1 Design Parameters Studied

Factors affecting driveline efficiency were examined to find ways to reduce losses and to determine the improvement in range which could result from these improvements.

Refinements in the estimates of motor weights were made by examining the motor designs in more detail. Calculations were made for magnetic flux in the air gap to confirm that the required overload torque could be achieved. Some modification of the computer subroutines were made to reflect the overload capacity of induction motors at breakaway torque. Variation in various design parameters for the induction motor was examined to determine the potential gain in range which can be achieved by improving the power factor of the motor or by reducing the slip.

Variations in gear ratios and shift points were examined to determine if the optimum operating points had been selected.

Different schemes for energy management via the use of the flywheel were also examined. Battery leveling and peak power shaving was also considered.

The battery weights were adjusted to give very nearly the same range for each candidate.

The losses in the transmission and final drive axle are each characterized by three coefficients (Table 12). The first coefficient used in the analysis represents the no-load drag torque at low speed. The value of the torque is affected by the bearing design and bearing preload. Taper roller bearings with high preload will give higher no-load torque than ball bearings or spherical bearings of modest preload. By careful design this friction can be lowered.

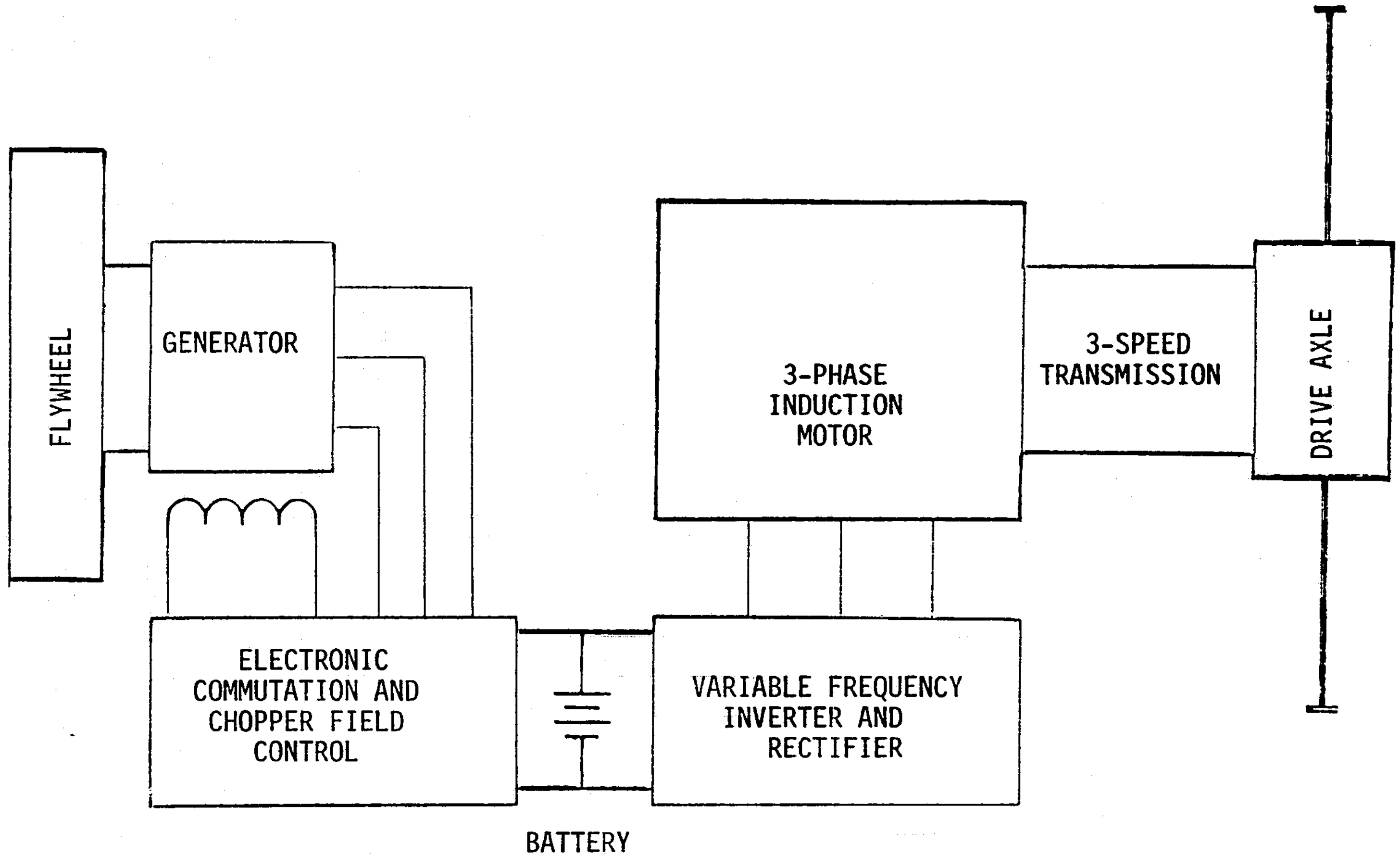

Figure 19. Candidate A6, AC Motor Drive

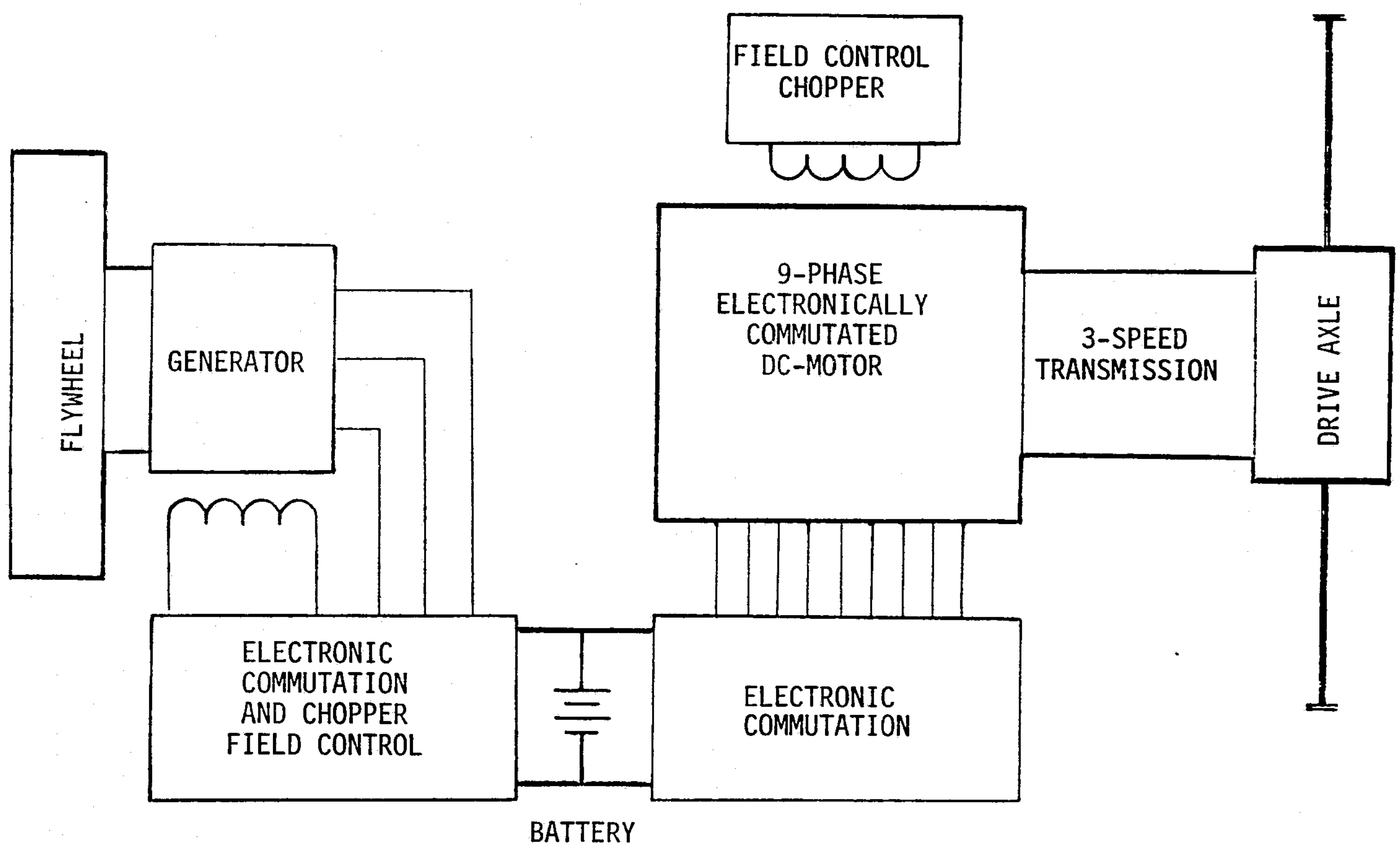

Figure 20. Candidate A8, Electronically Commutated DC Motor Drive

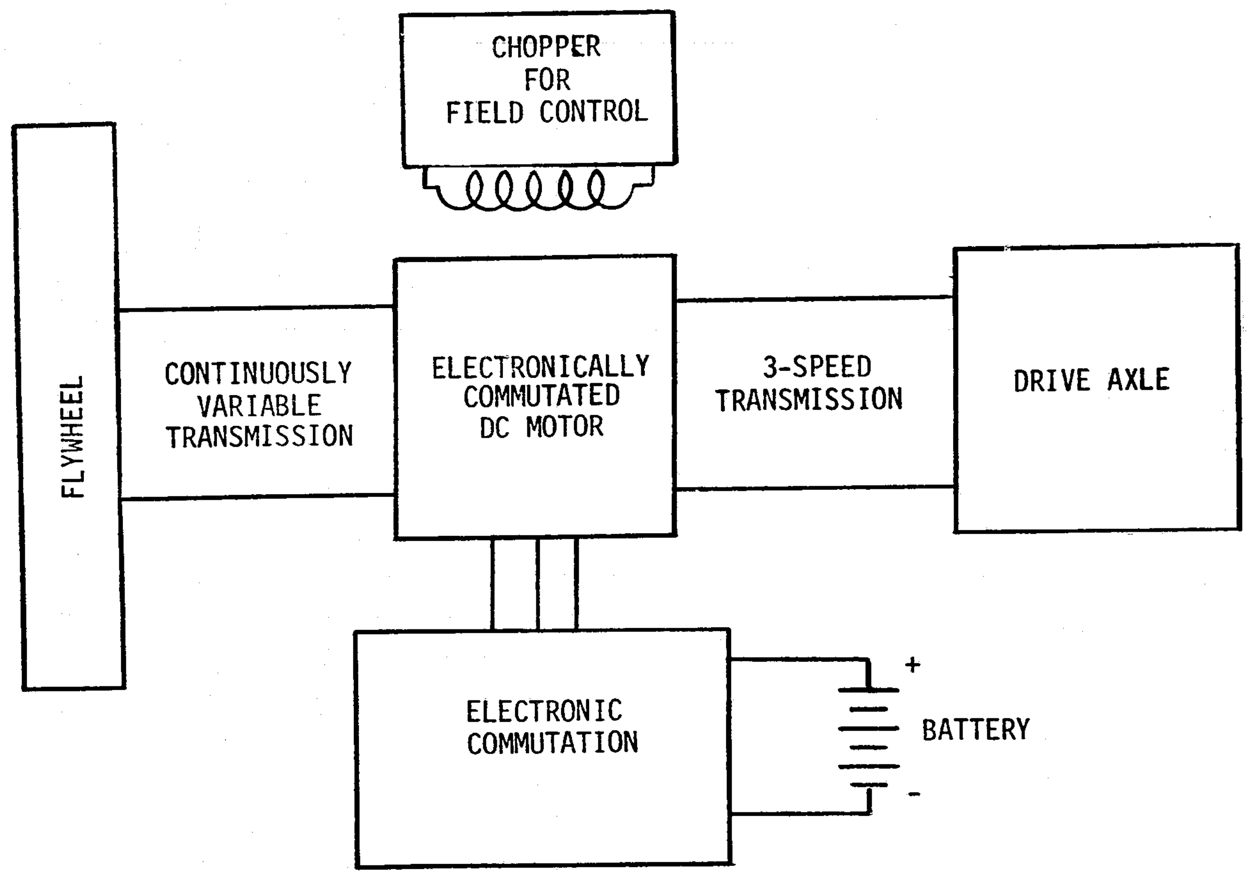

Figure 21. Candidate D2. DC Drive Motor and CVT

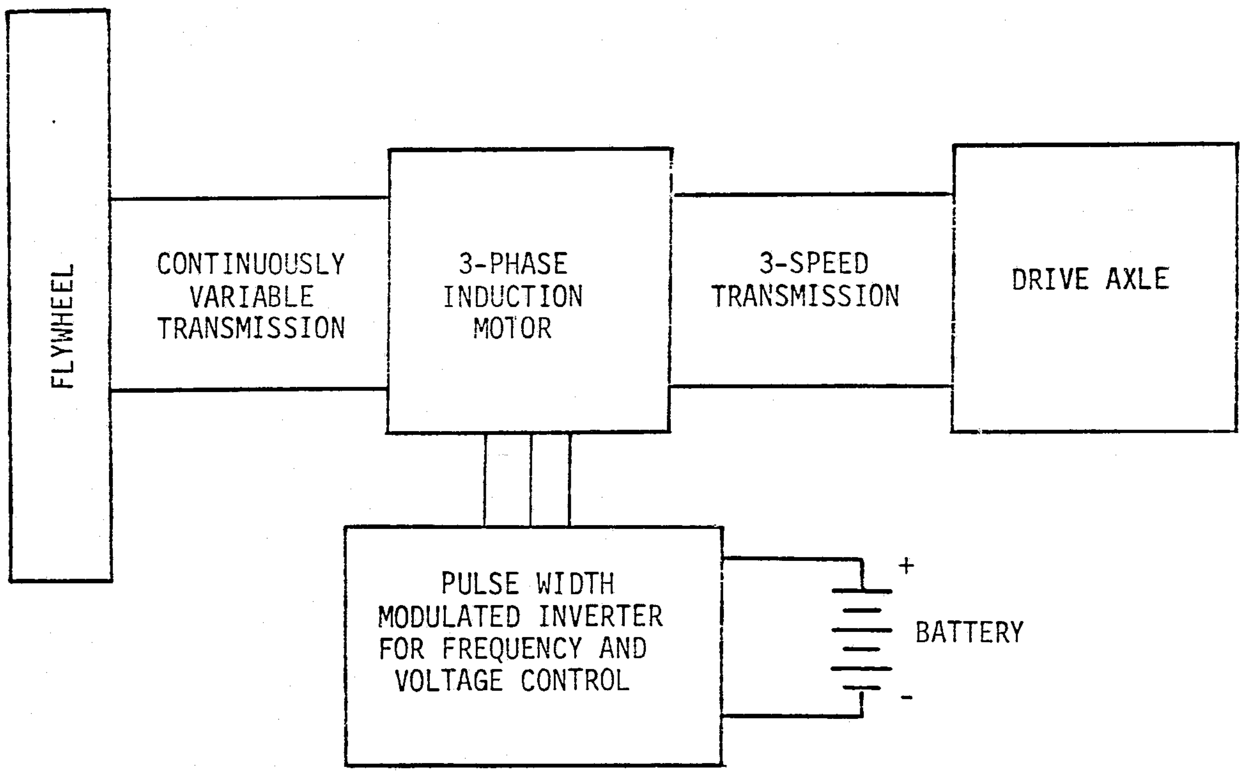

Figure 22. Candidate D4. AC Drive Motor and CVT

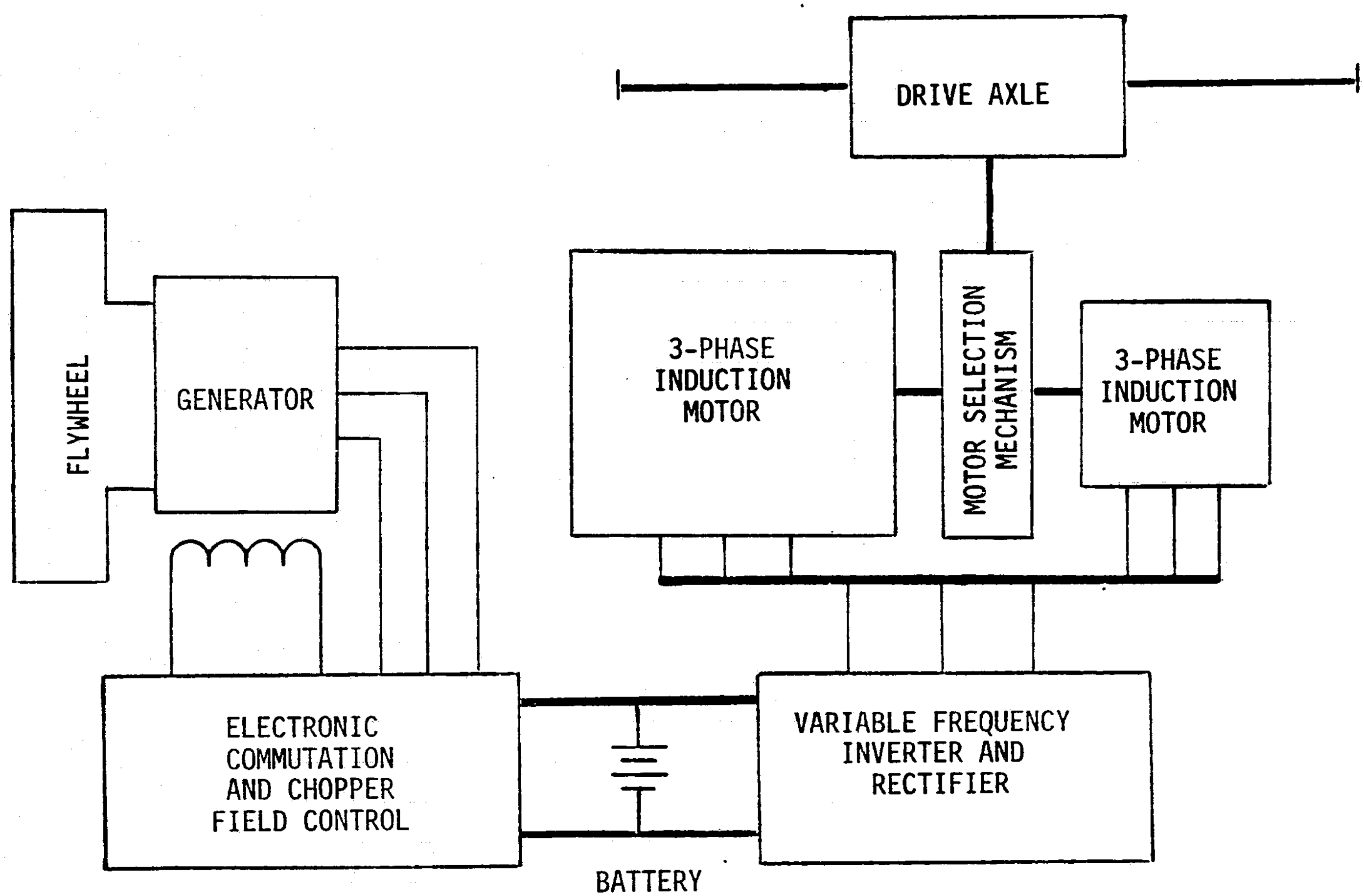

Figure 23. Candidate B5, Two AC Motors/Direct Drive

The second coefficient is for the viscous drag torque. The amount of torque associated with this coefficient is proportional to speed. The value of the coefficient is dependent upon the geometry of the transmission or axle and upon the viscosity of the lubricant. This too can be reduced by good design and careful selection of the lubricant.

The third coefficient is for the gear and bearing friction associated with the torque loading. The value of the frictional torque is dependent in part on the geometry of the gear train and the unit loading on the bearings. The value of torque is also dependent upon the properties of the lubricant.

Reductions of these coefficients were arbitrarily made to determine the potential improvement. The values examined are shown in Table 12. The effects on driveline efficiency and power loss are shown in Table 13. The improvements in range are shown in Figure 24.

The power required for the different driving conditions vary somewhat for the different candidates because of slight differences in their weights and efficiencies. Table 14 summarizes the peak power required for various driving conditions for the five candidates. The greatest power requirements are for the acceleration from zero to 55 mph in fifteen seconds and for braking in the deceleration portion of the SAE J227a Schedule D cycle. For both of these periods, the duration of the power pulse is short enough that the short-term overload capacity of the motor could provide the power, even though the continuous power rating is much lower. The power available for the acceleration on the six percent ramp can be higher than the continuous power rating of the motor because the duration of this six percent ramp acceleration is less than 30 seconds. The power required for the steady 89 km/h (55 mph) on a four percent grade is used to set the continuous power rating for the motor. Using this power as the continuous power rating, the overload factor for the six percent ramp acceleration is about 40 percent for the three non-CVT candidates and the overload factor for the zero to 89 km/h (55 mph) acceleration is about 100 percent.

The required short-term overload capacity of 100 percent is normal for electric motors. Air gap flux calculations and peak current allowances show that the motor designs considered for these propulsion systems have about 150 percent short-term overload capacity. The subroutine for representing the ac motors were modified to assure that the maximum torque exceeds 200 percent of rated torque.

Variations in design parameters for the induction motor will give different amounts of overload capacity. A range of different values of rated slip and power factors were examined for motors having the same rated power, speed and efficiency. The characteristics of these different designs are shown in Table 15. For constant efficiency at the design point, a low slip motor has low rotor resistance (R2) and higher stator resistance (R1). Permitting the slip to rise by use of higher rotor resistance, requires that the stator resistance be lowered to keep the efficiency up. The starting torque increases as the rotor resistance increases and permits higher slip at the breakaway torque, however, the maximum power does not increase. The drop in speed due to increased slip is not offset by increase

Table 12. Loss Coefficients Used in Driveline

FOR POINT #	I	II	III	IV
AXLE:				
A_0	.6779	.4519	.2260	.1692
A_1	$.135 \times 10^{-3}$	$.09 \times 10^{-3}$	$.045 \times 10^{-3}$	$.3383 \times 10^{-4}$
A_2	.02712	.01808	.00904	$.89 \times 10^{-2}$
TRANSMISSION:				
T_0	.2260	.1507	.0753	.05637
T_1	$.451 \times 10^{-5}$	$.3 \times 10^{-5}$	$.15 \times 10^{-5}$	$.1128 \times 10^{-5}$
T_2	.09039	.0602	.0301	.0301

$A_0 - T_0$ = NO LOAD TORQUE AT LOW SPEED Nm

$A_1 - T_1$ = VISCOUS TORQUE COEFFICIENT Nm/rpm

$A_2 - T_2$ = GEAR & BEARING FRICTION Non-dimensional

Table 13. Transaxle Losses

ROAD POWER Watts	POWER MOTOR Watts	Δ Watts	DRIVE LINE EFFICIENCY (Percent)
ORIGINAL AXLE - TRANSMISSION LOSS FACTORS POINT I			
6136	7869	1733	77.9
21475	24929	3454	86.1
55251	61194	5943	90.3
LOSS FACTORS REDUCED BY 1/3 FROM POINT I			
6136	7273	1137	84.4
21475	23752	2277	90.4
55251	59179	3928	93.4
LOSS FACTORS REDUCED BY 2/3 FROM POINT I			
6136	6697	561	91.6
21475	22603	1128	95
55251	57199	1948	96.6
POINT IV LOSS FACTORS FOR CONCEPT A6, D4. HIGHER SPEED AC MOTOR SYSTEMS ONLY			
6136	6614	478	92.8
21475	22520	1045	95.4
55251	57112	1861	96.7

Figure 24. DRIVELINE EFFICIENCY VS. RANGE

- SAE J227a SCHEDULE D. Cruise portion 72 km/h (45 mph)
- VALUE IN ( ) AFTER CONCEPT NUMBER IS ROAD POWER IN WATTS

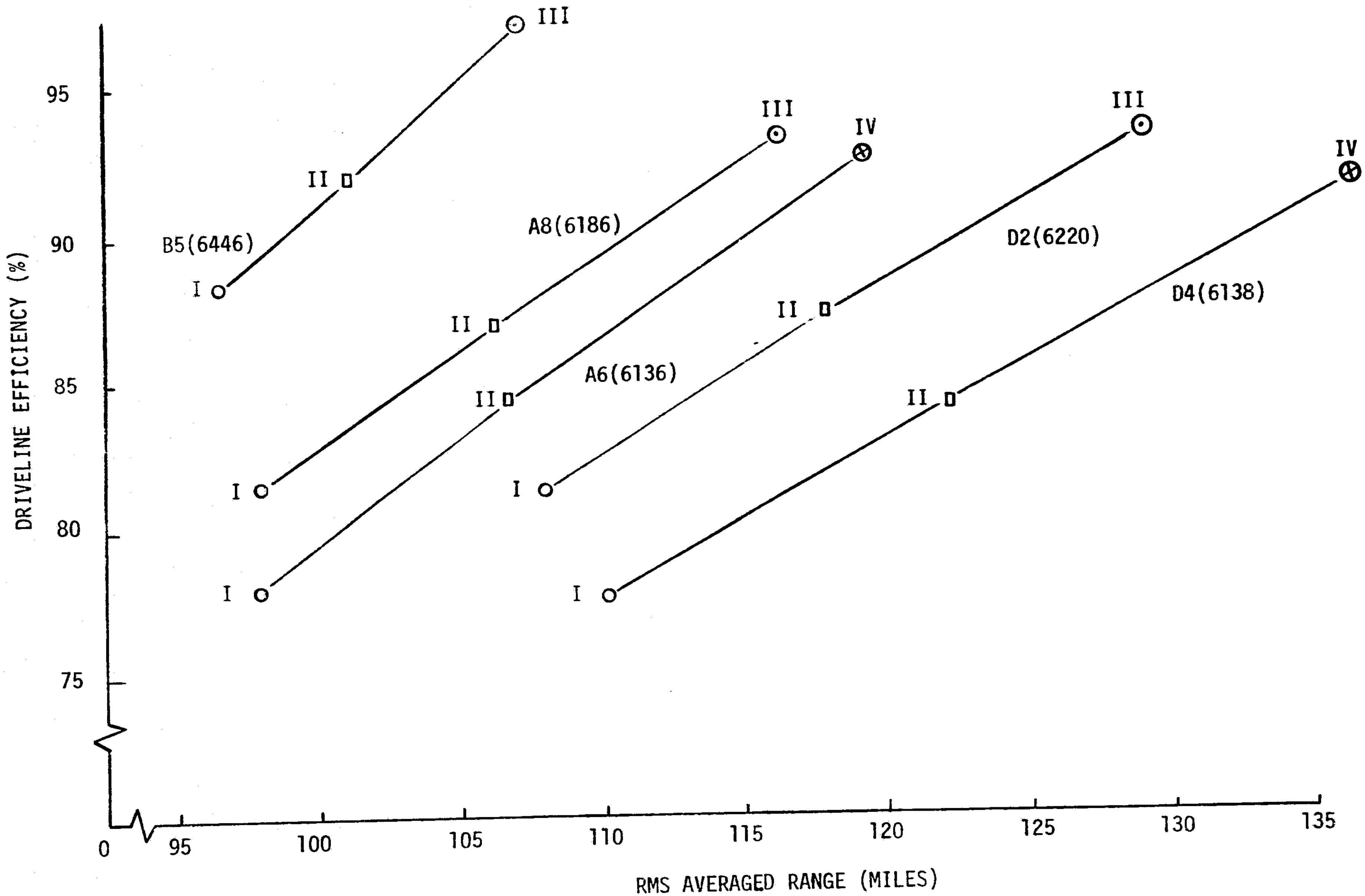

Table 14. Summary Table of Peak Motor Power Requirements For AEVA Concepts A6, A8, B5, D2, and D4 For Various Driving Modes

CONCEPT	A6	A8	B5	D2	D4
TEST WT, kg	1605	1681	1866	1641	1577
	PEAK MOTOR POWER REQUIRED IN WATTS				
DRIVING MODES					
45 MPH CRUISE (J227a Schedule D)	6056	6094	6357	6036	6003
CONST. POWER ACCEL. (J227a Schedule D)	19661	20243	21864	8274 (11406)*	8232 (11154)*
CONST. POWER DECEL. (J227a Schedule D)	48003	49186	57915	2022 (-50251)*	2014 (-49130)*
ACCEL. FROM 0 TO 55 IN 15 SECS.	49690	50676	55600	16158 (33663)	15965 (32935)*
STEADY 65 MPH ON LEVEL	13665	13714	14049	13624	13581
STEADY 55 MPH ON 4% GRADE	25237	25651	27771	25271	24885
ACCEL. ON 6% GRADE FROM 0 TO 40 MPH IN 920.83 FEET	34717	35431	38727	24425 (10379)*	23982 (10155)*

*Power supplied or absorbed through the CVT-Flywheel link

Table 15. AC Induction Motor Analysis for Various Slips and Power Factors

Motor Ratings:

Rated Power	36000 watts
Base Speed	7200 rpm
Maximum Speed	9000 rpm
Efficiency	91%
Rated Voltage	238 Volts

Table

Slip	Power Factor	Maximum Power	Maximum Torque	R1	R2	R3	X1	X2	X3	X1/X3
%	%	watt	Nm	Ω	Ω	Ω	Ω	Ω	Ω	%
1	84	77298	106.6	.0785	.02011	140.8	.2063	.2060	4.632	4.45
2	84	76508	109.8	.06379	.04649	143.7	.2052	.2049	4.678	4.38
3	84	75533	113.1	.04878	.061602	146.6	.2043	.2040	4.725	4.32
4	84	74546	116.4	.03345	.08299	149.7	.2037	.2034	4.774	4.27
4	80	75567	118.8	.03034	.08299	149.6	.1986	.1978	3.860	5.14
4	88	73692	114.4	.03671	.08299	149.8	.2046	.2129	6.296	3.24

in torque as shown in this table. This loss in power is somewhat deceptive as the power values are for a constant frequency input to the motor which allows the motor to slow down as the slip increases as it would for a normally operated ac motor. However, for the electric vehicle the frequency is increased as slip increases so that the motor does not actually slow down. The main value of the table is the display of resistances and reactances associated with different values of slip and power factor. The table shows clearly that the ratio of leakage to magnetizing reactance must be low to achieve a high power factor and shows that very low rotor resistance is required to achieve a low value of slip.

The different values of slip and power factor were examined for motors of the same efficiency at the design point power and speed; however, they will have different efficiency at powers and speeds other than that at the design point. Consequently, the range and energy consumption per mile can be different as shown in Table 16 for Schedule D cycle. The motor with lower slip does not give better range because the reduction in I^2R losses in the rotor is more than offset by an increase in I^2R losses of the stator. Increasing the power factor increases the range and decreases the energy consumption. Unfortunately it will be very difficult to achieve a power factor much higher than 88 percent.

Table 16. SAE J227a Schedule Cycle Range Obtained for Motors Listed in Table 15

Slip %	Power Factor %	Range km	Range (Miles)	Energy Consumption Wh/mi	Energy Consumption MJ/km
1	84	168.98	(105.00)	222.68	.498
2	84	170.04	(105.66)	221.60	.495
3	84	171.05	(106.29)	220.59	.493
4	84	172.01	(106.88)	219.65	.491
4	80	169.25	(105.17)	222.50	.498
4	88	174.66	(108.53)	216.94	.485

Increasing the battery weight increases the vehicle range by increasing the on-board energy storage, but does so at the expense of greater vehicle weight. The vehicle weight increases by more than the increase in battery weight because the vehicle structural weight must be increased to carry the additional battery weight. This increase in vehicle weight causes an increase in energy consumption. The additional battery and structural weight will also cause an increase in initial cost of the propulsion system. The effects of battery weight on vehicle weight and range is shown in Table 17. The desired range is 161 km (100 miles) so the battery weight should be adjusted to give this range. Figure 25 shows the range as a function of lead-acid battery weight and Table 18 summarizes the vehicle weights and energy consumption with the battery weights adjusted to give a range of 161 km (100 miles).

Table 17 . Battery Weight vs. Range

Driving mode: SAE J227a Schedule D
Battery model used: Root mean square averaging

Concept	Battery Weight		Lead-Acid		Nickel-Zinc		Test Weight	
	kg	(lb)	km	(mi)	km	(mi)	kg	(lb)
A6	635	(1400)	169.17	(105.12)	375.63	(233.41)	1739	(3835)
	600	(1322)	162.35	(100.88)	365.13	(226.88)	1693	(3733)
	249	(550)	54.08	(33.61)	175.35	(108.96)	1238	(2730)
A8	635	(1400)	164.04	(101.93)	366.75	(227.89)	1767	(3895)
	621	(1370)	160.53	(99.75)	360.65	(224.10)	1749	(3856)
	249	(550)	48.90	(30.39)	163.89	(101.84)	1266	(2791)
B5	635	(1400)	151.07	(93.87)	345.52	(214.70)	1911	(4213)
	675	(1490)	161.24	(100.19)	363.14	(225.65)	1964	(4330)
	249	(550)	41.86	(26.01)	149.66	(93.00)	1410	(3109)
D2	635	(1400)	181.13	(112.55)	389.66	(242.13)	1786	(3937)
	567	(1250)	160.67	(99.84)	353.64	(219.74)	1698	(3743)
	249	(550)	56.02	(34.81)	165.	(102.53)	1285	(2833)
D4	635	(1400)	193.86	(120.46)	412.61	(256.39)	1740	(3837)
	531	(1170)	160.70	(99.86)	354.2	(220.15)	1605	(3538)
	249	(550)	61.41	(38.16)	176.40	(109.61)	1240	(2733)

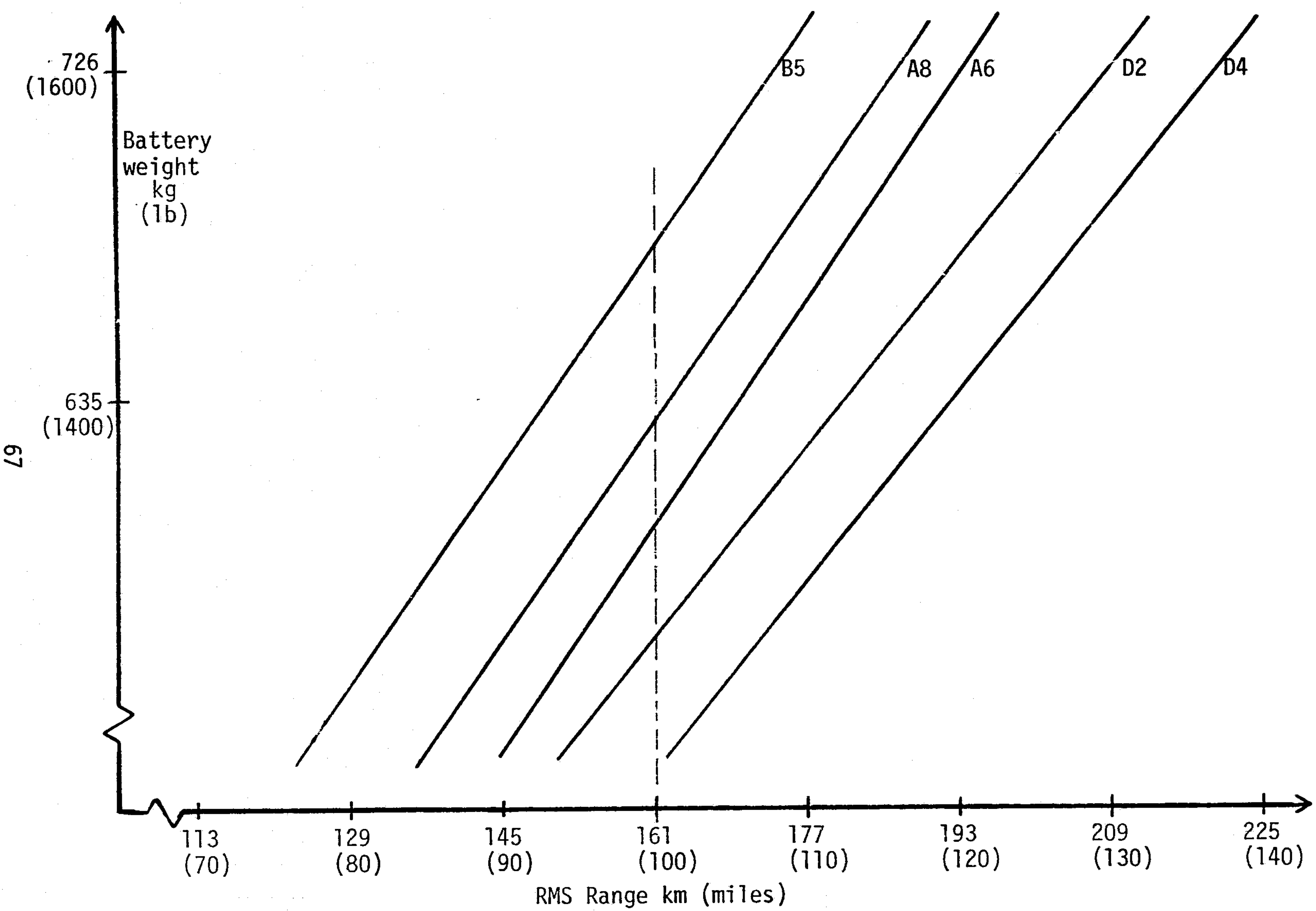

Figure 25. Battery Weight vs. Range with Lead Acid Batteries
SAE J227a Schedule D

Table 18. Battery Weight vs. Range

Lead Acid Battery Weight Needed for 161 km (100 mi) Range for SAE J227a Schedule D

CONCEPT	Battery WEIGHT		PROPULSION SYSTEM WEIGHT		VEHICLE TEST WEIGHT		RANGE		ENERGY CONSUMED PER MILE	
	kg	(lb)	kg	(lb)	kg	(lb)	km	(Miles)	MJ/km	(Wh/Mile)
A6	562	(1239)	181	(400)	1605	(3539)	161	(100)	.482	(215.91)
A8	594	(1310)	200	(442)	1681	(3705)	161	(100)	.514	(230.11)
B5	649	(1430)	294	(648)	1866	(4113)	161	(100)	.559	(249.97)
D2	549	(1210)	211	(465)	1641	(3617)	161	(100)	.487	(217.87)
D4	525	(1158)	197	(435)	1577	(3476)	161	(100)	.466	(208.39)
Range for SAE J227a Schedule D with 249 kg of Ni-Zn Batteries										
A6	249	(550)	181	(400)	1239	(2731)	175.35	(108.96)	.426	(190.66)
A8	249	(550)	200	(442)	1266	(2791)	163.89	(101.84	.454	(203.17)
B5	249	(550)	294	(648)	1410	(3109)	149.82	(93.01)	.493	(220.71)
D2	249	(550)	211	(465)	1285	(2834)	165.	(102.53)	.458	(204.96)
D4	249	(550)	197	(435)	1240	(2733)	176.40	(109.61)	.430	(192.32)

7.2 Control Modes

The controls for power flow are summarized in Table 19. The ac motor frequency is controlled in a manner to give a desired amount of slip. The controller thus needs a motor speed signal so that motor-rotational frequency can be compared to the controller output frequency. The voltage is increased linearly with frequency until the maximum voltage allowed by the battery occurs. The maximum voltage should be reached as the motor reaches its base speed.

In addition to controlling motor power and flywheel power, the motor speed is set within prescribed limits by shifting the gears in the multi-speed transmission. A range of gear ratios were examined as were a range of shift points to assure that the shift points selected match the motor efficiency curve. The differences in range resulting from differences in gear ratios are shown in Table 20. The variation in range is trivial indicating that the selected ratio is very close to an optimum value. The change in shift procedure shown in Table 21 produced a range improvement by making the up-shift point to top gear dependent upon torque requirement. For a full power acceleration, the up-shift point is delayed. This change permits the zero to 55 mph full-power acceleration to stay in second gear while allowing the 45 mph cruise portion of the Schedule D to be in top gear. An extra four to five percent range appears possible by such up-shifts.

7.3 Energy Management

The use of a high-power flywheel energy storage device can provide a substantial increase in range and performance for an electric vehicle if the energy to and from the flywheel is properly managed. Good management (ref. 18) of available energy can have a beneficial effect on battery life and can increase the amount of energy that can be extracted from the battery. There are several reasons why more energy can be extracted. One reason is that the total energy output capacity of the battery is greater if the battery power is low. Batteries can be designed for higher power or for greater energy but not always for both high power and high energy simultaneously. The use of a flywheel in a way that reduces the battery power level increases the extractable energy. (ref. 19) The battery power level can be reduced by leveling the battery current drain or by eliminating some of its peak power periods.

Another reason why more energy can be extracted is that a criteria for judging the discharge of a battery is the inability of the vehicle to meet minimum acceleration requirements. The flywheel can provide the extra boost of power for acceleration even though the battery is nearly discharged and not capable by itself to provide the needed power. This extra boost in power can compensate in part for battery degradation with aging or adverse temperature conditions.

The effective use of the flywheel is obtained when it is used to reduce peak current drain from the battery and to provide additional power for acceleration. Channeling all of the battery energy through the flywheel would

Table 19. Control Modes

CANDIDATE	DRIVE POWER CONTROL	FLYWHEEL POWER CONTROL
A6	Motor Voltage and Frequency	Generator Field Chopper
A8	Motor Armature Current Chopper Motor Field Current Chopper	Generator Field Chopper
B5	Two Motor Controllers For Voltage and Frequency	Generator Field Chopper
D2	Motor Armature Current Chopper Motor Field Current Chopper CVT Ratio, Rate of Change	CVT Ratio, Rate of Change
D4	Motor Voltage and Frequency	CVT Ratio, Rate of Change

Table 20. Range vs. Various Transmission Ratios for SAE J227a Schedule D Concept A6

Transmission Ratios High	Sec.	Low Gear	Range (Miles)
1	1.58	4.04	96.369
1	1.64	3.96	96.877
1	1.70	3.90	96.969
1	1.74	3.86	97.080
1	1.80	3.80	97.170
1	1.86	3.74	97.083

Table 21. Shift Point Evaluation

Shift Points:

First into second gear	38.41 km/h (35 ft/sec)
Second into third gear	82.30 km/h (75 ft/sec)

Range and Energy Consumption for SAE J227a Schedule D Driving Cycle

CONCEPT	PERFORMANCE CHARACTERISTIC	FIXED SHIFT POINTS	*UPSHIFT IF ACCELERATION = 0
A6	Range km, (mi)	163.41 (101.54)	170.04 (105.66)
	Energy Consumed kJ/km, (Wh/mi)	512. (228.78)	496. (221.6)
A8	Range km, (mi)	160.53 (99.75)	166.61 (103.53)
	Energy Consumed kJ/km, (Wh/mi)	540. (241.49)	525. (234.88)

*During cruise portion of SAE J227a Schedule D driving cycle acceleration equals zero. Upshift into third gear is done at 72.40 km/h (66. ft/sec).

not be an efficient way to utilize it unless it has very high in-and-out efficiency. The flywheel can add a parasitic load to the propulsion system in terms of its energy losses as well as adding an extra weight burden to the vehicle. Through proper utilization and sizing the advantages of power boosting and effective battery current reduction, the flywheel add benefits which more than offset its parasitic load. To be effective the it must be sized and used to minimize its energy losses and to maximize its use in recovery of braking energy, in reduction of effective battery power and in boosting vehicle performance.

Clearly, the vehicle usage has an impact upon the ability of the flywheel to be effectively used. A vehicle used mostly at steady cruise conditions has little opportunity to use the flywheel for acceleration or braking, However, a vehicle used in service involving a great deal of stop and go driving would use the buffer most often.*

To minimize the energy loss associated with the in-and-out efficiency of the flywheel the exchange of energy should be made under the most favorable conditions, i.e., those conditions where the best efficiency occurs if a choice is possible. Clearly, the need to meet acceleration and braking needs presents little choice. For both acceleration and deceleration a division of power from the battery and flywheel is possible. For recharging the flywheel from the battery, some choice of rate of recharge and timing of the recharge is possible.

Several schemes have been examined for the distribution of power for acceleration and deceleration. One scheme is to use the flywheel to supply power in proportion to the acceleration rate and absorb power in proportion to the deceleration rate. Another is to prejudge the power level over some driving cycle and set the battery power to satisfy the average needs and force the flywheel to deliver the time dependent deficiency or accept the excess. This is easy to accomplish in theory but is hard to do in practice. Still, another scheme is to set positive and negative limits on the battery current and have the flywheel provide the current in excess of the positive limit or accept negative current beyond the negative limit. A variety of flywheel recharge schemes are possible, but a recharge at the rate for the greatest efficiency is desired. A measure of the flywheel state of discharge is required for use by the recharge controller.

Figures 26, 27, and 28 illustrate the power and current in the Schedule D driving cycle for these three energy distribution schemes for candidate A8. Tables 22 and 23 show the range and energy consumption for candidates A8, D2, A6 and D4.

For the SAΓ J227a driving mode, setting battery current limits gives the greatest range and least energy consumption. For different driving modes, like acceleration from zero to 55 mph or the Federal Urban Driving

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*For example, the range improvement via use of a flywheel would be greater for the SAE J227A Schedule C than for the Schedule D because there are more stops and starts per mile for the Schedule C.

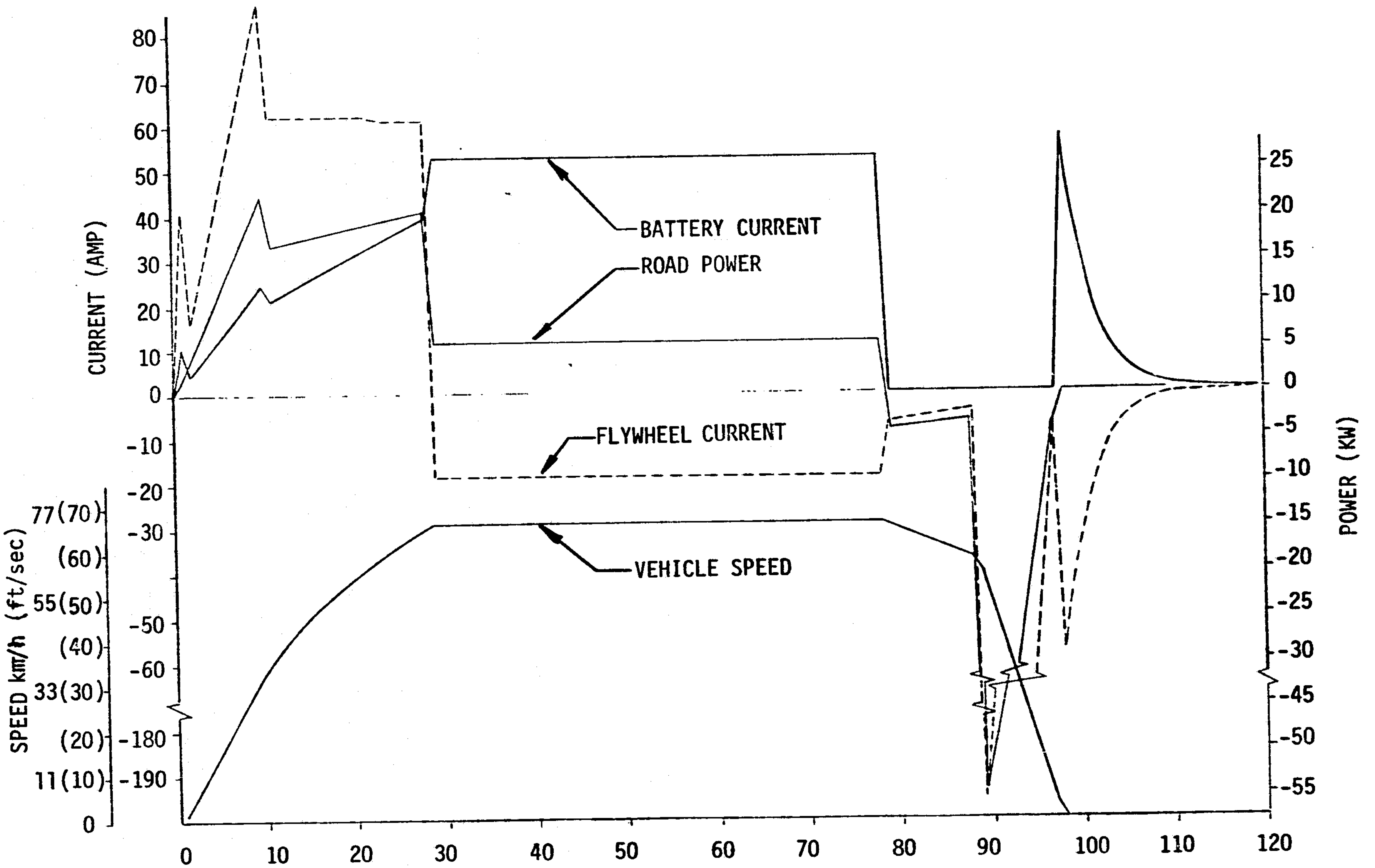

Figure 26. Concept A8. Flywheel/Battery Current-Acceleration Dependent

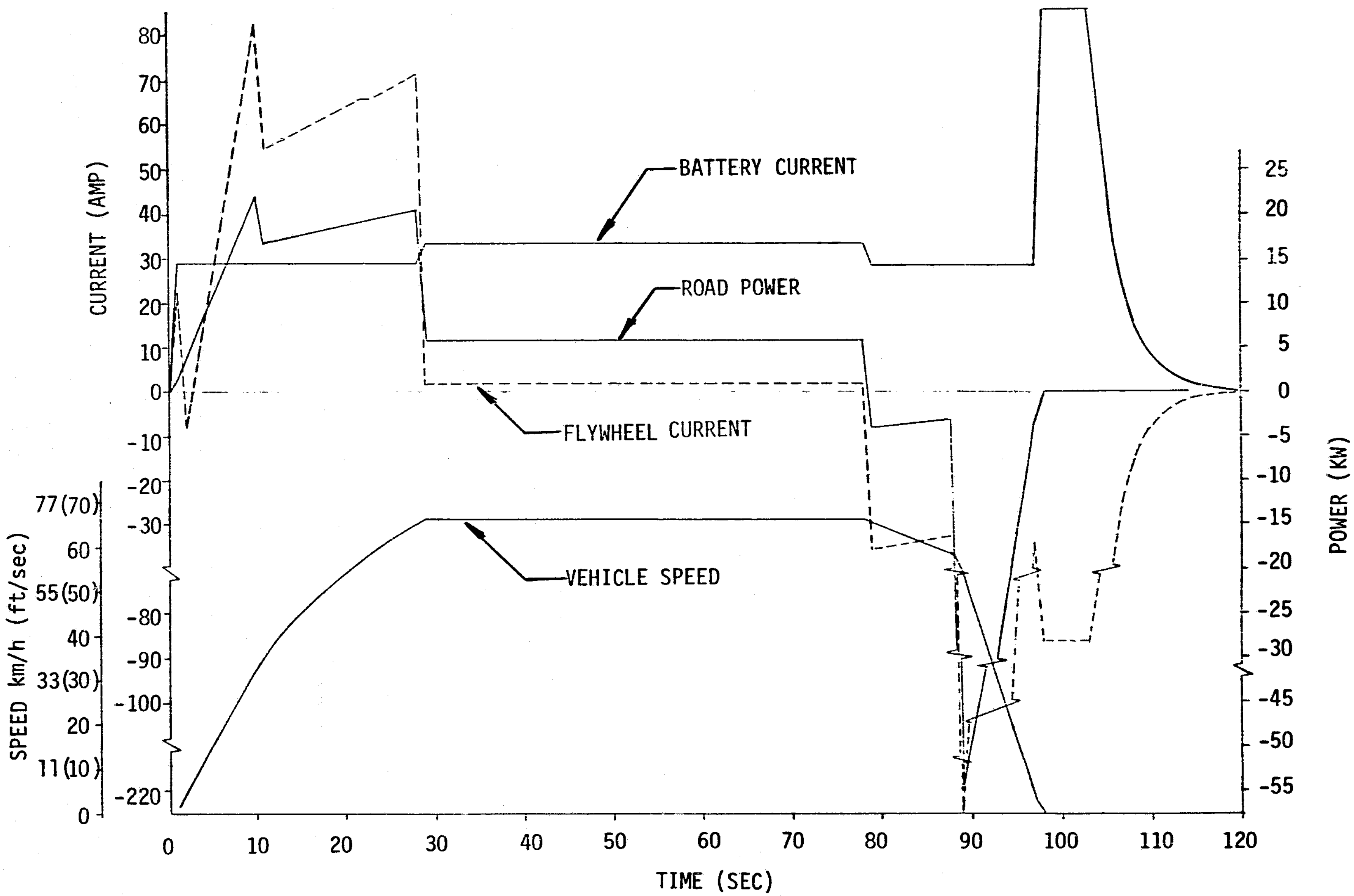

Figure 27. Concept A8. Battery Leveling

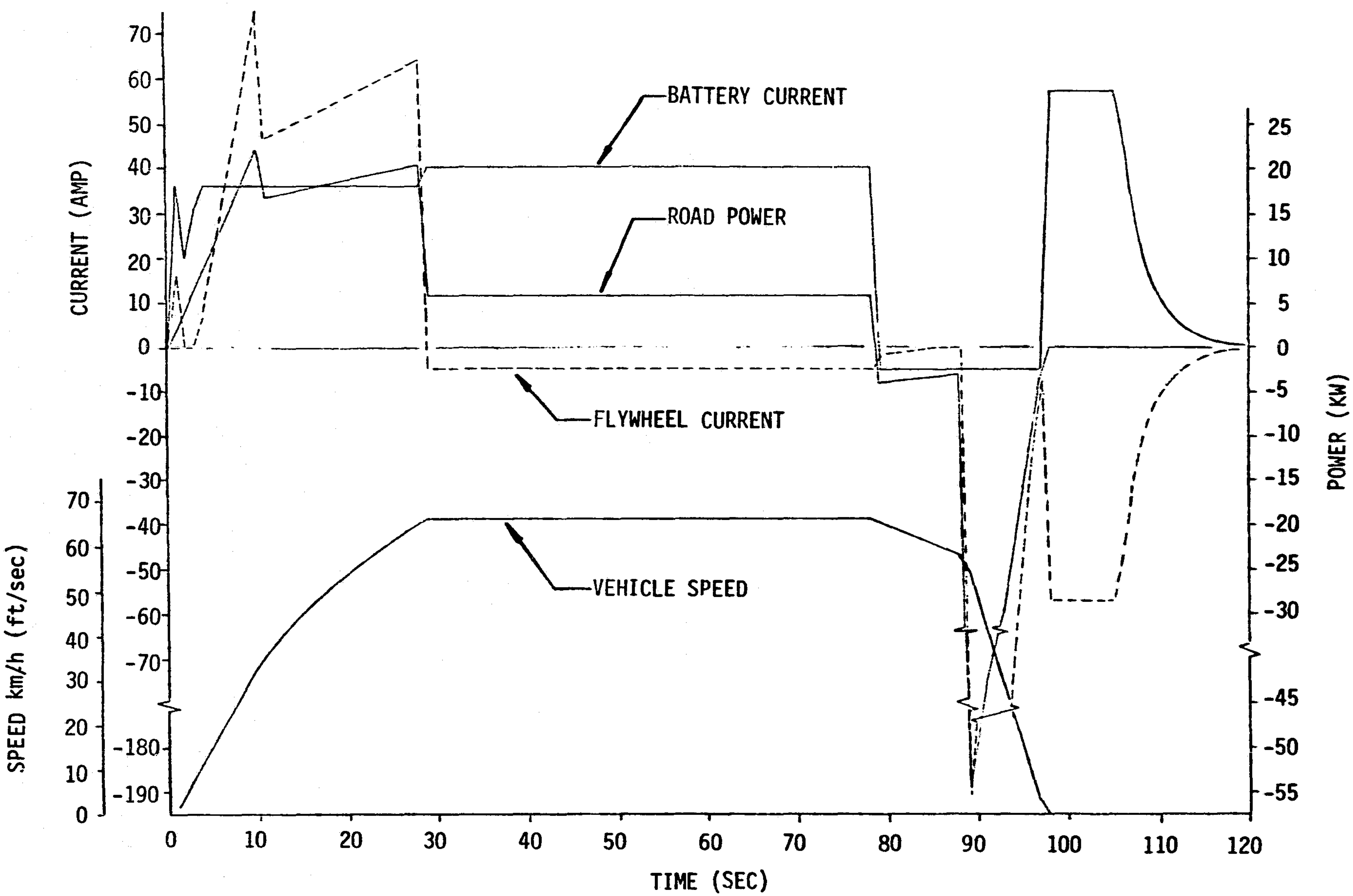

Figure 28. Concept A8. Preset Maximum Positive & Negative Current Limit

Table 22. Energy Management Scheme Evaluation

Concept D2. Brushless Separately Excited dc Motor with CVT Flywheel Buffer

Concept A8. Brushless Separately Excited dc Motor with Flywheel Buffer

Driving condition--SAE J227a Schedule D

Energy is battery, not wall plug energy

CONCEPT	PERFORMANCE CHARACTERISTIC	SCHEME: ACCELERATION DEPENDENT	SCHEME: BATTERY LEVELING	SCHEME: BATTERY CURRENT LIMITED
A8	Range km (mi)	160.5 (99.74)	163. (101.28)	171.4 (106.53)
	kJ/km (Wh/mi)	540 (241.49)	564. (252.32)	525. (234.96)
	Flywheel RPM * at End of Cycle	22359	22417	22358
D2	Range km (mi)	152.6 (94.84)	127. (78.95)	165.2 (102.67)
	kJ/km (Wh/mi)	504. (225.27)	616. (275.53)	493. (220.53)
	Flywheel RPM * at End of Cycle	22650	22362	22555

* Flywheel speeds indicate that recharge schemes function satisfactorily.

Table 23. Energy Management Scheme Evaluation

Concept A6. AC Induction Motor with Flywheel Buffer

Concept D4. AC Induction Motor with CVT Flywheel Buffer

Energy is battery, not wall plug energy

Driving Cycle: SAE J227a Schedule D

CONCEPT	PERFORMANCE CHARACTERISTIC	ACCELERATION DEPENDENT	BATTERY LEVELING	BATTERY CURRENT LIMITED
A6	Range km (mi)	169.77 (105.49)	176.85 (109.89)	182.55 (113.43)
	kJ/km (Wh/mi)	496. (221.91)	510. (227.88)	480 (214.57)
	Flywheel RPM at End of Cycle*	22359	22417	22359
D4	Range km/(mi)	160.1 (99.48)	119.12 (74.02)	158.18 (98.29)
	kJ/km (Wh/mi)	473 (211.52)	605. (270.78)	469. (209.91)
	Flywheel RPM at End of Cycle*	22646	22338	22562

* Flywheel speeds indicate that recharge schemes function satisfactorily.

Cycle (FUDC), varying the flywheel generator and battery current according to acceleration, gave the best overall results and this scheme was used in all further work of this study.

7.4 Performance Comparisons

After the candidate systems were optimized for best gear ratios, shift points, motor overload capabilities and energy management schemes, the battery weights were adjusted to give a uniform range in the Schedule D. cycle. All of the candidates meet the driving performance requirements. The weights and energy consumptions are summarized in Table 24. The two motor concept B5 has the greatest battery weight as well as the greatest total weight and energy consumption.

The CVT candidates require less battery weight and use less energy in the D cycle than do the A6 and A8 candidates. However, the CVT candidates have lower range for steady 45 mph driving.

The energy consumption per mile shown in the table is the battery energy rather than wall plug energy. Dividing by the battery and charger efficiencies brings the wall plug energy consumption to a value in excess of the goal of 559 kJ/km (250 Wh/mile).

For a charger efficiency of 85 percent and the given lead-acid battery efficiency of 60 percent, the wall plug energy consumption of the best candidate D4 increases from .466 MJ/km (208.3 Wh/mi) to .914 MJ/km (408 Wh/mi).

7.5 Cost Comparison

The life cycle cost for the five candidates are summarized in Table 25. (Cost was generated following cost estimating guidelines listed in Appendix D.) The B5 candidate is the least attractive although all five candidates meet the goal of a life cycle cost less than \$.05/km (\$.08/mile). The other four candidates are very close in cost. The energy costs of the CVT candidates are less than those for A6 and A8, however, the higher maintenance cost more than offset the energy savings. Lower acquisition costs are projected for the CVT candidates which compensate for the slightly higher operating cost compared to A6 and A8.

7.6 Candidates Recommended for Conceptual Design

All candidates in Table 24 appear to be capable of meeting range, performance and cost objectives. The candidates using CVT concepts D2 and D4 did not meet the constant 72.4 km/h (45 mph) range requirement of 209 km (130 miles) but this can be solved by adding approximately 20 kg (45 lbs) of lead-acid batteries. However, none appear to meet the wall plug energy consumption goal of 250 Wh/mile unless very efficient batteries and recharge units are used. All have some developmental risk which must be more fully studied.

Table 24. Candidate Weight/Performance Comparison

	CANDIDATES				
WEIGHT kg(lb)	A6	A8	B5	D2	D4
VEHICLE TEST WEIGHT	1605(3539)	1681(3620)	1866(4113)	1641(3553)	1577(3476)
BATTERY WEIGHT	562(1239)	594(1264)	649(1430)	549(1175)	525(1158)
MOTOR WEIGHT	41(90)	60(132)	168(371)	57(125)	41(90)
CONTROLLER WEIGHT	47(104)	47(104)	47(104)	24(54)	24(54)
TRANSMISSION WEIGHT	20(45)	20(45)	7(15)	20(45)	20(45)
AXLE WEIGHT	27(59)	27(59)	27(59)	27(59)	27(59)
FLYWHEEL WEIGHT	23(50)	23(50)	23(50)	23(50)	23(50)
GENERATOR WEIGHT	18(40)	18(40)	18(40)	--	--
CVT WEIGHT	--	--	--	63(139)	63(139)
PROPULSION SYSTEM WEIGHT	176(388)	195(430)	290(639)	214(472)	198(437)
BATTERY ENERGY PER MILE MJ/km(Wh/mi)					
"D" CYCLE	.482(216)	.514(222.8)	.599(249.9)	.487(212.4)	.466(208.3)
STEADY 45 MPH	.368(164.6)	.383(171.1)	.462(206.6)	.384(171.9)	.380(170.1)
RANGE km(mi)					
"D" CYCLE	161(100)	161(100)	161(100)	161(100)	161(100)
STEADY 45 MPH	226(140.6)	225(139.6)	207(128.6)	204(126.7)	203(126.1)

Table 25. Candidates - Propulsion System Cost Comparison

Candidates	A6 AC	A8 DC	B5 AC	D2 DC	D4 AC
Acquisition Cost	3460	3491	4207	3307	3287
Annualized Acquisition Cost	346	349.1	420.7	339.7	328.7
Discounted Annual Cost @ 2% Discount Rate					
Electricity	129.3	132.9	149.1	127.1	125.7
Repair & Maintenance	100.3	100.3	86.2	116.1	116.1
Battery Replacement	99.8	101.8	115.2	94.6	93.3
Power Train Salvage	-3.8	-3.8	-4.7	-3.6	-3.6
Battery Salvage	-25.3	-25.8	-29.2	-24.1	-23.7
Discounted Annual Operating Cost	300.3	305.4	316.6	310.1	307.8
Present Value of Cycle Cost/year	646.3	654.5	737.3	640.8	636.5
Present Value of Life Cycle Cost/mi	.065	.065	.074	.064	.064

All figures are in 1976 dollars.

In selecting candidates for conceptual designs, it seems appropriate that systems with minimized development risks should be preferred. Since the performance differences and life cycle cost difference among A6, A8, D2 and D4 are not great, other factors such as the balancing of developmental risks and the keeping of options open lead to the recommended candidates, A6 and D2.

The flywheel/generator of A6 provides a special source and sink for the reactive kVA of the three-phase ac induction motor and may simplify the development of the dc to ac inverter controller capable of regeneration over a wide-speed range.

The D2 candidate with its dc motor and its stable field excitation removes an element of developmental risk which partly offsets the higher risk associate with the development of a suitable CVT.

Recommended Candidates for Task III Studies

A6 AC Induction Motor With Flywheel/Generator Unit

D2 Electronically Commutated DC Motor With Flywheel/CVT Unit

8. CONCEPTUAL DESIGN

In the design trade-off studies two advanced propulsion candidates were selected for conceptual design. Layout drawings of components were prepared. Design details for the inverter and control circuit were examined to confirm the ratings of semiconductor components. Sizes and types of CVTs were examined for their suitability.

Safety factors and component layout constraints force several modifications of the configurations and sizes of components emerging from the design trade-off studies. Most significant of these changes are the selection of a battery voltage of 96 volts, the use of transistorized choppers and inverters, and the reduction in the size and energy storage of the flywheel from 6.84 MJ (1900 Wh) to 2.44 MJ (678 Wh.)

Appendix I and II list the specifications of the two conceptual designs.

8.1 System Voltage and Semiconductor Types

During the preliminary analysis and design trade-off studies a system voltage of 240 volts dc was considered with SCRs being used for switching in the inverters and choppers. This voltage is higher than commonly used in electric vehicles, but seemed reasonable for an advanced concept which would require a high battery weight to achieve the desired range of 161 km. The higher voltage would allow a lower current for a given power, and this lower current would give lower losses in the semiconductor switches. The lower current would also allow smaller wiring for motor connections. Switching with SCRs is compatible with the higher voltage and was believed to be more efficient and less expensive than switching with transistors. (refs. 20,21) However, as the designs evolved the practical limitations of SCRs became apparent. (ref. 22).

The postulated advantages of high voltage had to be compared with the known disadvantages. Numerous battery manufacturers were contacted regarding the practicality of higher voltages, and all were discouraging (ref. 23).

An increase in battery voltage would require an increase in the number of cells. As presently manufactured the cell sizes would not be decreased enough to provide an efficient utilization of space and weight. A 50-amp hour cell uses the same mechanical accommodation as a 75-amp hour cell. A large number of small cells would require more maintenance than a small number of large cells. (ref. 24) The reliability of the small cells may also be less than that for the large cells. It is believed that the attempt to increase lift truck voltages from 36 volts to 72 volts was unacceptable because there was a higher cost for servicing the additional cells.

Higher voltages increase the danger of fire and electrocution. There is a danger of leakage current on the outside of the cells and across the trays. Good housekeeping and cleanliness can reduce the danger but at an increase in maintenance cost. It is common practice in car systems to group the cells in separate trays and to avoid having more than 24 volts between adjacent batteries. In spite of these practices sudden fires are still a problem.

High voltage dc is much more hazardous than high voltage ac.(refs. 25,26) A dc voltage will sustain an arc at a level where an ac voltage will not. The danger of electrocution from dc is much greater than from ac because a person cannot let loose from the dc source. Of course, protection from the hazards are possible as high voltage dc is used for light rail and trolley bus transportation systems. However, the special means for protection will add to the cost and may not always be effective. (ref. 27) The use of lower voltage will not completely solve the safety problems, but will make the solutions easier and less expensive.

The potential gain due to use of higher voltage is an improvement in controller efficiency and a reduction in controller cost by lowering the current rating of the semiconductor switches. However, analysis of a nominal 100 volt dc system shows that reasonably high efficiency at an acceptable cost is obtainable.

Trading off potential safety hazards, maintenance cost and efficiency gains, it appeared that a nominal 100 volt dc system should be designed. Considering six-volt batteries at 75 pounds each, a system with 1200 pounds of batteries has 16 such batteries and a total of 96 volts. The conceptual designs were based on 96 Vdc.

Examination of inverter and chopper circuits and frequency requirements for the high speed motors, made it apparent that device shut-off times would be a very serious problem with SCRs Pulse width modulation and high frequency chopping would simply not be possible with SCRs

Of course, low frequency systems compatible with SCRs could be considered but the size and weights of components for a low frequency system are unattractive. A chopping or modulating frequency of about four kHz appear to be desirable. Much lower frequencies would require large reactors to keep the ripple current low. (ref. 28) Much higher frequencies would require special magnetic materials to minimize eddy current losses. The limitations of power diode turn-off times will prevent use of very high frequencies.

Transistorized choppers and inverters are used for the conceptual design rather than SCRs The projected controller efficiency of 96 percent should be attainable in the near future.

In mass production power transistors would be matched closely to the traction motor voltage and amperage, providing highest efficiency at reduced cost. It also should be possible to integrate traction motor and the power section of the controller in one unit just as it is done in today's car alternator reducing the cost and size even further.

8.2 Description of Concept A6

This propulsion system uses a three-phase ac induction motor for propulsion power. The drive is through a three-speed transmission and final drive gear combined in a transaxle. The arrangement is for a front-wheel drive which allows effective regenerative braking for most normal braking situations. Conventional four-wheel hydraulic brakes are used when more rapid braking is required.

The electrical power supplied to the drive motor comes from the battery and from a flywheel/generator energy unit with the division of power from these two sources controlled in such a way as to limit the current to and from the battery. The electrical energy from these two sources is delivered at 96 volts dc to a three-phase inverter which gives a three-phase ac output of the desired voltage and frequency to drive the induction motor or to provide braking by forcing the induction motor to operate as a generator to return energy to the flywheel or battery.

The principal characteristics of this design are summarized in Table 26. More complete specifications and drawings are given in Appendix A. The layout of the components are shown in Figure 29.

More complete details of the vehicle configuration and components are shown in the following drawings (located in Appendix A):

DRAWING NUMBER	DRAWING
131D051	Flywheel
131D052	Homopolar Inductor Generator
131D053	Flywheel--Dc Generator
131D054	Stator-Rotor Ac Traction Motor
131D055	Motor-Transaxle Assembly
131D057	General Arrangement
131F056	Schematic--Concept A6 (included as Figure 33)

8.2.1 Current Waveforms and Harmonic Losses

Because of its high cost and complexity the dc to ac controller for the ac induction motor of the A6 concept has been of major concern. The controller consists primarily of a dc to ac inverter with a variable frequency and voltage output. The output frequency is controlled to give a desired amount of slip for the induction motor. The desired positive slip is proportional to the driver-controlled position of the accelerator pedal and desired negative slip is determined by the driver via the position of the brake pedal. For a constant air gap flux, the torque of the induction motor is approximately proportional to the slip. The output voltage of the motor controller is maintained approximately proportional to the frequency in order to produce the desired air gap flux in the motor. The output waveform of the inverter and the means of controlling frequency and voltage have been studied.

Table 26. General Propulsion System Specification

Design Concept A6

Curb weight	1400 kg (3218 lbs)
Battery weight	556 kg (1226 lbs)
Propulsion system weight less battery	178 kg (392 lbs)
Traction Motor	
3-phase ac induction	
Rated power	26 kW
Base speed	7200 rpm
Efficiency	91%
Power factor	.84
Weight	41 kg (90 lbs)
Rated Voltage	75 Vac
Fiber Composite Flywheel	
Total stored energy	2.44 MJ(678 Wh)
Maximum speed	46300 rpm
Total weight	16 kg (35.3 lbs)
Flywheel Motor/Generator	
Brushless DC	
Peak power	45 kW
Base speed	23158 rpm
Maximum speed	46300 rpm
Efficiency	87%
Weight,	20 kg (43.3 lbs)
Transaxle 3-speed	
Weight	49 kg (109 lbs)
Controllers - variable voltage and frequency	
Rated power	63.5 kVA
Weight	52 kg (114 lbs)
Battery/Lead-Acid	
Specific energy	40 Wh/kg (18 Wh/lb)
Specific power	100 W/kg (45 W/lb)
Efficiency	60%
Propulsion System Performance	
Range for steady 45 mph cruise	225 km (140 miles)
Range for SAE J227a Schedule D	161 km (100 miles)
Acceleration - 10 to 55 mph	15 sec

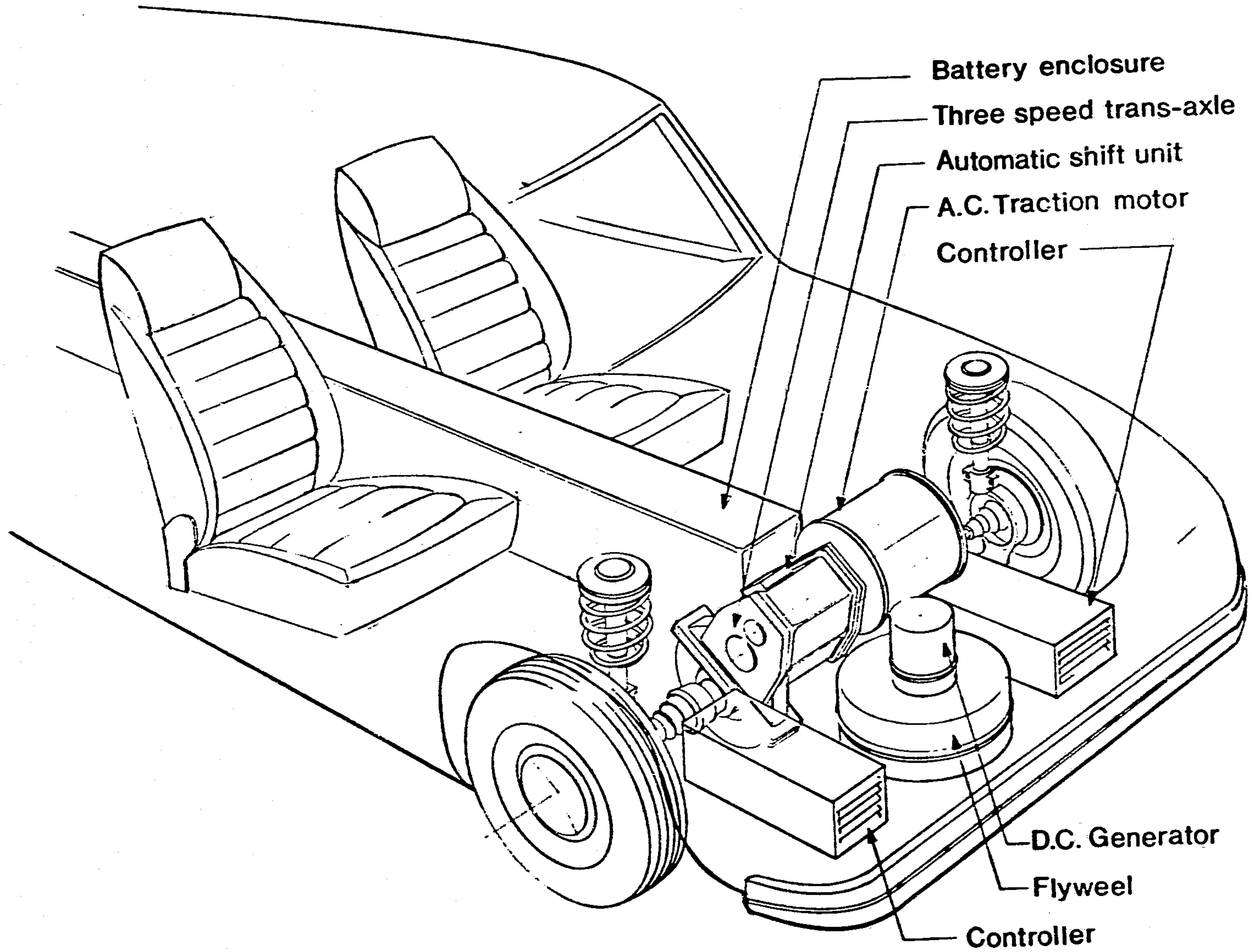

Figure 29. Design Concept A6

The output voltage waveform will not be a pure sinusoidal wave but will be more nearly a rectangular pulse wave as shown in Figure 30. This wave will contain harmonics which presumably could cause undesirable energy losses and torque fluctuations. To determine the effects of harmonic content on energy losses, the rectangular pulse was resolved into its Fourier series components which were then used as input voltage for the motor's equivalent circuit.

In the three-phase motor, the harmonics which are multiples of three will produce no current, so these may be ignored. Those odd harmonics which have a harmonic number that is one less than a multiple of three will produce a negative slip due to a reverse rotation of magnetic field and those with a harmonic number one greater than a multiple of three will give positive slip and forward rotation of magnetic field. To solve for the current and losses in the equivalent circuit of Figure 31, the values of slip and reactances which are frequency dependent must also be solved. For the higher harmonics, the reactances increase substantially and cause a significant reduction in the current components.

Table 27 shows the harmonic amplitudes for unity height rectangular pulses of various pulse widths. The magnitude of the fundamental increases as the pulse width increases. The amplitude of the third, ninth and other harmonics of multiples of three are shown although they produce no current in the three-phase circuit. The fifth harmonic can be set to zero by use of a pulse of 72^o or 144^o, however, a pulse width greater than 120^o is difficult to accommodate in a three-phase circuit.

For a delta-connected, three-phase motor with a 240 volt* rectangular pulse, the leg voltages for the fundamental and various harmonics are shown in Table 28 for pulses of various widths. The motor current components associated with the voltage harmonics have been computed using the equivalent circuit for a wide range of load conditions. The value of the fundamental current component varies with loading condition, but the current components associated with the harmonic are practically independent of load because the effective impedance of the motor at the high frequencies of the harmonics is nearly independent of motor torque, is highly reactive, and increases almost linearly with frequency. The current values are shown in the table for the maximum load condition. The table shows that the current components drop off very rapidly as the harmonic number increases.

The power losses associated with the various harmonics are shown in Table 29. The losses for the fundamental are quite large because the motor is at its maximum torque. These losses will decrease as the motor power decreases because the efficiency increases at lighter load.

The losses associated with the harmonics remain independent of load. The summation of all the losses due to harmonics are very small for all pulse widths.

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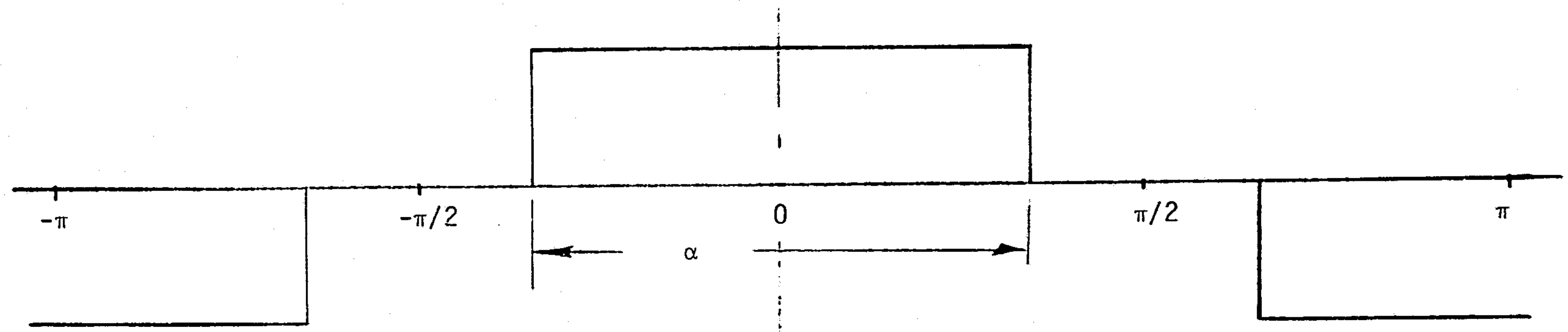
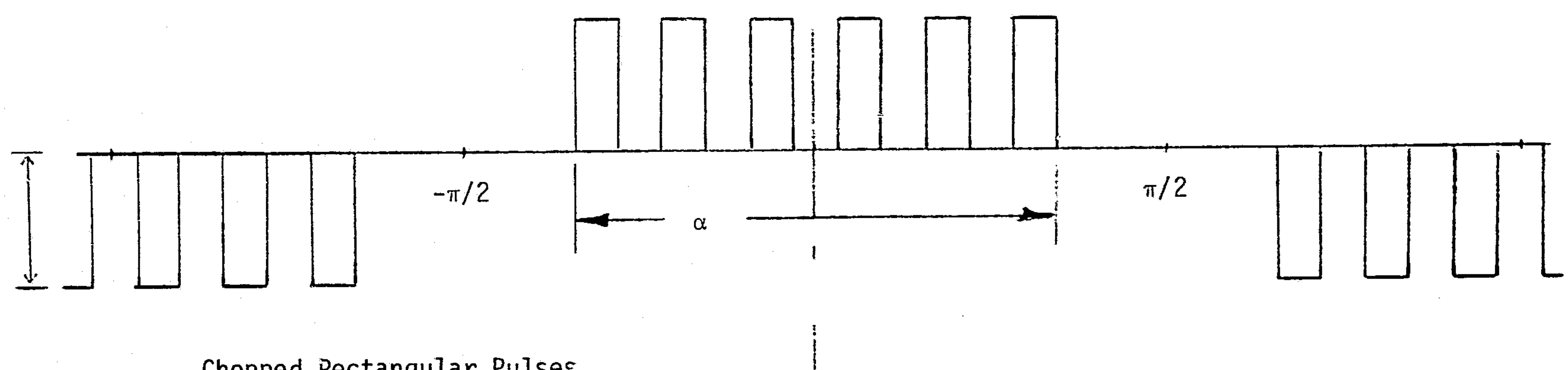
*The 240 volt was convenient to use initially. The system voltage was subsequently reduced to 96 volt but this does not change any of the basic conclusions as all quantities scale directly with power and kVA held constant. The motor losses are independent of design voltage.



Rectangular Pulses

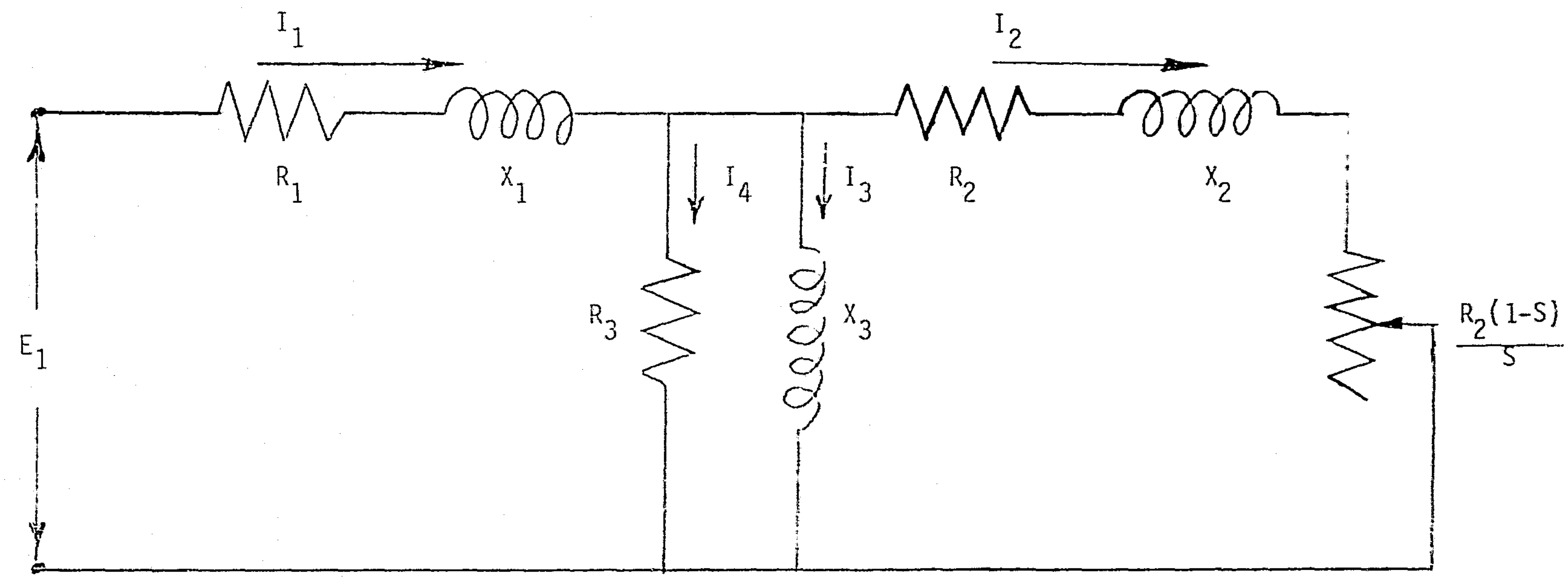


Chopped Rectangular Pulses

α = pulse width

V_p = peak voltage (battery voltage minus controller voltage drop)

Figure 30. Voltage Waveform From Inverter



S	=	Slip	
E_1	=	Phase voltage	V/phase
I_1	=	Stator current	A/phase
I_2	=	Rotor current	A/phase
I_M	=	$I_4 + I_3$ = Exciting current	A/phase
R_1	=	Stator resistance	Ω/phase
R_2	=	Rotor resistance	Ω/phase
R_3	=	Iron loss equivalent resistance	Ω/phase
X_1	=	Stator leakage reactance	Ω/phase
X_2	=	Rotor leakage reactance	Ω/phase
X_3	=	Magnetizing reactance	Ω/phase

Figure 31. Equivalent Circuit of Induction Motor

Table 27. Harmonic Amplitudes of Pulsed Wave

Harmonic No.	Amplitude for Various Pulse Widths, α				
	60^{o}	72^{o}	90^{o}	120^{o}	144^{o}
1	.6366	.7484	.9003	1.1027	1.2109
3	.4244	.4036	.3001	.0000	-.2494
5	.1273	.0000	-.1801	-.2205	.0000
7	-.0909	-.1730	-.1286	.1575	.1069
9	-.1415	-.0832	.1000	.0000	-.1345
11	-.0579	.0680	.0818	-.1002	.1101
13	.0490	.0931	-.0692	.0848	-.0576
15	.0849	.0000	-.0600	.0000	.0000
17	.0375	-.0712	.0530	-.0649	.0440
19	-.0335	-.0394	.0474	.0580	-.0637
21	-.0606	.0356	-.0429	.0000	.0577
23	-.0277	.0526	-.0391	-.0479	-.0325
25	.0255	.0000	.0360	.0441	.0000
27	.0472	-.0448	.0333	.0000	.0277
29	.0220	-.0258	-.0310	-.0380	-.0418
31	-.0205	.0241	-.0290	.0356	.0391

Table 28. Leg Voltage and Current Associated With Harmonics of Pulsed Wave at Maximum Torque

	Pulse Width								
	60^{0}		90^{0}		120^{0}		144^{0}		
Harmonic No.	V RMS	I RMS	V RMS	I RMS	V RMS	I RMS	V RMS	I RMS	Power Factor
1	108.00	170.60	152.80	241.30	187.20	295.50	205.50	324.50	.726
5	21.60	10.75	30.60	15.20	37.40	18.60	0.00	0.00	.019
7	15.40	5.49	21.80	7.76	26.70	9.50	18.10	6.45	.043
11	9.82	2.22	13.90	3.14	17.00	3.85	18.68	4.23	.014
13	8.31	1.59	11.80	2.25	14.40	2.76	9.77	1.87	.029
17	6.36	.931	8.99	1.32	11.00	1.61	7.47	1.09	.016
19	5.69	.745	8.04	1.05	9.85	1.29	10.82	1.45	.026
23	4.70	.509	6.64	.719	8.14	.881	5.52	.598	.018
25	4.32	.431	6.11	.609	7.49	.742	0.00	.000	.027
29	3.73	.320	5.27	.453	6.45	.554	7.09	.608	.022
31	3.48	.280	4.93	.396	6.04	.485	6.63	.532	.029

C-2

Table 29. **Losses Per Leg Associated With Harmonics of Pulsed Wave at Maximum Torque**

Power and Losses in Watts per Leg

Harmonic No.	Losses at Pulse Width 60^{0}	90^{0}	120^{0}	144^{0}
	Power = 10404	20809	31215	37645
1	2971	5942	8914	10750
5	12.500	24.900	37.400	0.000
7	3.440	6.880	10.300	4.750
11	.660	1.320	1.980	2.390
13	.371	.742	1.110	.513
17	.155	.310	.464	.214
19	.110	.220	.330	.398
23	.063	.126	.189	.087
25	.050	.100	.149	.000
29	.033	.067	.100	.121
31	.028	.056	.084	.102
Homonic Loss $\sum_{5}^{31}$	17.41	34.72	52.11	8.59

The values of the current components in Table 29 are used in conjunction with the power factors of Table 28 and the signs of the Fourier coefficients in Table 27 to generate a resultant current waveform. This waveform is obtained by simply adding up the harmonic components. By superimposing the current waveform upon the on/off diagram for the semiconductors in the simplified inverter circuit of Figure 32 the current has been resolved into paths through the diodes and switching units (shown as NPN transistors) and a suitable summation of these currents gave the current to or from the battery.

The average and RMS value of current through the diodes and transistors was found by integrating the waveforms for each unit. The average current from the battery agrees with that calculated on the simple basis of electrical power to the motor. The average current through the diodes agrees closely with that calculated simply on the basis of the reactance kVA of the motor being handled by the diodes and the average current in the transistors on the basis of the resultant kVA of the motor. Improving the power factor of the motor reduces the average current in the semiconductors.

The waveforms for the current from the battery showed a very large ripple at six times the electrical frequency of the motor. This ripple could have a very undesirable effect upon the battery. A large commutating capacitor will be necessary to protect the battery from the high frequency ac current components and to protect the transistors from high voltage spikes.

8.2.2 Control Circuits

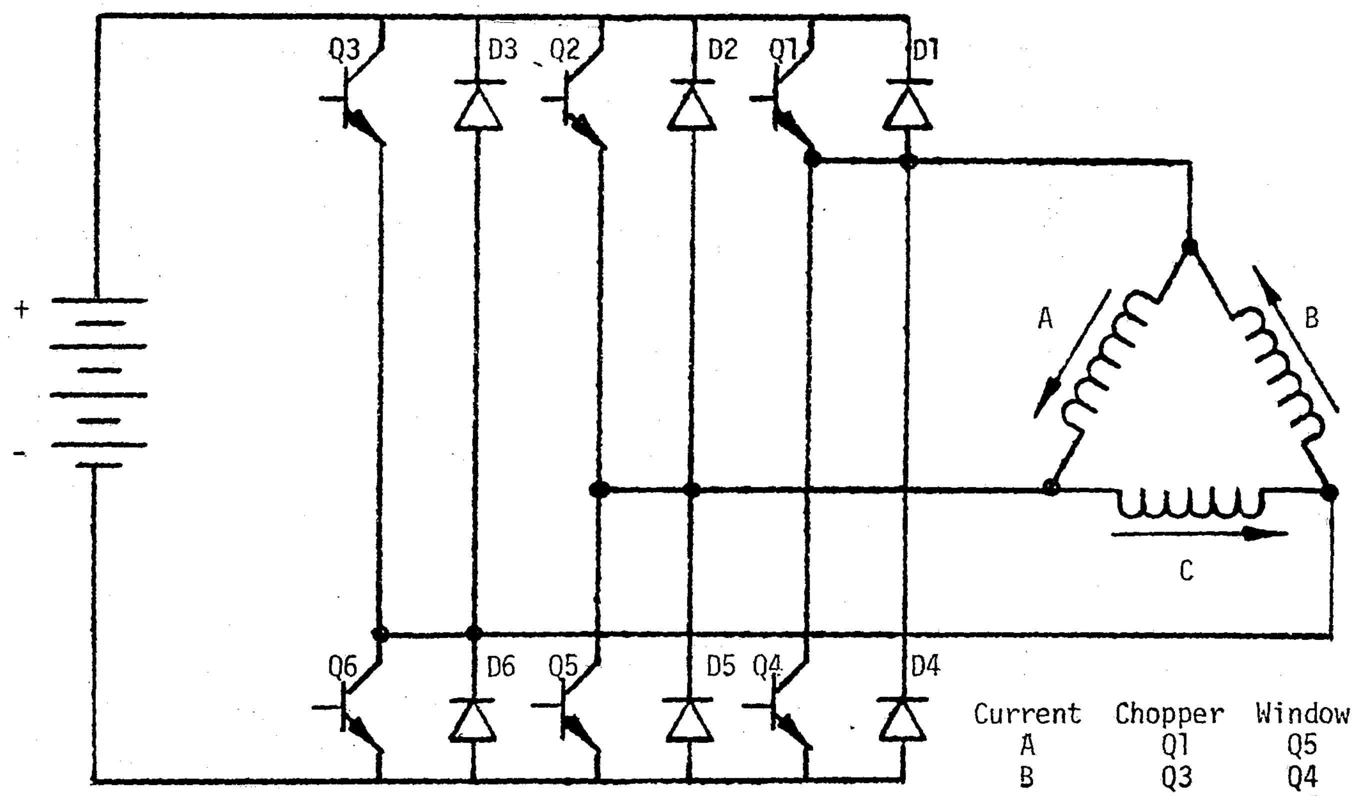
The control circuit diagram is shown in Figure 33 with more detail on Drawing 131F056.

8.2.2.1 Slip Controller

The motor slip is calculated, with the use of a standard divider and a difference amplifier, from the following equation:

$$s = \frac{n_s - n}{n_s}$$

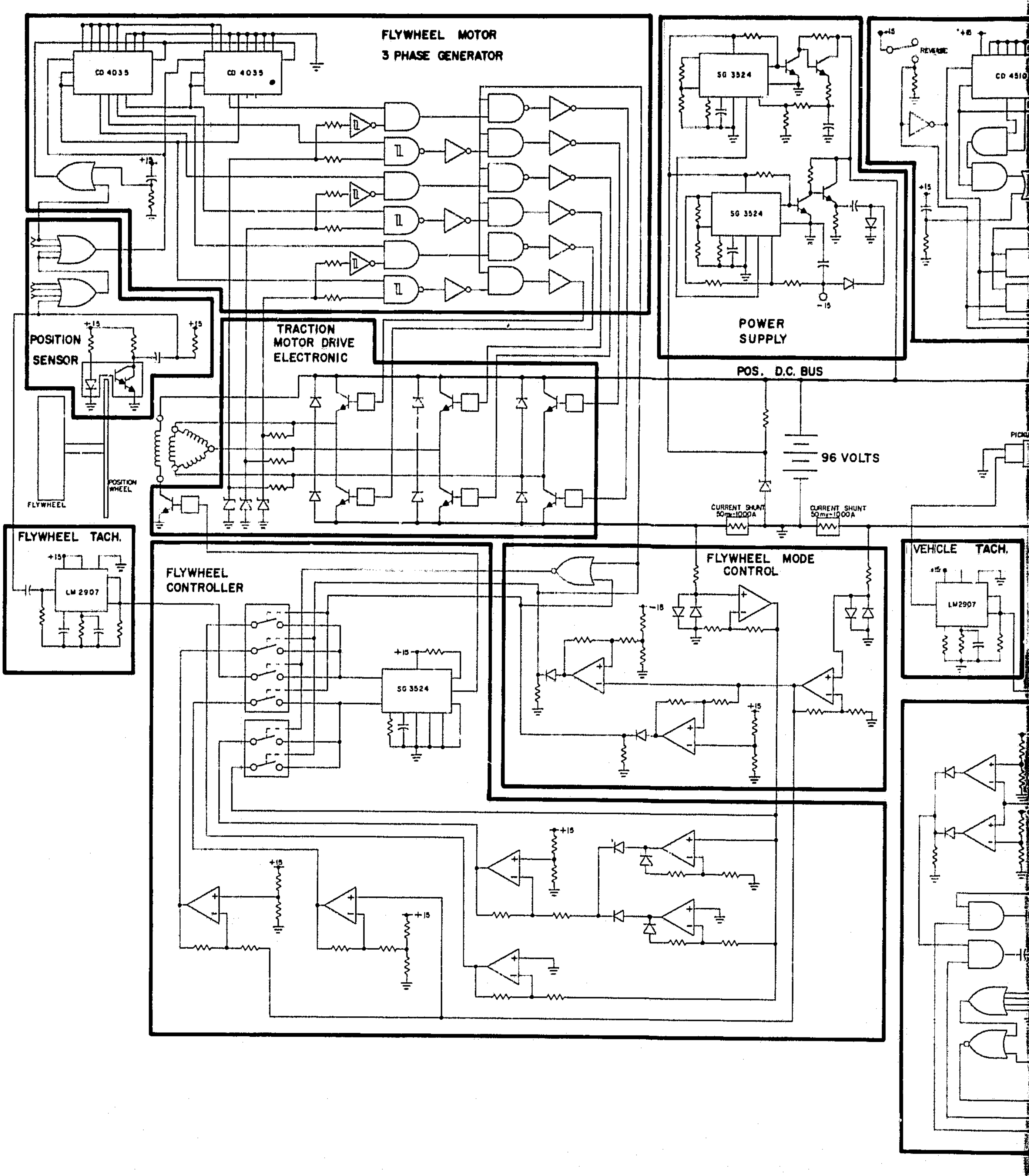
The synchronous frequency (n_s) is proportional to the control voltage of a Voltage to Frequency Converter (V.C.O.) The rotor frequency (n) is determined by the rotor tachometer. The slip is controlled with feedback techniques around an operational amplifier. The slip figure is fed back to the inverting junction while the output controls the V.C.O. Since the output frequency of the V.C.O. is the synchronous frequency, any signal on the noninverting input of the op amp represents a slip command. The slip will therefore be regulated to a level proportional to this signal.



When Q6 turns off, D3 may conduct.
When Q5 turns off, D2 may conduct.
When Q4 turns off, D1 may conduct.

Current	Chopper	Window	FW Diode
A	Q1	Q5	D4
B	Q3	Q4	D6
C	Q2	Q6	D5
-A	Q2	Q4	D5
-B	Q1	Q6	D4
-C	Q3	Q5	D6

Figure 32. Simplified Inverter Circuit


FLYWHEEL MOTOR
3 PHASE GENERATOR
CD 4035
CD 4035
POSITION SENSOR
FLYWHEEL
POSITION WHEEL
TRACTION MOTOR DRIVE ELECTRONIC
SG 3524
SG 3524
POWER SUPPLY
REVERSE
CD 4510
POS. D.C. BUS
96 VOLTS
CURRENT SHUNT 50mv-1000A
CURRENT SHUNT 50mv-1000A
FLYWHEEL TACH.
LM 2907
FLYWHEEL CONTROLLER
SG 3524
FLYWHEEL MODE CONTROL
VEHICLE TACH.
LM2907

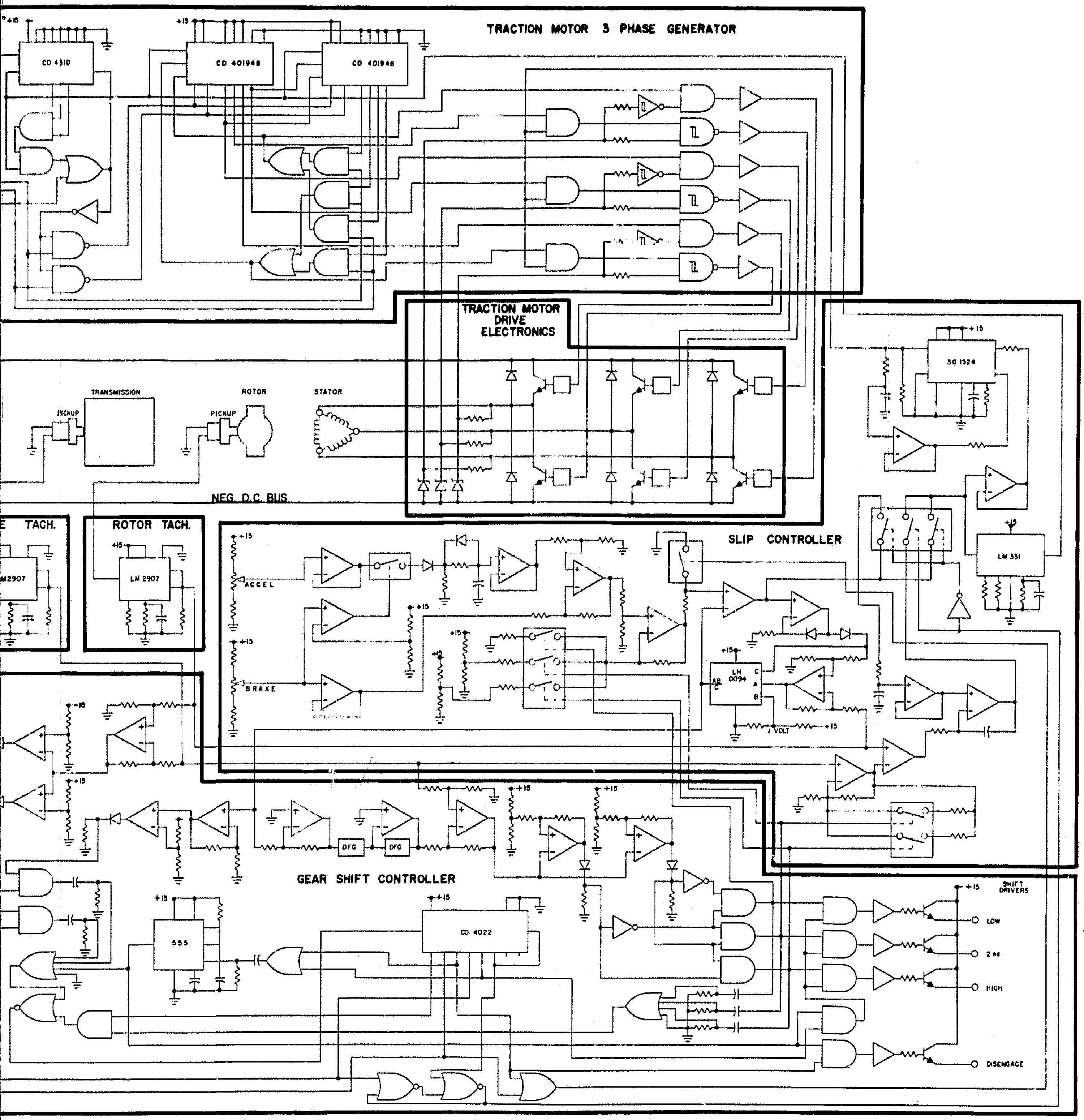


Figure 33. A6 Control Circuit Diagram

The applied motor voltage varies linearly with frequency to the point of magnetic saturation. This is accomplished through the use of Pulse Width Modulation (P.W.M.). The Pulse Width is directly proportional to the synchronous frequency voltage until it reaches the saturation point.

8.2.2.2 Traction Motor Three-Phase Generator

The three-phase generator develops the control signals for the six power transistors that drive the traction motor. The signal sequence is periodic and its frequency is equal to the V.C.O. output frequency. The P.W.M. signal is imposed on one half of the transistors to provide voltage control. A unique feature is that the system also monitors the line voltage to ensure that any two common devices will not turn on simultaneously. This allows the conduction angle of the generator to approach a maximum of 120°.

8.2.2.3 Gear Shift Controller

The gear shift controller performs two functions. It determines when to shift and into which gear. It also controls the shifting sequence. The shifting sequence is a function of a six-position counter. The normal mode is position zero at which the slip controller maintains command. A shift command increments the counter to position one which sets the slip to zero, and then increments the counter to position two. Position two maintains the slip at zero, provides a 400 msec pulse to disengage the gears, and then increments the counter to position three. Position three commands the slip controller to synchronize the drive gear with the selected gear. After synchronizing, the counter is incremented to position four. Position four provides a 400 msec pulse to engage the selected gear and then increment the counter to position five. Position five resets the counter to position zero and relinquishes command to the Slip Controller.

The incident of shifting and the intended gear are determined by the output level of a function between velocity and torque. As the difference between the signal representing rotor velocity and a signal derived from the slip cross two set points a shift pulse is generated. The output level relative to the two shift points can be decoded to determine the gear involved. A shifting sequence along with changing gears must also offset the slip to maintain an even torque at the wheels. The slip scale factor is also modified to match each gear. This allows the mechanical range of the accelerator to remain constant independent of the gear involved.

8.2.2.4 Rotor, Vehicle, and Flywheel Tachometer

Voltages proportional to the speed of the rotor, vehicle, and flywheel are developed using three integrated circuit tachometers.

8.2.2.5 Flywheel Mode Control

Current shunts are used to determine direction and magnitude of current to the flywheel and traction motor/generators. The signals proportional to the currents are then decoded to determine the mode of operation of the flywheel motor/generator. Three modes of operation exist. The first case is when the current to or from the traction motor/generator is between two specific points. In this mode the battery will supply the majority of the current while the flywheel is speed-regulated to maintain a nominal velocity. The second case is when current into the traction motor exceeds the upper set point. In this mode the flywheel motor/generator acts as a generator and the excess current to the traction motor comes from the flywheel. The final case is when current from the traction motor exceeds the lower limit. In this mode the flywheel motor/generator acts as a motor and accepts all excess current from the traction generator.

8.2.2.6 Flywheel Controller

The flywheel motor/generator is controlled through Pulse Width Regulation of the field. An integrated circuit P.W.M. is used at four kHz to drive the field chopping transistor. The modulator input can be a signal proportional to the current of either the traction or flywheel motor/generator, or it could be the flywheel tachometer output. Independent of the mode of operation, the field is reduced to produce motor action and increased to produce generator action.

8.2.2.7 Flywheel Three-Phase Generator

The three-phase generator develops the applied armature voltage required to operate the flywheel motor/generator as a motor. As with the Traction Motor Three-Phase Generator, the developed signal is a periodic three-phase square wave. The frequency of this signal is directly proportional to the rotor speed. The input clock is developed from a position wheel that is attached to the rotor. The generator also monitors line voltage to ensure that two common devices do not turn on simultaneously.

The ratio of power from the battery and from the flywheel is controlled by the voltage of the generator. Raising the generator voltage slightly above the battery voltage forces more current from the flywheel and less from the battery. Lowering the voltage during regeneration diverts more current to the flywheel and less to the battery.

8.2.2.8 Flywheel Motor/Generator Position Sensor

The position sensor is formed from a number of optical sensors that sense slots in the position wheel. As the slot passes by the sensor, a digital pulse is generated. The pulses are then combined to form the clock for the flywheel three-phase generator. The output of one of the sensors also serves to input the flywheel tachometer.

8.2.2.9 Power Supply

The plus and minus 15 volts are derived from two integrated circuit pulse width regulators. The chopping frequency is ten kHz.

8.2.2.10 Drive Electronics

The drive electronics consists of NPN Darlington transistors and diodes for the flywheel and generation modes. The transistors that are referenced to ground are driven directly through current amplifiers while the transistors that are referenced to the positive bus are driven from optical-isolators through current amplifiers. The optical-isolators are referenced to a voltage that is 15 volts below the positive bus. This voltage is developed through an integrated-circuit chopping regulator.

8.3 Description of Concept D2

Table 30 summarizes the characteristics of conceptual design D2. Appendix B lists the specifications in more detail.

The conceptual design of components and their layout within the vehicle configuration are shown in the following drawings (included in Appendix B):

Drawing Number	Title
131D081	Flywheel with Magnetic Coupling
131D082	3-speed Transaxle
131D084	DC Traction Motor
131D085	CVT
131D086	General Arrangement

This propulsion system shown in Figure 34 uses an electronically commutated dc motor with a separately excited field for propulsion during cruise and other light loads and uses power augmentation from a flywheel via a CVT for acceleration, braking and other high power requirements. The general flow of power is shown in Figure 35. The power from the flywheel is shown flowing through a magnetic coupling which acts to limit the torque and to permit de-coupling to reduce run-down losses. The power out of the magnetic coupling flows through a CVT to the drive motor with the CVT used to provide a speed match and to control the flywheel torque.

The CVT controls the power flow to and from the flywheel. The power from the flywheel can flow directly through the motor shaft to the transaxle to drive the vehicle. The power from the flywheel normally augments the electrical power produced by the motor due to current flow from the battery; however, the energy from the flywheel can be returned to the battery when the drive motor is in the generating mode. During regenerative braking, power flows from the drive wheels back into the flywheel via the CVT; however, part of the power can flow back into the battery.

Table 30. GENERAL PROPULSION SYSTEM DESCRIPTION

DESIGN CONCEPT D2

Curb weight	1474 kg (3250 lbs)
Battery weight	544 kg (1199 lbs)
Propulsion system weight without battery	205 kg (452 lbs)
Traction Motor	
Electronically commutated brushless dc	
Rated power	26 kW
Base speed	5400 rpm
Maximum speed	7800 rpm
Efficiency	90.4%
Voltage	96 Vdc
Weight	43 kg (95 lbs)
Fiber-Composite Flywheel	
Total stored energy	2.44 MJ (678 Wh)
Maximum speed	46300 rpm
Total weight	10. kg (35.3 lbs)
CVT	
Planetary cone type	
Maximum power	34 kW
Maximum/minimum speed input	46300/15400 rpm
Full load efficiency	94%
Weight	71 kg (157 lbs)
Magnetic Coupling	
Maximum power	36 kW
Base speed	23200 rpm
Weight	9 kg (20 lbs)
Transaxle - 3-Speed	
Weight	50 kg (109 lbs)
Controller	
9-phase chopper	
Rated power	29 kW
Weight	16 kg (34.8 lbs)
Battery - Lead-Acid	
Specific energy	40 Wh/kg (18 Wh/lb)
Specific power	100 W/kg (45 W/lb)
Efficiency	60%
Propulsion System Performance	
Range for steady 45 mph cruise	223.7 km (139 mi)
Range for SAE J227a Schedule D	160.9 km (100 mi)
Acceleration 0 to 55 mph	15 sec

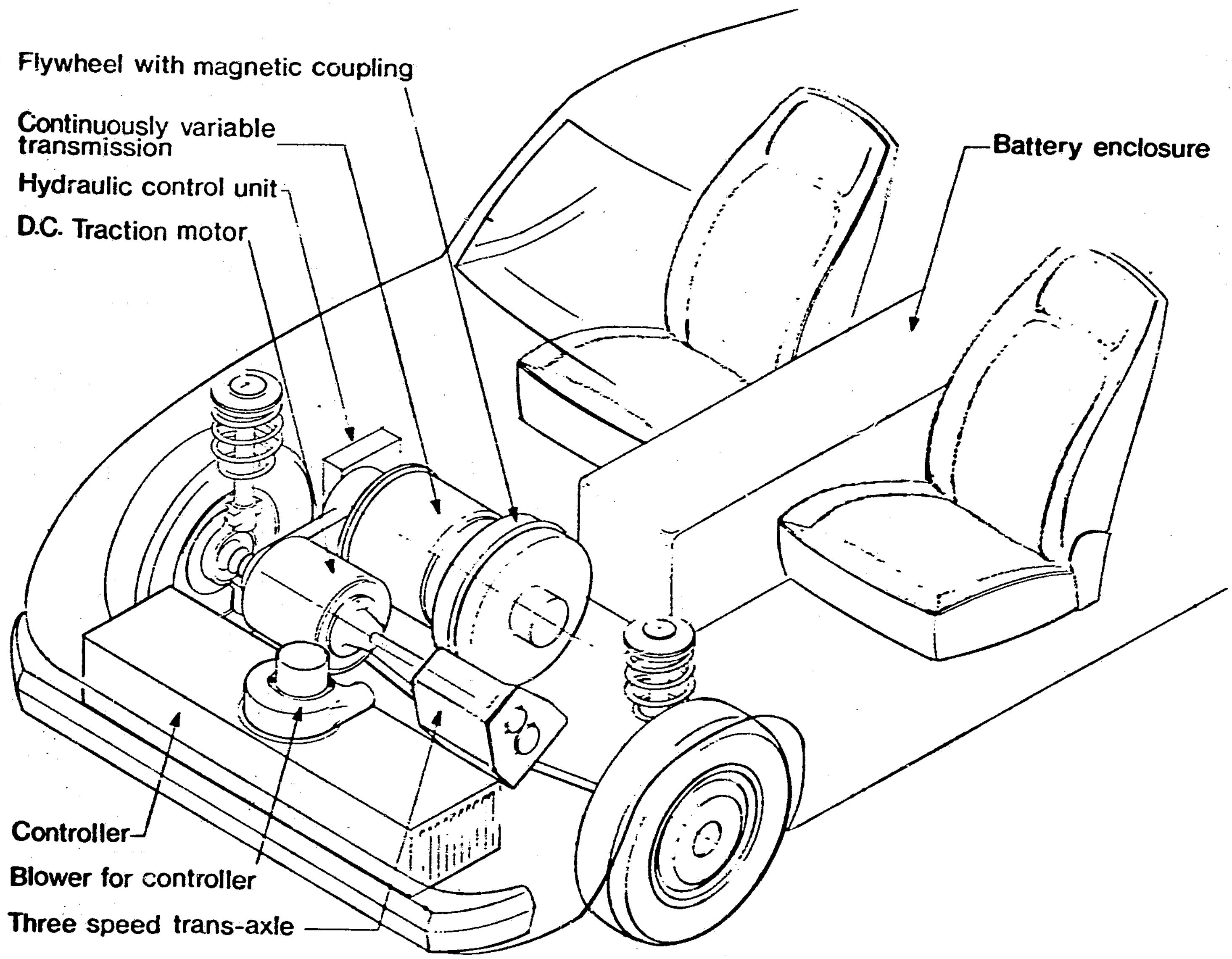


Figure 34. Concept D2

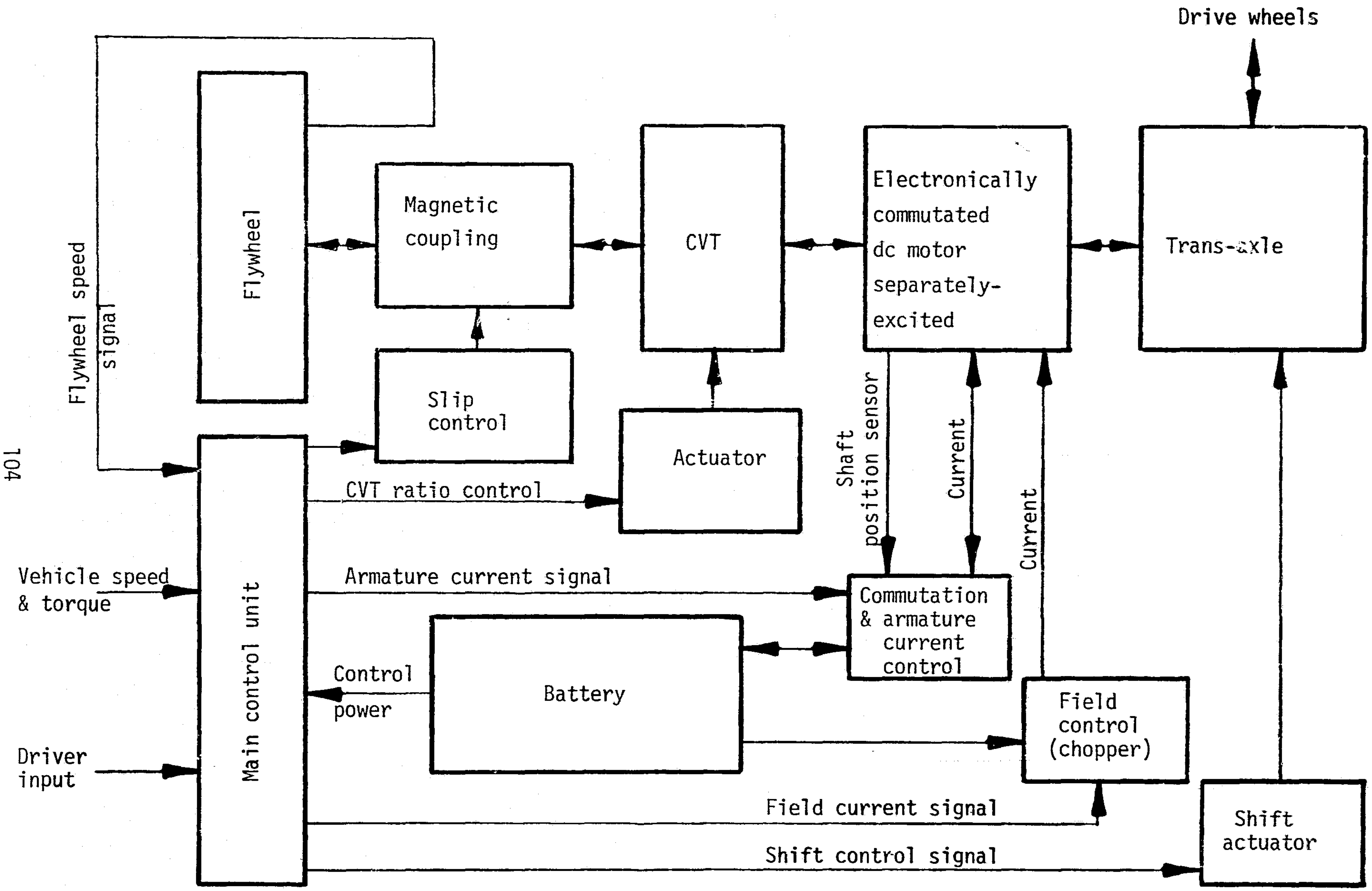


Figure 35. Power Flow - Candidate D2

The main power flow is to and from the drive wheels for propulsion and braking. This power flow is shared by the battery and flywheel with the battery normally supplying steady cruise power and the flywheel providing extra power for acceleration and braking. A secondary power path is for the flow of power between the flywheel and battery. This secondary path is primarily used for energy management to prevent the flywheel from over charging on a long downgrade or from running down from a succession of accelerations.

The power flow to and from the flywheel is controlled by the CVT, by changing the speed ratio to force the flywheel to slow down and give up part of its kinetic energy or to speed up to accept energy. The flow of power from the motor is controlled either by field current control or armature current control depending upon the speed of the motor. Above the base speed of the motor, field current is used to provide variable counter emf of the motor. Below the base speed, armature current control is used to provide variable torque for the motor.

The total power to the drive wheels is essentially the sum of the power from the drive motor and from the flywheel so the power flow from both units must be coordinated to give the total power flow to satisfy the driver input request. The driver input is mainly from the accelerator pedal or brake pedal and from each what the driver requests is essentially a positive or negative torque. For the flywheel to provide a specific torque output requires a specific rate of change of flywheel speed. This can be forced by a specific rate of change of CVT ratio. To maintain a continuous torque requires a continuous change in ratio. The actuator that forces this change in ratio is controlled in response to a torque signal generated from the measured slip in the magnetic coupling.

The motor torque is essentially proportional to the product of the armature current and the field flux. At speeds below the base speed, the field flux is constant so control of armature current provides control of motor torque. Above the base speed, the field is weakened to give lower counter emf to cause an increase in armature current. Torque control in this region can be obtained by control of field current if the armature and field current product is monitored.

The armature current flows through an electronic commutation unit which also provides chopper control of armature current below the motor base speed. This unit uses a motor shaft position sensor to control the timing for the turn-on and turn-off of the semiconductor switches.

The motor armature has nine separate coil circuits each of which is switched electronically. The timing for the circuits switching is shown in electrical degrees in Figure 36. The duration of each pulse is about 120^{o} electrical and the phase lag is 40^{o}. At any one time, three current paths are active. A possible circuit is shown in Figure 37. During the time that transistors 1, 2 and 3 are on, transistors 5, 6, 7 and 8 are on with 8 turning on as five turns off.

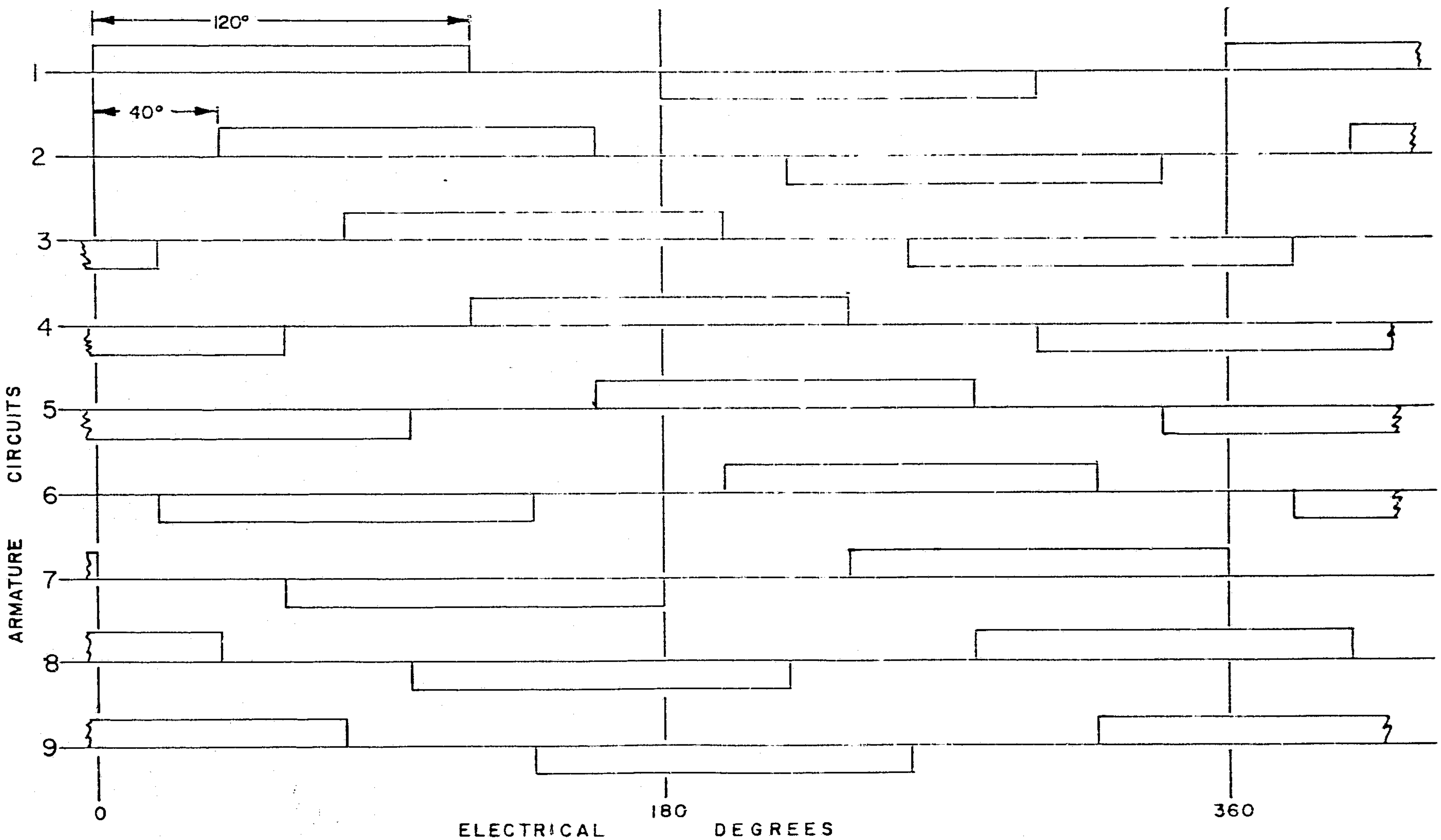


Figure 36. Timing for Semiconductor Switches for Nine-Phase Motor

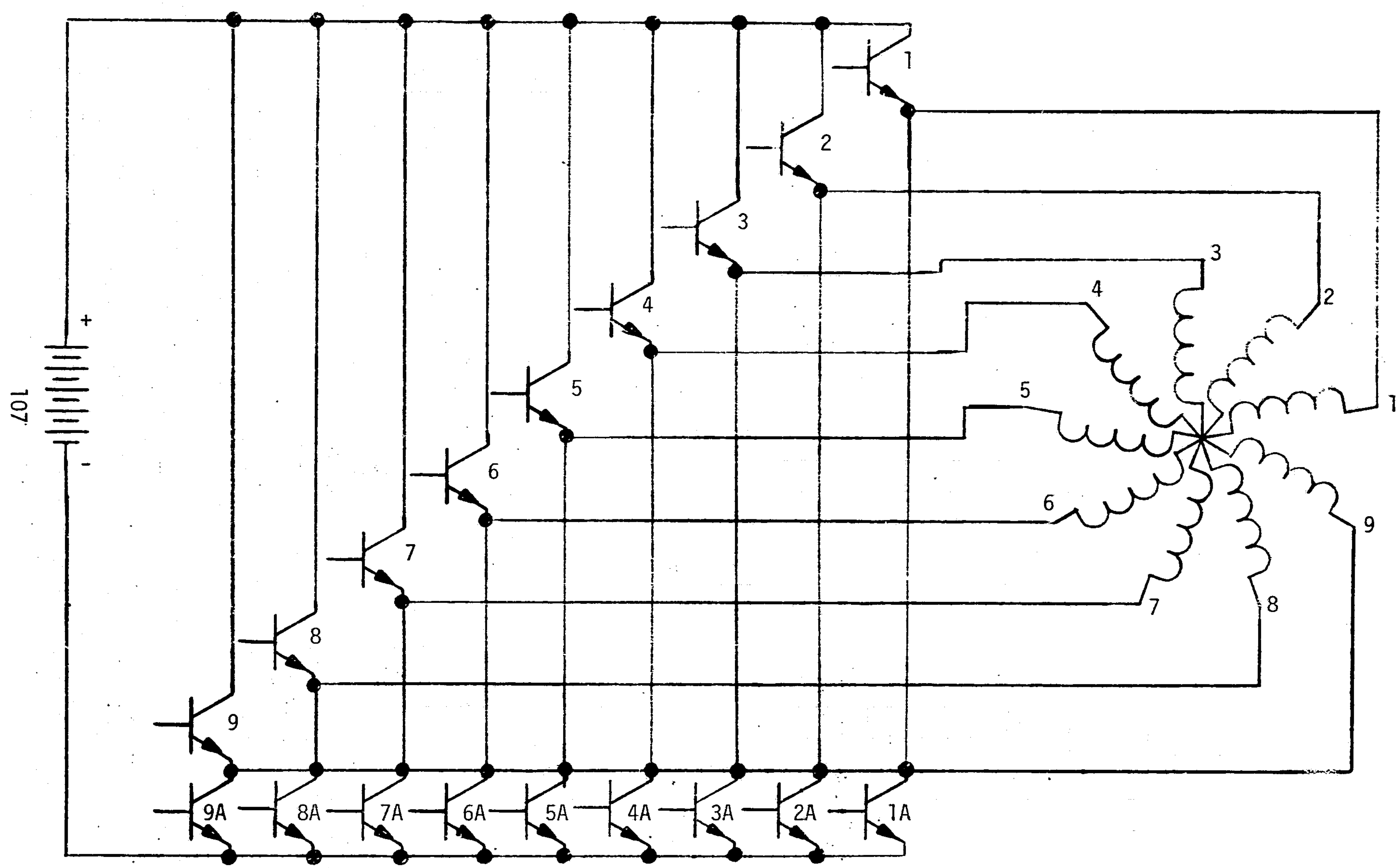


Figure 37. Electronic Co ,tation Switches for Nine-Phase Motor

The circuit shows 18 NPN transistors which would be parallel to 18 diodes (not shown) which could carry the current back to the battery in the generating mode of operation and which would act as freewheel diodes during chopper operation.

A simplified circuit showing the operation of the commutation unit during drive and generation modes is shown in Figure 38. This simplified circuit shows coils 1 and 5 with the other seven coils left off for clarity. Positive current for coil 1 flows through Q1 or D1a and negative current through Q1a or D1. Below the base speed, motor power is controlled by chopping the armature current. As shown, Q1 and Q5 act as choppers with D1a and D5a acting as freewheel diodes. When Q1 is chopping the current for coil 1 the current path back to the battery is through either Q5a, Q4a, Q6a or Q7a depending upon the shaft position and when Q5 is chopping the return is via Q2a, Q1a, Q9a or Q8a.

During the generator mode of operation when the speed is less than the base speed, there is inadequate voltage for recharging the battery, and the commutation unit must also act as a chopper controlled voltage booster. Current to recharge the battery flows through D1 and D5. During the portion of the motor cycle when D1 provides the recharge path, Q1a acts as a booster chopper. While D5 provides the recharge path, Q5a acts as a booster chopper.

A variety of signals are needed for control of the commutation unit. The motor shaft position determines the timing for gross switching of the semiconductors. The motor speed and positive or negative power requirements determine the chopper on-off ratios.

The number of semiconductor switches required for the electronically commutated motor circuit is 18 or nine times that requires for a conventional chopper used with a mechanically commutated motor; however, three sets of switches simultaneously carry current so that the current ratings of the semiconductors are lower by about one third than those for a conventional chopper.

8.4 Flywheel Size and Energy Rating

The flywheel examined during the preliminary analysis and design trade-off studies had a total kinetic energy of 6.84 MJ (1900 Wh) to continually provide a 2.52 MJ (700 Wh) energy reserve for braking or acceleration. For a 1642 kg (3620 pound) vehicle test weight, the charge in kinetic energy corresponds to the vehicle's potential energy change due to an elevation change of 152 m (500 feet). This is not an unusual elevation change in a hilly area, but could represent an unusual energy change for level terrain. For the vehicle operated mostly on level terrain, an excessively large flywheel is an undesired burden. Consequently, it was decided that the maximum energy change could be set to that required for the Federal Urban Driving Cycle (FUDC). Examining the A6 concept over the "D" cycle and FUDC showed a maximum energy swing of .412 MJ (114.34 Wh) for the "D" cycle and .749 MJ (208 Wh) for the FUDC. An energy swing of .9 MJ (250 Wh) was selected as a new design criteria for the energy buffer.

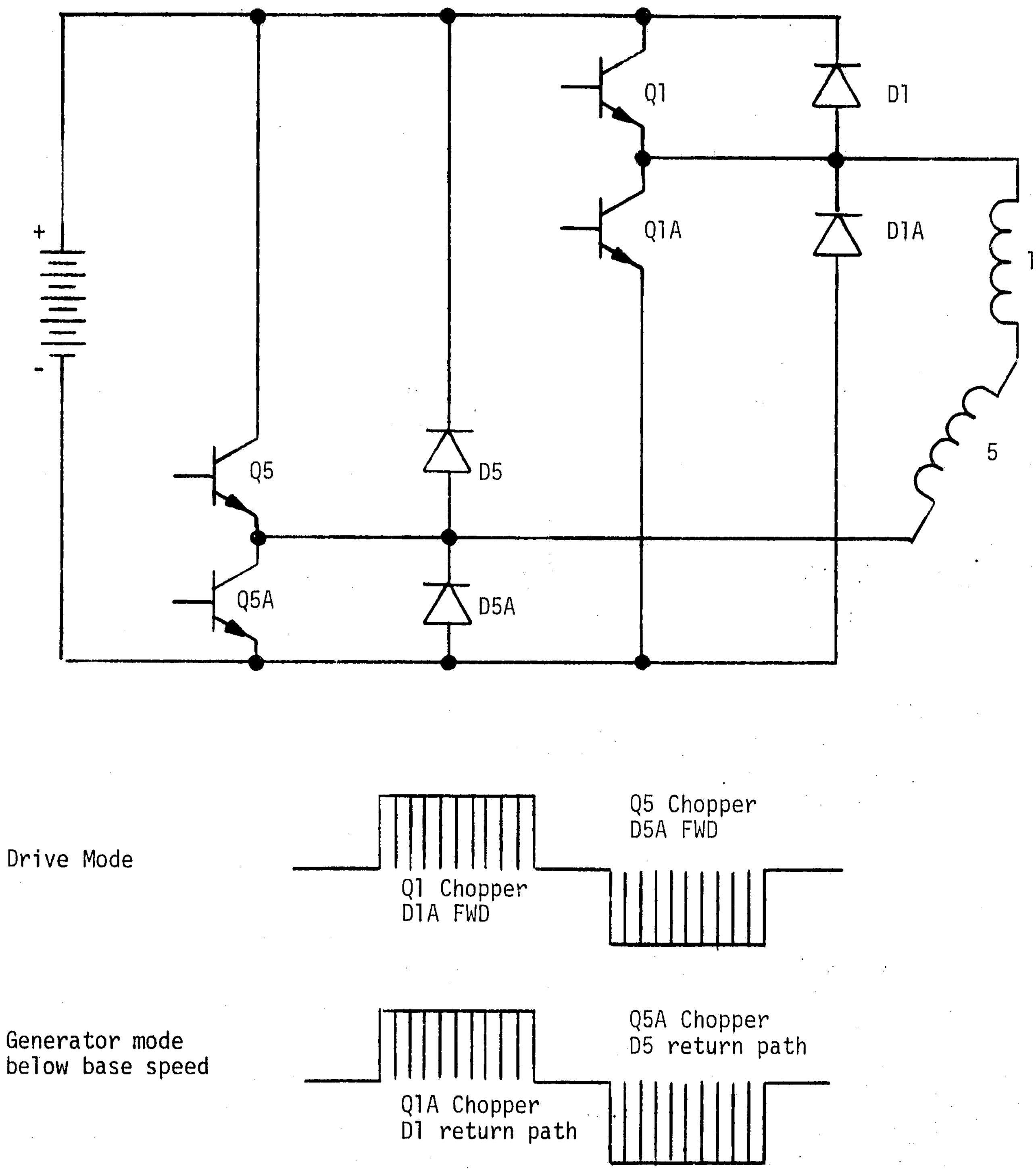


Figure 38. Electronically Commutated Motor Switches

Transistors Provides Chopping for Drive
and Generator Modes and For Commutation

Figure 39 shows the energy swing on either side of the operating point and shows that the total kinetic energy at the maximum flywheel speed is 2.44 MJ (678 Wh). This results in a smaller flywheel than initially considered based on the hilly terrain of the San Francisco Bay Area. The smaller flywheel spins at higher speed and allows the generator used with the flywheel to be smaller and of lighter weight. The smaller flywheel is easier to accommodate in the available vehicle space and has a lower gyroscopic moment.

The flywheel/generator unit is shown in Figure 40. The combined weight is 35.6 kg (78.6 pounds) for the stored energy of 2.44 MJ (678 Wh) and power level of 48.5 kW.

8.5 CVT Types

Several types of CVTs were examined. It seemed desirable to have the input shaft for the CVT operated at flywheel speed. No CVTs are available which can accept a 46,000 rpm input. A new design of a traction-type CVT seems possible and desirable. The high speed of the input shaft would allow low torque. The high speed/low torque combination seems like an ideal combination for a traction-type device. The Nasvytis type speed (ref. 7) reducer appears to work well in the high speed/low torque region. The alternative appears to be the development of a high-speed CVT or the use of a first-stage speed reducer such as the Nasvytis type device to bring the speed and torque to a value that can be accommodated by CVT designed for the more conventional speed domains.

In any case, it appears necessary to provide a means of decoupling the flywheel from the CVT and for providing a limit to the torque transmitted to prevent damage to the CVT if excessive overloads were to occur. An electro-magnetic coupling using the limited slip induction design rather than a synchronous design is simpler to control and can satisfy the requirements for limiting the maximum torque through control of field excitation current. The design can also provide a hermetic vacuum barrier for the flywheel housing.

If the high-speed type CVT is to be developed, it would have to have high efficiency and be light weight to be acceptable. Several types of designs were considered. A planetary ball and cone design appeared to have inadequate torque and was rejected. Multiple-tapered cones with adequate crown to reduce "spin torque" and viscous drag appear to hold some promise.

Layout drawings using hypothetical CVTs of the high-speed and conventional speed types were prepared. It appears that adequate space is available for either type if they can be developed to give acceptable efficiency and life.

8.6 Vehicle Performance

The vehicle weights, range and energy consumption are summarized in Table 31.

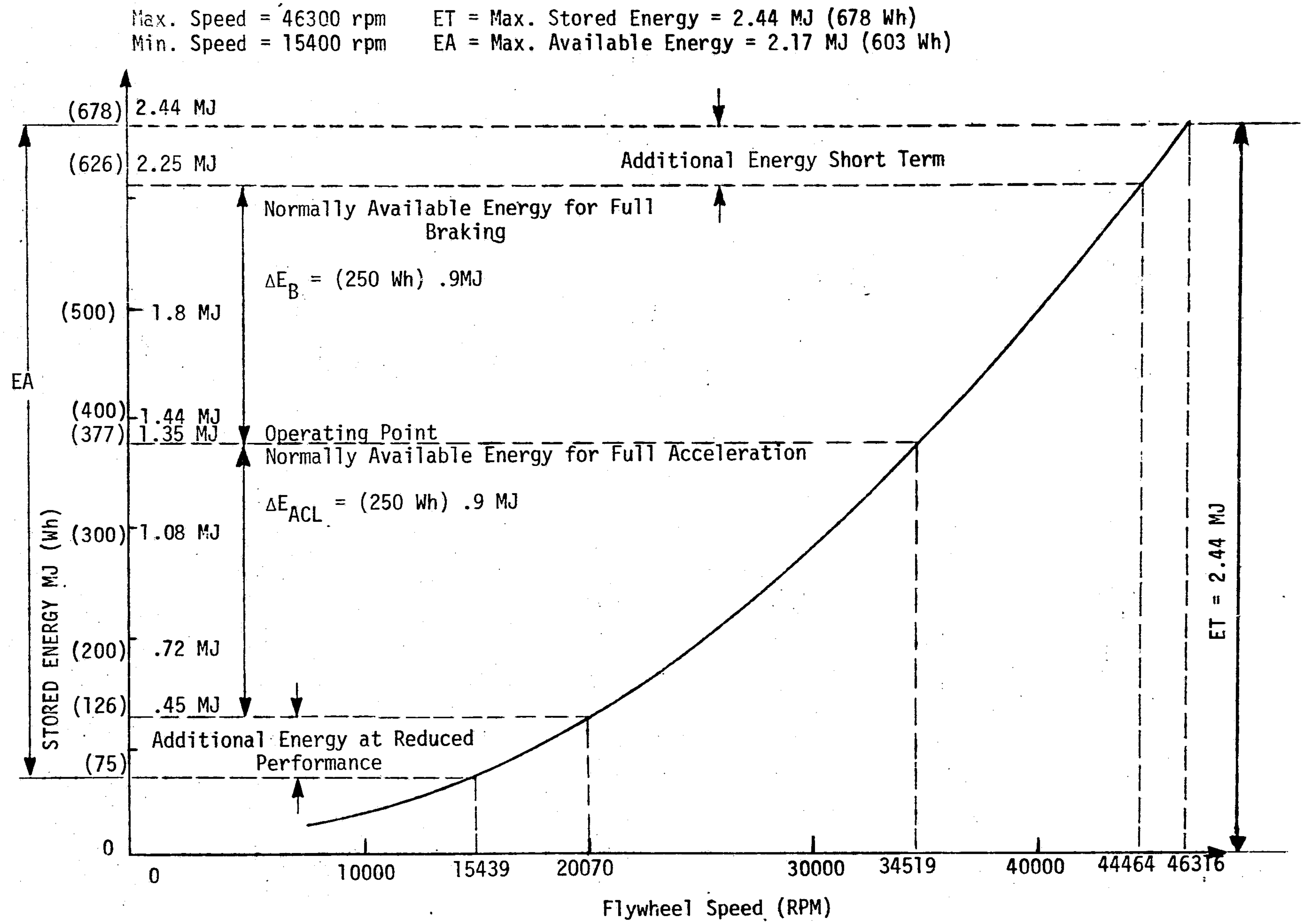


Figure 39. Flywheel Stored Energy vs. Flywheel Speed

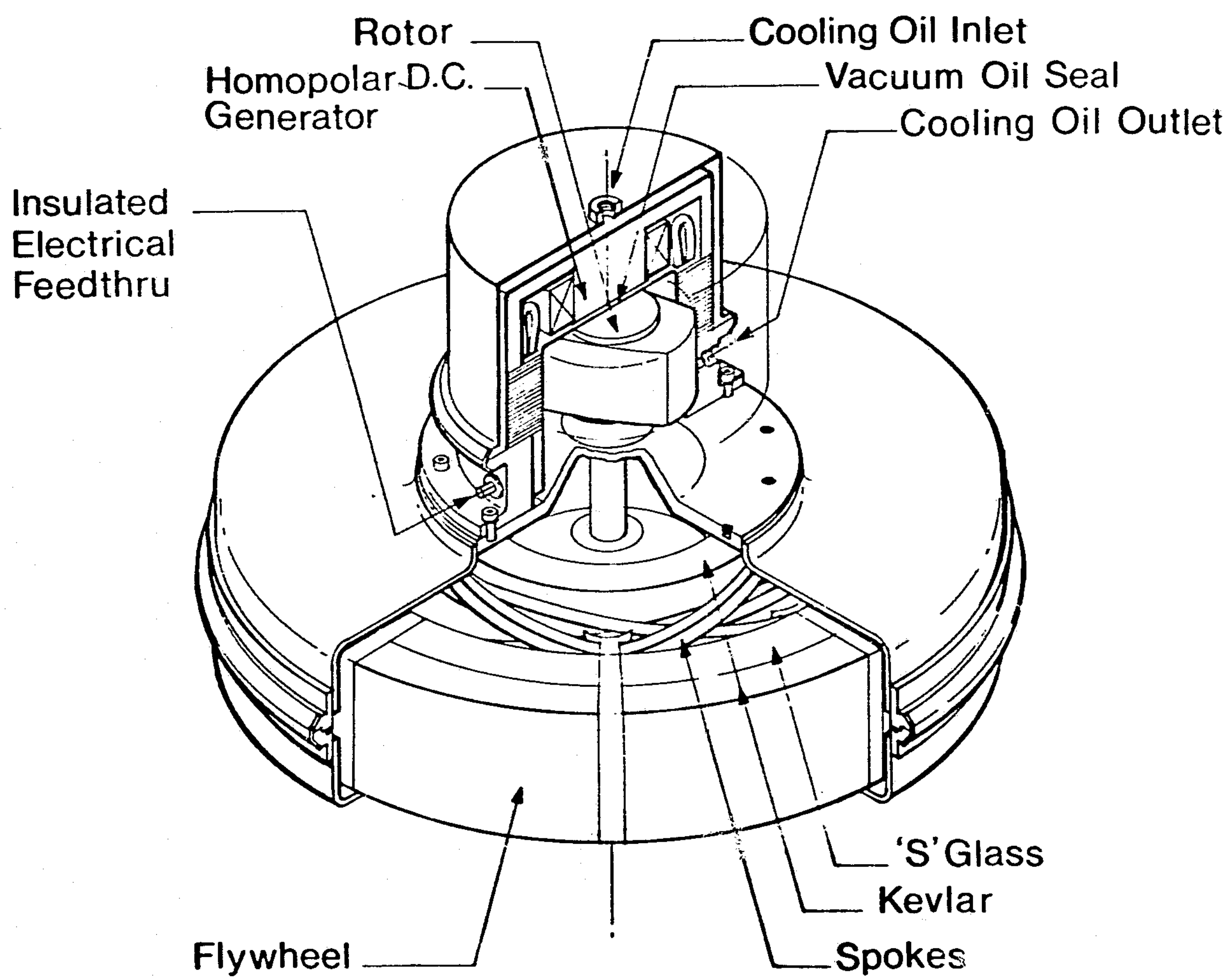


Figure 40. Flywheel/Generator Unit

Table 31. Candidate Weight/Performance Comparison

	Candidates	
Weights, kg (lbs)	A6	D2
cle Curb Weight	1460 (3218)	1474 (3250)
Battery Weight	556 (1226)	544 (1199)
Axle	27 (59)	27 (59)
Transmission	23 (50)	23 (50)
Motor	41 (90)	43 (95)
Controller	52 (115)	16 (35)
Flywheel	16 (35)	16 (35)
Generator	19 (43)	--
CVT	--	81 (178)
Propulsion System Weight	178 (392)	205 (452)
Energy Per Mile, MJ/km (Wh/mi)		
"D" Cycle		
From Battery	.472 (212)	.469 (210)
From Wall plug	.79 (353)	.783 (350)
Steady 45 mph	.37 (165)	.365 (163)
Range, km (mile)		
"D" Cycle	161 (100)	161 (100)
Steady 45 mph	228 (142)	224 (139)

From the table it can be seen that the vehicle curb weights and the battery weights are within one percent of each other. The weights of the propulsion systems on the other hand show a fifteen percent or 60 pound difference in weight. This difference is mainly due to the greater weight of the CVT, 80.5 kg (177.5 lbs) versus 38.2 kg (84.3 lbs) weight of the generator/controller combination. Because of the better (anticipated) efficiency of the CVT, the energy consumption over the SAE J227a Schedule D driving cycle is less for Concept D2 than for A6, and only 544 kg (1199 lbs) of batteries are needed partly offsetting the higher propulsion system weight.

Both concepts meet all range and acceleration goals but both concepts failed to meet the Wh/mile wall plug energy consumption goal with lead-acid batteries. To meet the 250 Wh/mile wall plug energy consumption goal with lead-acid batteries, range has to be sacrificed or the efficiencies of the propulsion system components pushed close to 100 percent.

With nickel-zinc batteries, it is possible to meet both range and energy consumption goals. However, the higher life cycle cost of a nickel-zinc battery system more than offset the gain in energy consumption.

8.7 Propulsion System Cost Comparison

The life cycle cost of the conceptual designs are summarized in Table 32.

Guidelines for life cycle cost calculations were provided by NASA Lewis Research Center and appear in Appendix D. In addition to the life cycle cost guildelines, the following specific information regarding battery cost and life were provided by NASA Lewis and are listed in Table 4.

The number of miles attainable per 80 percent discharge is 80 miles with battery weight adjusted to give a range of 100 miles per full discharge. For the specific number of 80-percent discharges (Table 4), this results in a 6.4 year life for lead-acid and a four year life for nickel-zinc batteries.

Today's prices (1979) were converted into 1976 dollars by using an average eight percent inflation rate.

On critical high technology units where no mass production cost factors are available, cost was estimated based on Task III Conceptual Designs and drawings. The critical units are:

Flywheel
Homopolar Inductor
Continuously Variable Transmission (CVT)
Electronic Controllers

On items where existing technology can be applied current prices or unit prices were used. These current prices were then subsequently reduced to 1976 dollars.

More detailed information on operating/life cycle cost appears in Tables D1 to D9 in Appendix D.

Table 32. Propulsion Systems - Cost Comparison

	A6	D2
Battery Acquisition Cost	1301	1273
Propulsion System Acquisition Cost (with battery)	3175	3123
Annualized Acquisition Cost	317.5	312.3
Discounted Annual Cost @ 2% Discounted Rate		
Electricity	126.6	125.4
Repair & Maintenance	61.5	102.8
Battery Replacement	99.8	97.7
Power Train	-3.7	-3.6
Battery Salvage	-26.6	-26.0
Discounted Annual Operating Cost	257.6	296.
Present Value of Life Cycle Cost/yr	575.0	608.0
Present Value of Life Cycle Cost/ km (Cost/mi)	.036(.058)	.038(.061)

9. DISCUSSION OF RESULTS

The preliminary analysis of 28 candidate propulsion systems and the subsequent design analysis of the five most promising concepts show clearly that a relatively large amount of on-board energy storage such as batteries is required to provide the desired range and that a power booster element such as a flywheel is desirable to provide peak performance especially as the batteries near their discharge point. The analysis also shows the desirability of efficient regenerative braking capable of handling brief periods of very high power. The effects of returning braking energy directly to the battery at high power levels is not known with certainty. (Ref. 18) It is possible that brief high power "shocks" could have a beneficial effect on battery life and output, (Ref. 29) but it is likely that a greater efficiency of energy recovery can be achieved by returning the braking energy to a power booster such as a flywheel. (Ref. 30, 31)

There are two significant reasons for favoring the return of braking energy to a flywheel rather than to the battery. One is that the charge-discharge efficiency of the battery is estimated to be as low as sixty percent for lead-acid and seventy percent for Ni-Zn. The other is that it is much more efficient to deliver braking energy directly to the flywheel than indirectly to it by way of the battery as additional power conversion steps are required.

The study also shows that high-speed, light-weight motors are beneficial even though they will require multi-speed transmissions to provide the increased torque required at the drive wheels at low vehicle speed. The multi-speed transmission appears to provide an efficient and cost-effective means of producing high torque at the drive wheels. The alternative is to use a direct drive with a larger and more expensive propulsion motor. The alternative is technically less attractive in terms of cost, weight and efficiency, but may be more attractive in the market place. The absence of shift points and possible "jerk" could be an important selling point, but a difficult one to evaluate.

The trade-offs between dc drive motors and ac drive motors were studied. The main drawback of present dc motors is their mechanical commutation. The brushes have friction and wear problems as well as a voltage drop. At high speed, commutation problems such as sparking at the brushes and flashover limit the output of a given size armature. A brushless dc motor could eliminate these problems of the commutator, but replace it with the problems of an electronic commutation circuit and makes this type dc motor similar in cost and complexity to the ac motor for vehicle propulsion. Both dc and ac type motors have similar weights, efficiencies and cost.

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The electronically-commutated dc motor is essentially a synchronous motor with an inverter triggered by a shaft position sensor, which locks the inverter frequency and phase to the motor speed and shaft position. By forcing the frequency and phase to follow the motor rather than vice-versa, the synchronous motor then possesses all the characteristics of a separately-excited dc motor. The fact that the field current for this type dc motor can be separately controlled provides it with a significant advantage over the induction motor especially for its operation as a generator during regeneration.

The electronically-commutated dc motor always maintains a good phase relationship between the applied voltage waveform and the generated counter emf; whereas, the induction motor will sometimes operate at a very poor power factor with substantial mismatch of the applied voltage waveform and the generated counter emf. Consequently, over much of the operating range the peak-to-average current ratio for the semiconductor devices for the inverter for the induction motor will be higher than those for the electronically-commutated dc motor. In the final analysis the suitability of the electronic conversion and control units will be the deciding factor. The added cost of the features required to insure regeneration with an induction motor could wipe out any cost savings due to the squirrel cage rotor.

Initially, it was thought that the current controllers and inverters should use SCRs rather than transistors for switching. For a given power rating an SCR controller costs less than one using transistors; however, the turn-off times for SCRs are too long to permit the desired switching rates.(Ref. 28) Chopper frequencies of about four kHz appear to be ideal. Much lower freouencies will require excessively large reactors to filter out undesirable current ripple. Much higher frequencies would require reactors with special core materials to prevent excessive eddy current losses. Such reactors would be bulky or costly. Presently available transistors should be considered for the design initially, but as more efficient types such as field effect devices (Ref. 32) become available these should be substituted. Better and cheaper transistors are vitally important to the development of electric vehicles.

Initially, it was thought that systems using higher voltage would be more attractive than those using lower voltage, because the former would have lower current for a given power. However, other factors such as safety, battery reliability and maintenance indicate very high voltages are not necessarily desirable. A higher voltage would require a larger number of small cells with a corresponding increase in maintenance. Higher dc voltages increase the danger of electrical arcs and increase the shock hazards. The risks of arc and electrocution go up rapidly as the voltage is increased above 100 volts dc. It is true that the use of higher voltages would reduce the required current rating of the semiconductors and thus reduce their cost; however, the cost savings would not compensate for the increased safety hazards and decrease in battery reliability. Moreover, the power losses in semiconductors operating in a 96 volt dc system can be acceptably low.

Several items are crucial to the design concepts. These are the following:

1. High-speed flywheel subsystems

2. High-speed homopolar inductor/generator and inverter/controller system

3. High-speed, light-weight, three-phase induction motor and inverter/controller

4. High-speed, light-weight, electronically-commutated, separately-excited dc motor including electronics.

5. High-speed CVT suitable for use with a flywheel energy input and suitable ratio-controller unit

Of these, the item of greatest developmental risk appears to be the CVT. The flywheel development may at first appear to be equally risky; however, the risk involves only how much energy can be stored for a given weight. That a flywheel can store energy and that adequate power can be generated is not in doubt. The questions are how much power, energy, weight and cost. In contrast, the questions for the CVT is whether it can be done with any reasonable life, weight or cost. Will a continuously variable traction device operating at high speed have adequate torque and efficiency? Will the churning losses and slippage be excessive? Without tests and experimentation these questions can not be answered.

If they were developed, their service and maintenance costs are expected to be higher than those for the electrical conversion system. The extra cost of service and maintenance could offset any potential gain for the CVT-based propulsion systems; however, the projected overall efficiency for the propulsion systems using the CVTs are higher than those with the flywheel/generator systems. Considering the potential advantages, it is too early to positively conclude that the service and maintenance costs would completely offset the energy savings. It should be recognized that such a development program may not succeed in providing a unit at an acceptable cost.

Some work is presently underway on subsystems using various flywheel designs and much lower energy levels. The work should be expanded to cover a wider range of energy and flywheel designs.

A variety of types of power boosters to provide peak power performance are possible. It appears that a flywheel-type booster is the most attractive type. Using a fiber-composite flywheel, such a unit can have very high specific power and specific energy without an excessive gyroscopic moment. When used with a generator for converting its kinetic energy to electrical energy, high conversion efficiencies can be obtained and the power flow to and from the flywheel can be easily controlled. The developmental risks for such a system are not excessive.

The optimum stored energy in the flywheel is dependent upon terrain as well as the velocity profile of the driving cycles. A vehicle operated on hilly terrain could benefit from a larger flywheel energy storage than one operated on level terrain. On level roads, the ability to absorb or release about 250 Wh of kinetic energy will suffice for most anticipated driving conditions without danger of flywheel rundown or overspeed. This requires a total energy swing of 500 Wh.

Flywheels used in cars should be safe, inexpensive and have high specific energy (MJ/kg (W-hr/lb)). Several flywheel designs like shaped steel disk and multi-ring fiber composite have been investigated. As can be seen from published reports (ref. 19) the flywheel specific energy of fiber composites is 1.6 - 4 times higher than for shaped steel disk designs. In order to store the same amount of energy in a shaped steel disk, the shaped steel disk flywheel would weigh more than twice as much as a fiber composite flywheel. The greatest penalty lies in the heavier containment structure (approximately five times) needed for steel flywheels to give adequate protection.

The maximum wall plug energy for SAE J227a Schedule D (.559(250) MJ/km (Wh/mi)) requirement, with a given battery efficiency of sixty percent (lead-acid) and an assumed charger efficiency of 85 percent is .285 (127.5) MJ/km (Wh/mi) with vehicle/battery characteristics as listed in Tables 2 and 3. For a propulsion system efficiency as high as 86 percent, the wall plug energy consumption was computed 65 percent higher than the target of .559 (250) MJ/km (Wh/mi). With lead-acid batteries, it would be very difficult to fulfill this requirement. With nickel-zinc batteries, being lighter and more efficient, the wall plug energy requirement can be met.

10. CONCLUSIONS

The preliminary analysis, design trade-off study and conceptual design lead to several general conclusions about the nature of an advanced propulsion system designed for a range of 100 miles of repeated SAE J227a Schedule "D" cycles.

1. There is no identifiable single "best" design to achieve the desired range and performance objectives, but rather a multitude of designs are possible.

2. If ISOA lead/acid batteries with a specific energy of 40 Wh/kg are used, a total battery weight of approximately 1200 pounds will be required, However, if nickel/zinc (Ni/Zn) batteries with a specific energy of 80 Wh/kg were used only 490 pounds would be required. Unfortunately the nickel/zinc batteries have shorter life and are much more expensive than the lead/acid batteries.

3. The cost of the initial supply of batteries would be about 22 percent higher for Ni/Zn and their replacement costs over the life of the vehicle are nearly double that for lead/acid.

4. The addition of a multi-speed transmission is worthwhile because in today's technology a suitable transmission would be light weight and reasonably inexpensive compared to the weight and cost increase associated with the increase in motor size required for direct drive.

5. Two general types of traction motors appear attractive for an advanced propulsion system in terms of their efficiency, specific power and potential for mass production. These are the multi-phase induction motors with squirrel cage rotors and the multi-phase synchronous motors of various designs, including the claw-power or Lundel design, the homopolar inductor design and the more conventional designs using either cylindrical or salient pole rotors with slip rings and brushes.

6. High-efficiency controllers capable of regenerative operation will be required. The waveforms needed for efficient inverter/rectifier operation will require pulse-width modulation with switching speeds in excess of that practical now with SCRs. High-power transistors with low losses such as the field effect devices now being developed appear to be necessary.

7. The study of candidates using CVTs to mechanically convert flywheel kinetic energy into vehicle propulsion, indicate that such units are potentially practical although they are probably heavier than the electrical conversion system. Much development work is required before suitable CVTs can be made available for this purpose.

11. RECOMMENDATIONS

The program has identified and examined a variety of attractive concepts for advanced propulsion systems which appear capable of significant performance improvements with little or no cost penalty, but do have some developmental risks. The field has been narrowed down to the most attractive concepts which we recommend for further design and developmental efforts.

1. The least developmental risk with high benefits is the A6 concept. It is recommended that a functional model of the propulsion system be designed, built and tested to verify the projected characteristics.

2. A detailed design for the concept A6 flywheel/generator subsystem and its electronics should be pursued in conjunction with developments in fiber-composite flywheels, bearings and vacuum vessels.

3. Tests and experimentation should be undertaken in an effort to develop a suitable CVT, and to confirm its probable cost and maintenance requirements.

4. The development of high-power transistors to operate in the vicinity of 100 volts dc should be encouraged.

5. Concurrent with the design of the functional model of the A6 propulsion system, there should be ongoing work on the development of an electronically-commutated, separately-excited dc motor suitable for vehicular propulsion. This effort should concentrate on a high-speed motor of 26 kW continuous power to operate with a 96 volt dc input.

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APPENDICES

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APPENDIX A

ADVANCED ELECTRIC VEHICLE PROPULSION SYSTEM

DESIGN CONCEPT: A6

GENERAL DESCRIPTION:

Flywheel buffered electric propulsion system using an ac induction motor as a traction motor and a flywheel coupled to an electrical generator to provide a power boost to augment the battery power for acceleration and regenerative braking.

General Propulsion System Specification

Design Concept A6

Curb weight	1400 kg (3218 lbs)
Battery weight	556 kg (1226 lbs)
Propulsion system weight less battery	178 kg (392 lbs)
Traction Motor	
3-phase ac induction	
Rated power	26 kW
Base speed	7200 rpm
Efficiency	91%
Power factor	.84
Weight	41 kg (90 lbs)
Rated Voltage	75 Vac
Fiber Composite Flywheel	
Total stored energy	2.44 MJ(678 Wh)
Maximum speed	46300 rpm
Total weight	16 kg (35.3 lbs)
Flywheel Motor/Generator	
Brushless DC	
Peak power	45 kW
Base speed	23158 rpm
Maximum speed	46300 rpm
Efficiency	87%
Weight	20 kg (43.3 lbs)
Transaxle 3-speed	
Weight	49 kg (109 lbs)
Controllers - variable voltage and frequency	
Rated power	63.5 kVA
Weight	52 kg (114 lbs)
Battery/Lead-Acid	
Specific energy	40 Wh/kg (18 Wh/lb)
Specific power	100 W/kg (45 W/lb)
Efficiency	60%
Propulsion System Performance	
Range for steady 45 mph cruise	225 km (140 miles)
Range for SAE J227a Schedule D	161 km (100 miles)
Acceleration - 10 to 55 mph	15 sec

TRACTION MOTOR SPECIFICATION

Design Concept A6

TYPE: 4-pole, 3-phase induction motor cooled by thermostatically-controlled blower,* squirrel cage, f = 300 Hz @ 9000 rpm

Rating	
Power	
Continuous	26000 watts
Peak (30 seconds)	50000 watts
Torque	
Continuous	41.2 Nm (30.42 lb-ft)
Peak	96.2 Nm (70.99 lb-ft)
Base speed	7200
Maximum speed	9000
Line voltage	74.85 ac
Line current	
Continuous	263 A
Peak (5 sec)	640 A
Peak (30 sec)	600 A
Power factor (nominal)	84%
Efficiency (nominal)	91%
Slip	2%
Number of rotor slots	28
Number of stator slots	36

Dimensions	mm	in
Housing, O.D.	254	10
Housing, I.D.	220	8.68
Stator laminations, I.D.	159	6.25
Stator slot depth	23	.90
Stator slot width	6	.25
Stator core stack length	89	3.5
Air gap diameter	158	6.25
Shaft diameter	47	1.88
Shaft length	292	11.5
Rotor slot width	3	.125
Rotor slot depth	6	.25
Bearing O.D.	89	3.5

*Weight, power and cost of blower are included in motor, controller weights, losses and cost.

TRACTION MOTOR SPECIFICATION - Con't

Weights	kg	lbs
Stator iron	12.9	28.5
Stator copper	7.9	17.5
Rotor iron	8.6	19.
Rotor copper	1.6	3.5
Shaft	2.3	5.
Bearings	.4	1.
Aluminum housing	3.1	7.
Aluminum end bells	3.4	7.5
Miscellaneous hardware	.4	1
Total Unit Weight	40.6	90.

Winding description

Stator: Two layer, short pitch winding at 7/9, two coil sides/slot

Rotor : Copper squirrel cage

Losses at rated power

Ohmic	1717 watts
Hysteresis	128 watts
Eddy current	257 watts
Bearing friction	231 watts
Windage	231 watts
Total	2564 watts

BATTERY TO MOTOR CONTROLLER

DESIGN CONCEPT A6

TYPE: Variable voltage, variable frequency, 3-phase pulse-width modulated inverter

Ratings

kVA rating, 30 seconds	63.5 kVA
kVA rating, continuous	45 kVA
Voltage	
Input	96 V
Output	75 V
Output current, 50 seconds	600 A
Output current, continuous	263 A
Output frequency	1-300 Hz
Pulse width modulation frequency	4000 Hz

Power Loss

@ 60 kVA	2300 W

Efficiency

@ 60 kVA	96 %

Cooling Method

*Forced air cooling

Weight	29.4 kg (65 lbs)

Control Method

Positive slip requirement specified by driver via accelerator pedal position.

Negative slip requirement specified by driver via brake pedal position.

Voltage controlled as linear function of frequency via control of on/off ratio of pulse width modulator.

*Power of blower (100 watts max) is included in motor and controller losses.

FLYWHEEL

DESIGN CONCEPT A6

TYPE: Bi-annulate rim fiber-composite

Maximum speed	46316 rpm	
Maximum stored energy	2.44 MJ (679 Wh)	
Available energy for a 3:1 speed range	2.17 MJ (603 Wh)	
Specific energy	64.3 Wh/kg (29.18 Wh/lb)	
Flywheel dimensions	mm	in
Inner ring, S-2 glass/epoxy		
I.D.	253	9.99
O.D.	303	11.93
Outer ring, Kevlar 49/epoxy		
I.D.	303	11.93
O.D.	362	14.25
Height	99	3.88
Hub - aluminum with kevlar reinforcement		
Kevlar O.D.	140	5.75
I.D.	127	4.79
Aluminum hub I.D.	111	4.39
Weights	kg	lbs
Rings	8.4	18.52
Spokes	.47	1.03
Hub	1.60	3.53
Balancing weights	.09	.19
Total	10.56	23.27
Housing	5.44	12.00
Total	16.00	35.27
Vacuum		
Bearings	Ball bearings	

Seals - hermetically sealed

FLYWHEEL MOTOR-GENERATOR

DESIGN CONCEPT A6

TYPE: Brushless, dc, homopolar inductor design.
Number of poles = 4

Rating		
Power		
Continuous	23 kW	
Peak	45 kW	
Torque		
Continuous	8.08 Nm (7.00 lb-ft)	
Peak	18.50 NM (13.69 lb-ft)	
Base Speed	23158 rpm	
Maximum Speed	46316 rpm	
Efficiency	87%	
Voltage	96 Vdc	
Current		
Continuous	276	
Peak	560	
Number of Phases of Armature Winding	3	
Frequency	1544	
Dimensions,	mm	in
Rotor, O.D.	94.9	3.74
Rotor, flux return path diameter	57.1	2.25
Armature Stack Length	65.	2.56
Armature Slot Depth	20.3	.8
Armature Slot Width	5.1	.2
Armature, O.D.	157.2	6.19
Field Coil O.D.	94.7	3.73
Field Coil I.D.	57.1	2.25
Overall Length	139.9	5.51
Weights,	kg	lbs
Rotor	2.9	6.3
Armature Iron	4.8	10.6
Armature Copper	3.8	8.5
Field Pole Iron	5.5	12.2
Field Coil Copper	2.	4.4
Bearings	.3	.6
Miscellaneous	.3	.6
Total Unit Weight	19.6	43.2

Winding description

Armature - lap winding and equalizing connections

Field - Concentric wound

Losses at 23000 watt output	2990 watts
Ohmic	2489 watts
Hysteresis	167 watts
Eddy current	167 watts
Bearing friction	167 watts

Power needed to circulate oil is included in the Ohmic losses.

HIGH SPEED GENERATOR CONTROLLER

DESIGN CONCEPT A6

TYPE: Variable voltage, 3-phase electronic commutation with chopper field circuit and armature control

Ratings

kVA rating, 30 seconds	48.5 kVA
Input voltage, maximum	96 Vdc
Output voltage	75 Vac
Output current, 30 seconds	621 A
Output frequency	1544 Hz

Power Loss

At full load (48.5 kW)	1986 watts
Efficiency at (48.5 kW)	96 %

Cooling

Air cooled - forced air cooling provided by thermostatically controlled blower.

Weight

22.6 kg (50 lbs)

Control Method

Shaft position sensor for phase and frequency control.
Field Current control of counter emf.

Power of blower (100 watt max.) is included in motor and controller losses.

TRANSAXLE

DESIGN CONCEPT A6

TYPE: 3-speed with electronically controlled gear changing mechanism

Final drive gear

Ratio	7.2666
Bearing type	ball bearing
Maximum torque input	418 Nm (308 lb-ft)
Maximum torque output	3042 Nm (2244 lb-ft)
Weight	17.7 kg (39 lbs)

Axle

Axle weight	9.0 kg (20 lbs)

Transmission

Gear ratios	1, 1.74, 3.86
Bearing type	ball bearing
Maximum torque input	109 Nm
Maximum Torque output	418 Nm
Maximum speed input	9000 rpm
Weight	20.4 kg (45 lbs)

Gear shift mechanism

Electronically controlled Weight	2.2 kg (5 lbs)

Transaxle Drive Line Efficiency

@ 6614 W input	92.77 %
@ 22520 W input	95.35 %
@ 57112 W input	96.74 %

Weight of Complete Transaxle	49.4 kg (109 lbs)

BATTERIES

TYPE: Lead-acid (nickel-zinc)

Battery characteristics

Specific energy	40 (80) Wh/kg
Specific power	100 (150) W/kg
Cycle life (80% discharge)	800 (500)
Cost	50 (75) $/kWh
Efficiency	60 (70) %

Total installed battery weight (lead-acid) 556 kg (1226 lbs)

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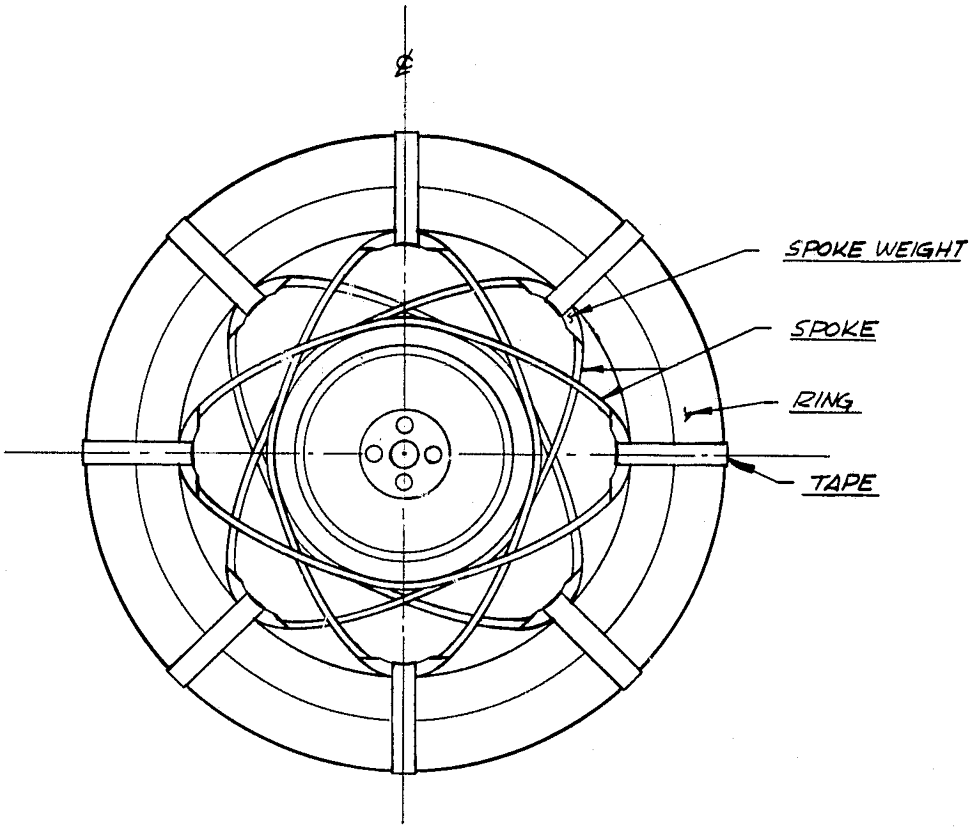

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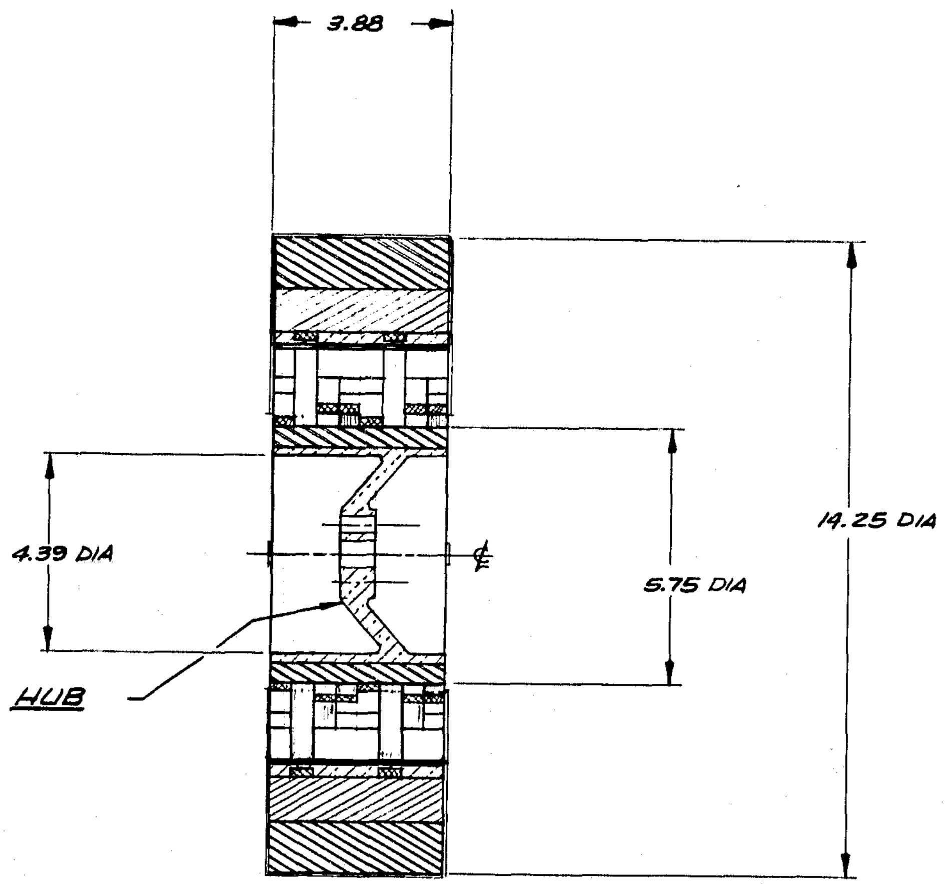

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WILLIAM M. BROBECK AND ASSOCIATES
1235 TENTH ST., BERKELEY, CALIF. 94710
TELEPHONE 415-524-8664

ADVANCED E.V. PROPULSION SYSTEM
CONCEPT "A6" & "D2"
FLYWHEEL

DRG. NO. 131 D051
SCALE 1/2
JOB 131-3-3

	NAME	DATE
DRAWN	MARTER	7-3-79
CHECKED	[signature]	7-15-79
SUPERV.	[signature]	7-15-79
RELEASED	[signature]	11-15-79

MATERIAL ~

SURFACE TREATMENT ~

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES ✓
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

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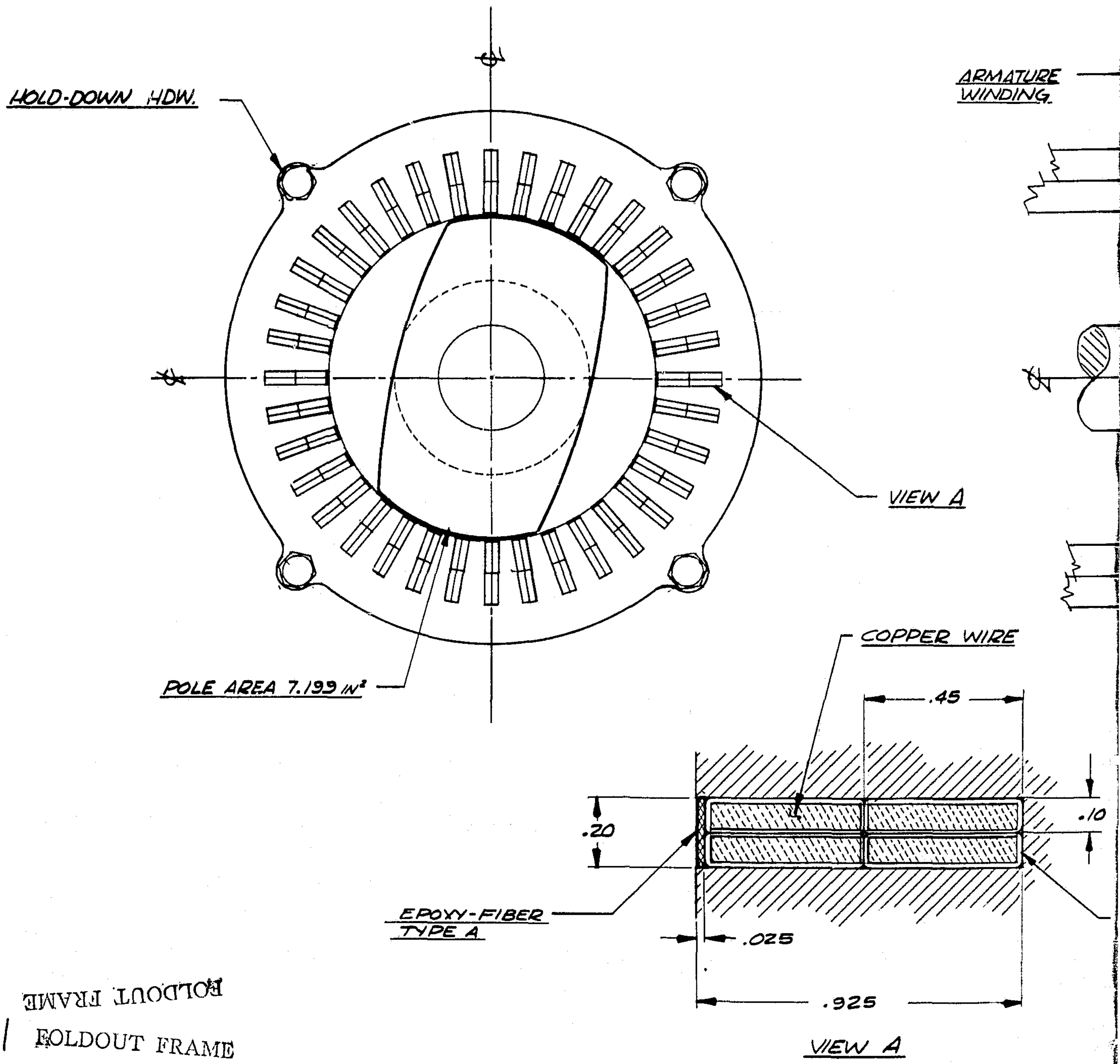

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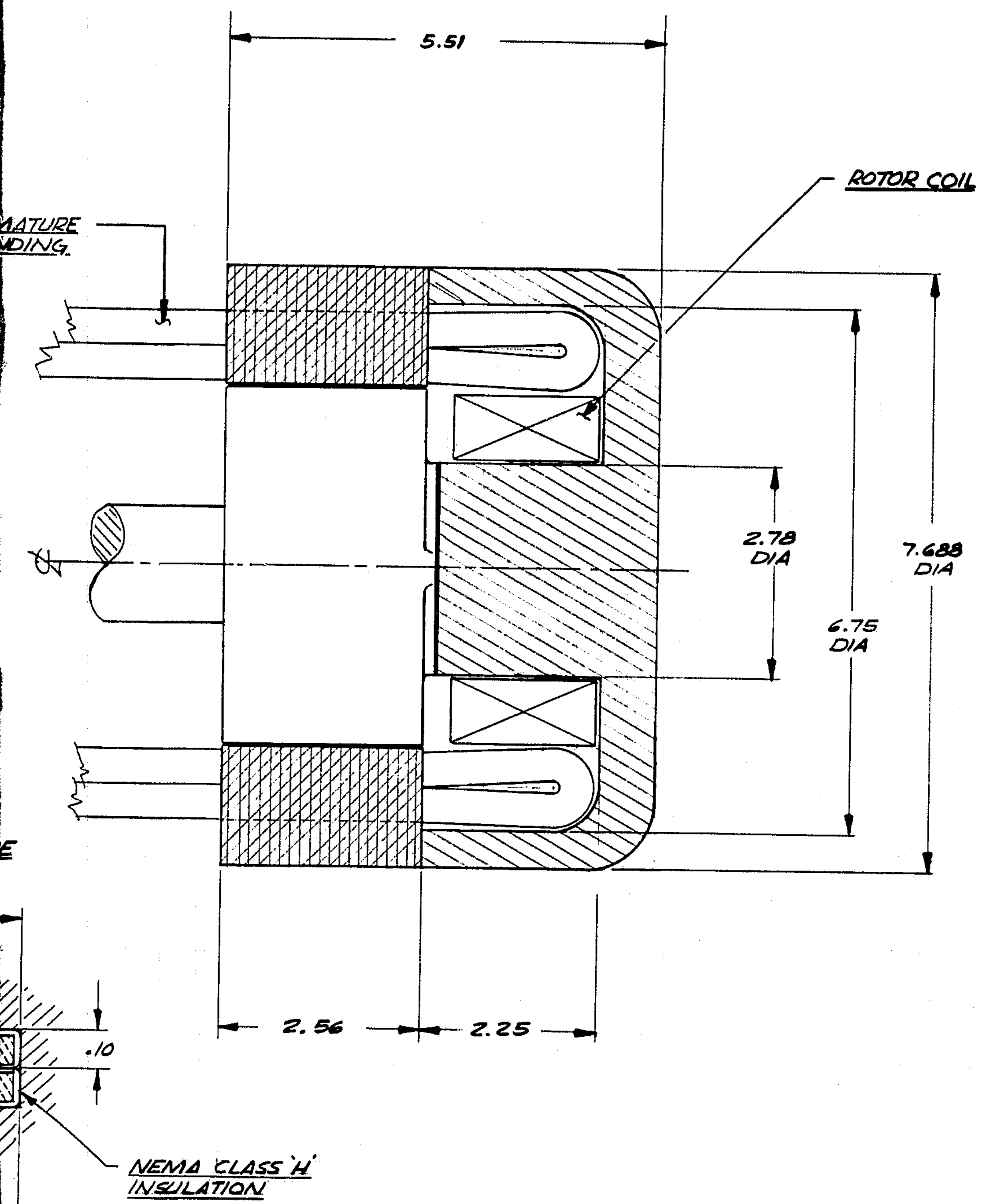

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WILLIAM M. BROBECK AND ASSOCIATES
1235 TENTH ST., BERKELEY, CALIF. 94710
TELEPHONE 415-524-8664

ADVANCED E.V. PROPULSION SYSTEM
CONCEPT 'A6'
HOMOPOLAR DC. GENERATOR

	NAME	DATE
DRAWN	MARTER	6-11-79
CHECKED	[signature]	7-15-79
SUPERV.	[signature]	7-15-79
RELEASED	[signature]	11-15-79

SCALE FULL
JOB 131-3-3
DRG. NO. 131D052

MATERIAL AS SPECIFIED
SURFACE TREATMENT

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES √
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

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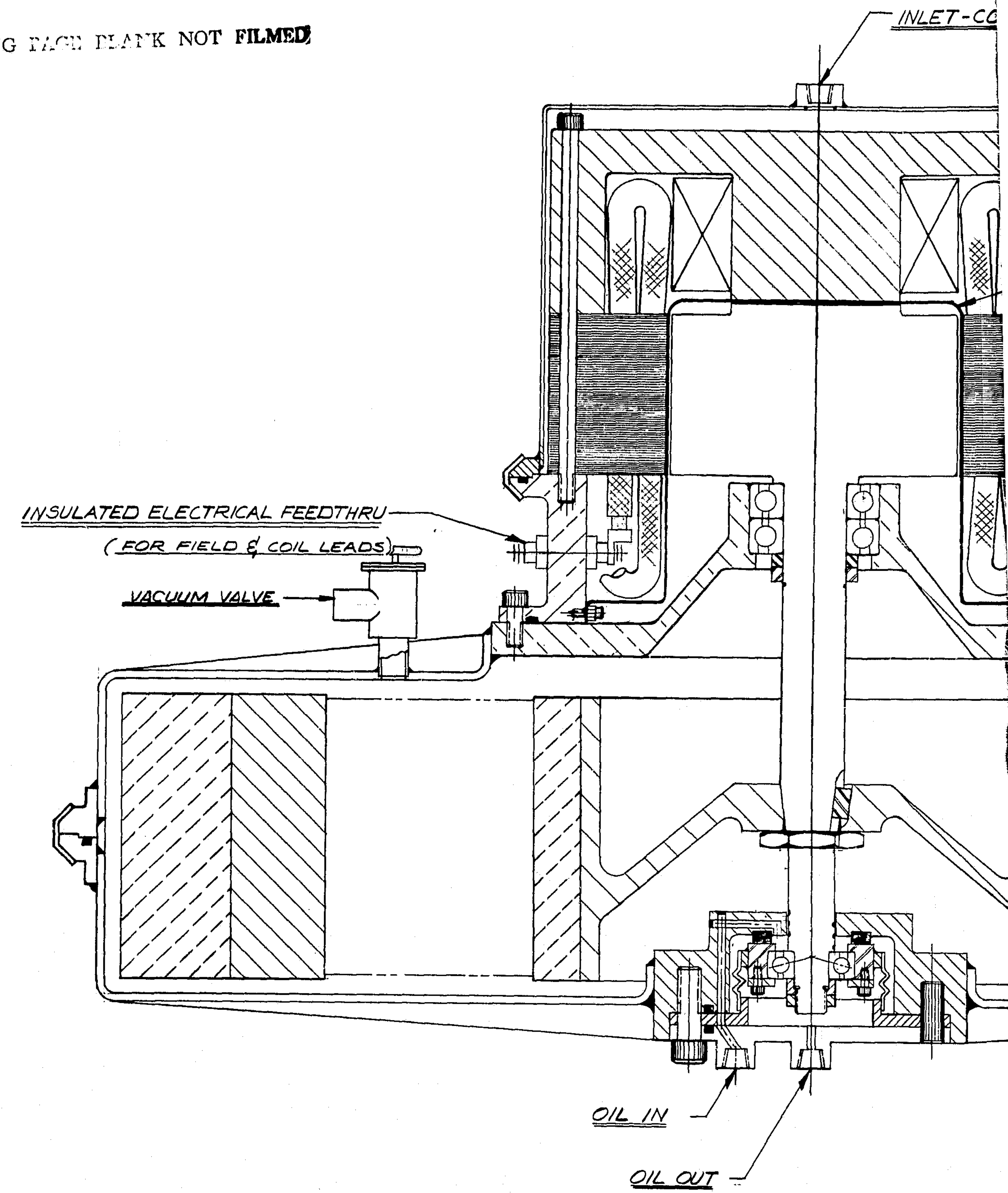

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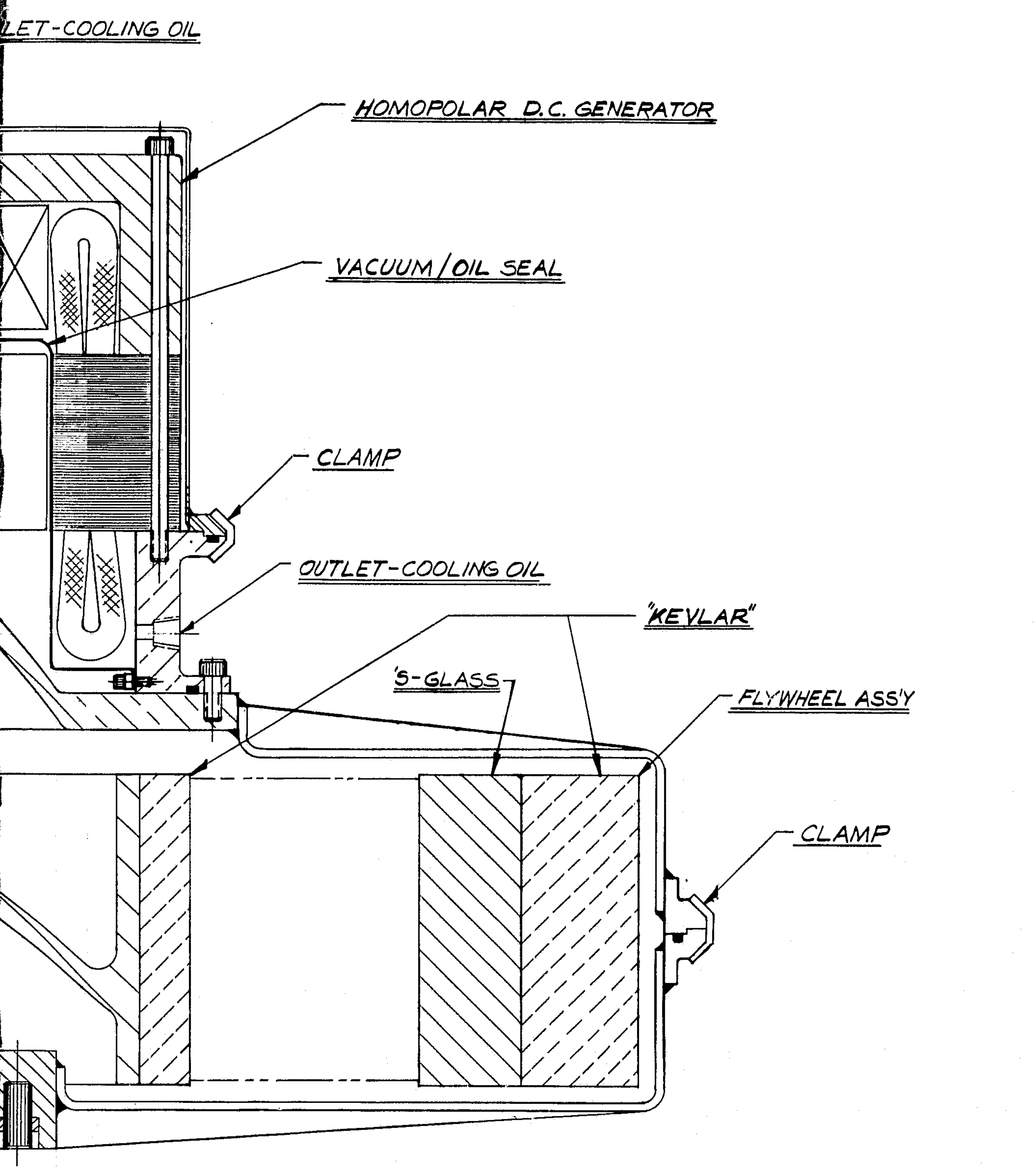

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1235 TENTH ST., BERKELEY, CALIF. 94710
TELEPHONE 415-524-8664

ADVANCED E.V. PROPULSION SYSTEM
CONCEPT A6
FLYWHEEL-D.C.GENERATOR ASS'Y

SCALE NONE
JOB 131-33
DRG. NO. 131 D053

	NAME	DATE
DRAWN	T Pickett	May 1979
CHECKED	[signature]	7-15-79
SUPERV.	[signature]	7-15-79
RELEASED	[signature]	11-15-79

MATERIAL ~
SURFACE TREATMENT ~

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES ✓
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

2 FOLDOUT FRAME

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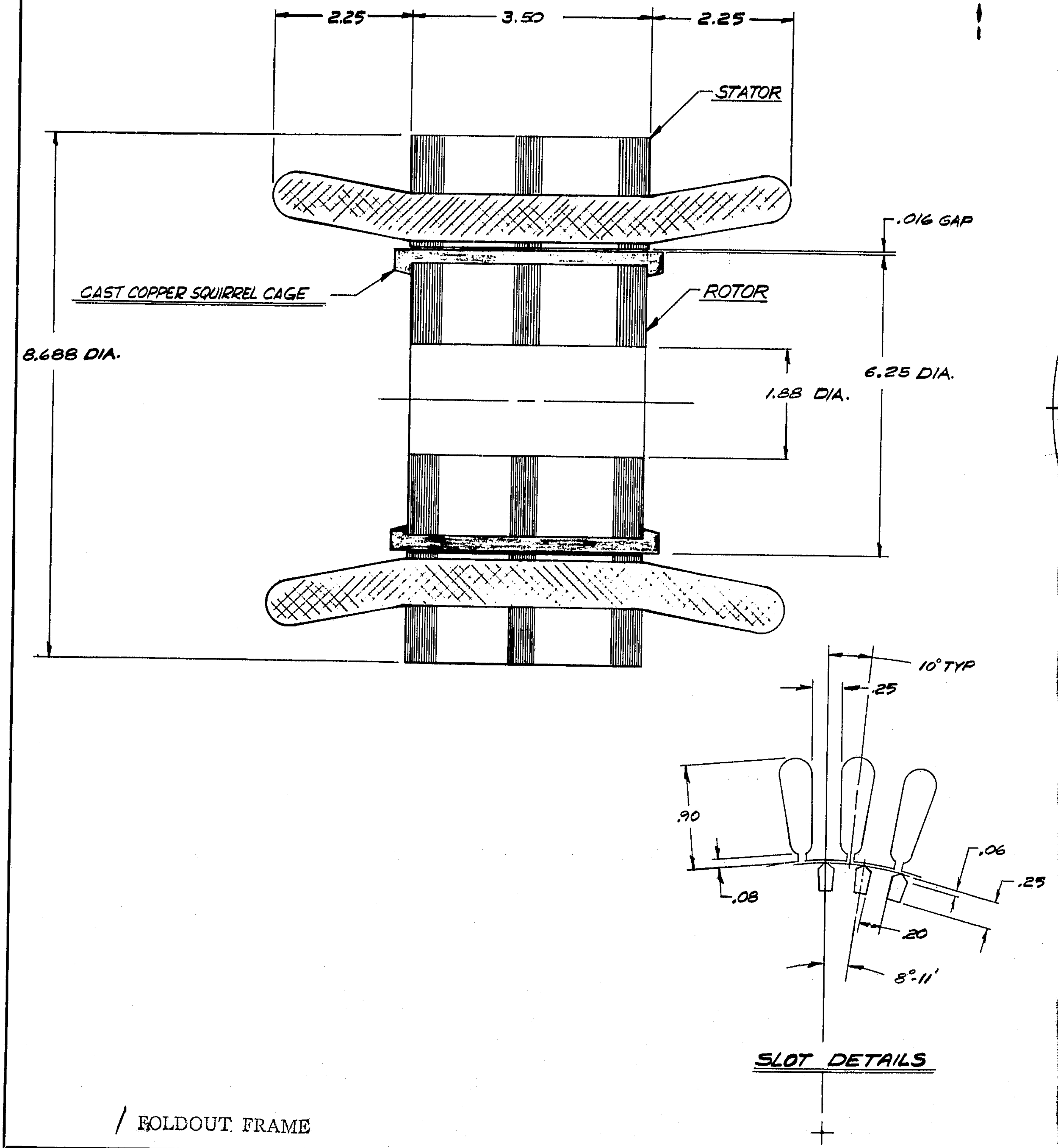

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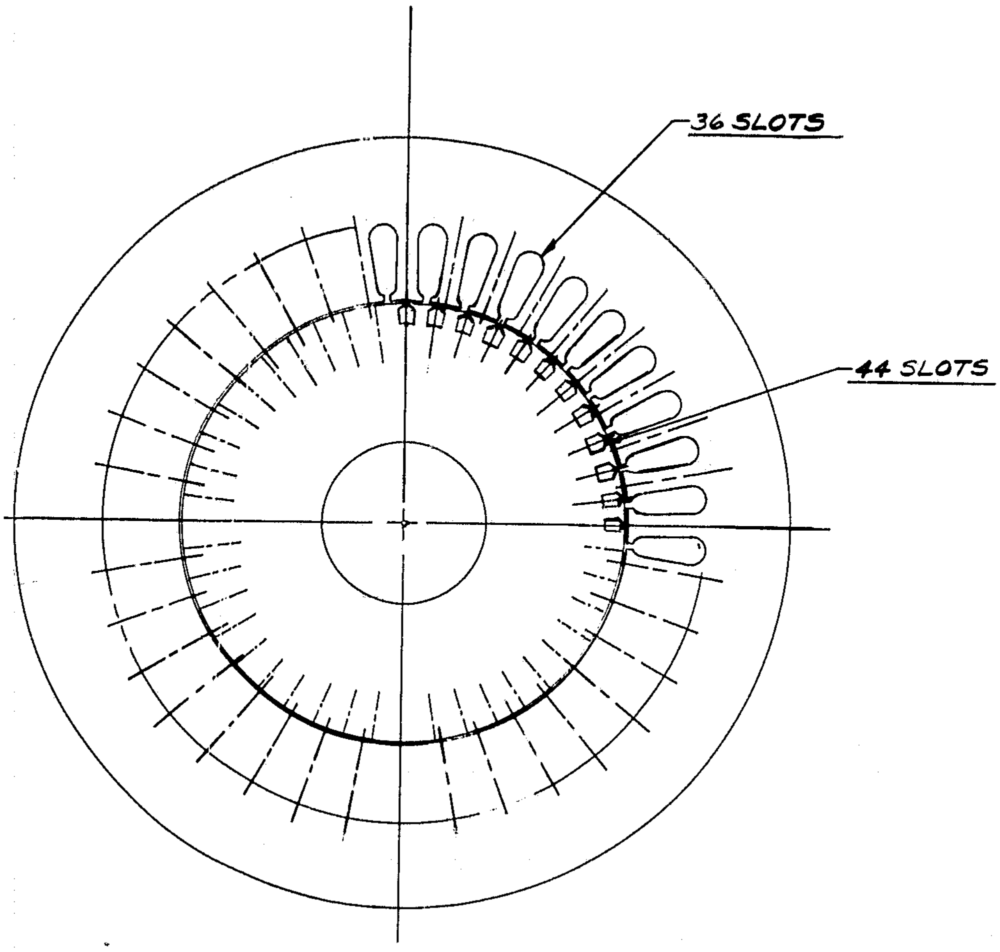

.06
.25

MOTOR CHARACTERISTICS:

26 KW, 7200 RPM
POWER FACTOR - 0.8
EFFICIENCY - 91%

FOLDOUT FRAME

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES √
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

MATERIAL ~
SURFACE TREATMENT ~

	NAME	DATE
DRAWN	T. Pickett	3.20/79
CHECKED	H. Lyle	7-15-79
SUPERV.	H. Lul	7-15-79
RELEASED	R. [illegible]	11-15-79

ADVANCED E.V. PROPULSION SYSTEM
CONCEPT A6
STATOR, ROTOR-TRACTION MTR.

WILLIAM M. BROBECK AND ASSOCIATES
1235 TENTH ST., BERKELEY, CALIF. 94710
TELEPHONE 415-524-8664

SCALE FULL
JOB 131-3.2
DRG. NO. 131D054

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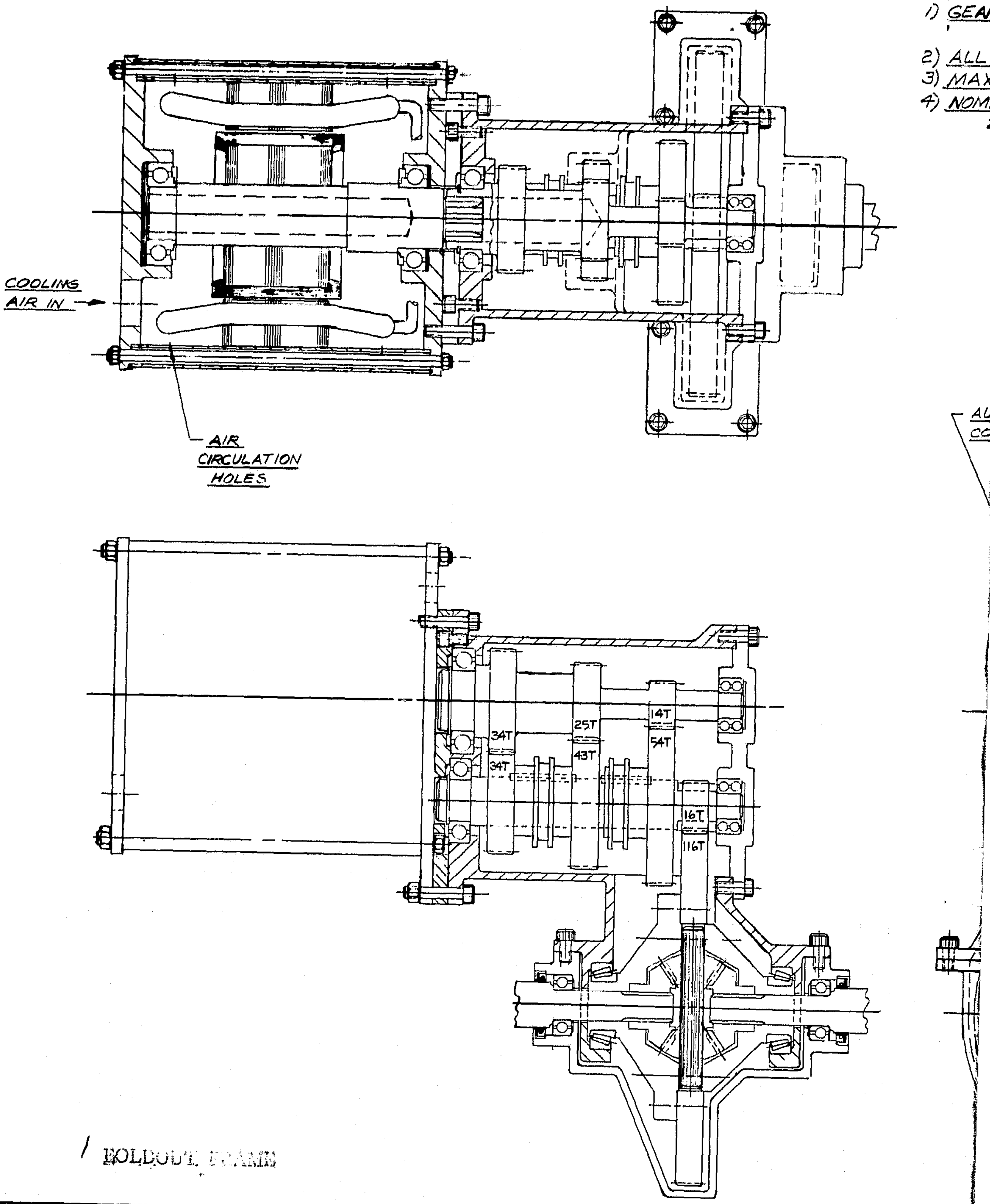

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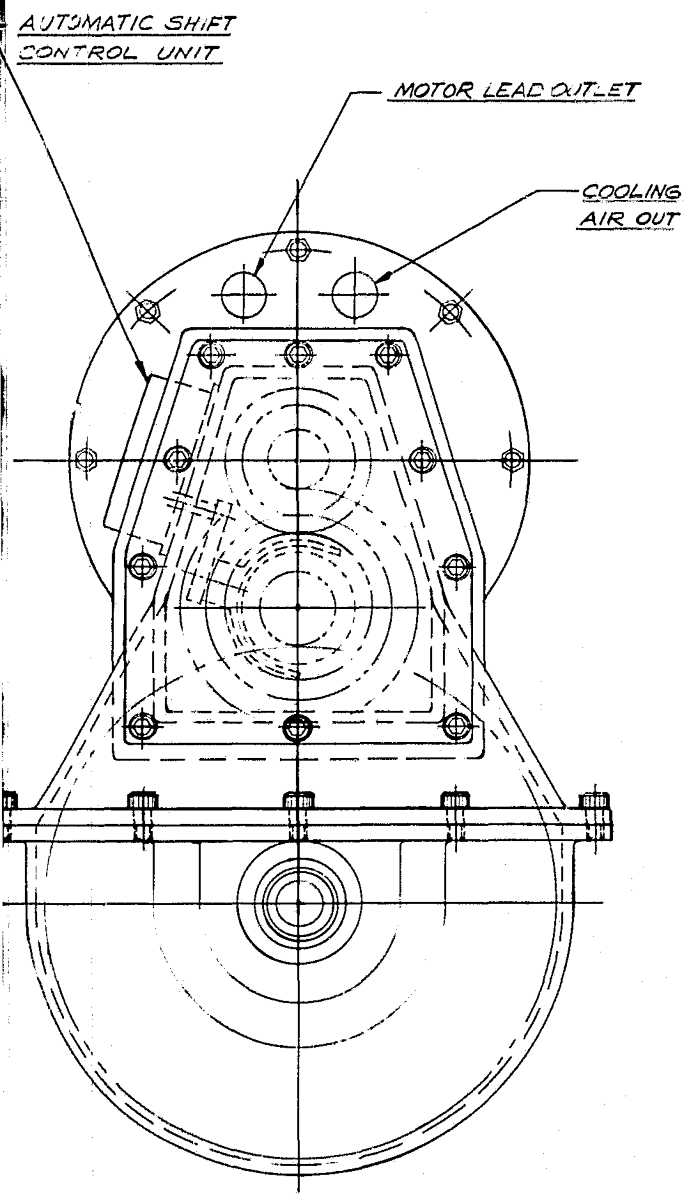
EAR RATIOS; 1ST: 3.8571 2ND: 1.7200 3RD: 1.000
DIFFERENTIAL: 7.2500
LL BEARINGS OIL LJBRICATED
AXIMUM MOTOR SPEED = 9000RPM
OM. MOTOR SPEC'S:
26 KW, 7200 RPM, 41 Nm.



2

WILLIAM M. BROBECK AND ASSOCIATES
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TELEPHONE 415-524-8664

SCALE 1/2
JOB 131-33
DRG. NO. 131D055

ADVANCED E.V. PROPULSION SYSTEM
CONCEPT 'A6'
MOTOR-TRANSAXLE ASS'Y

	NAME	DATE
DRAWN	T Pickett	May 20 79
CHECKED	[illegible]	7-15-79
SUPERV.	[illegible]	7-15-79
RELEASED	[illegible]	11-15-79

MATERIAL ~
SURFACE TREATMENT ~

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES ✓
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

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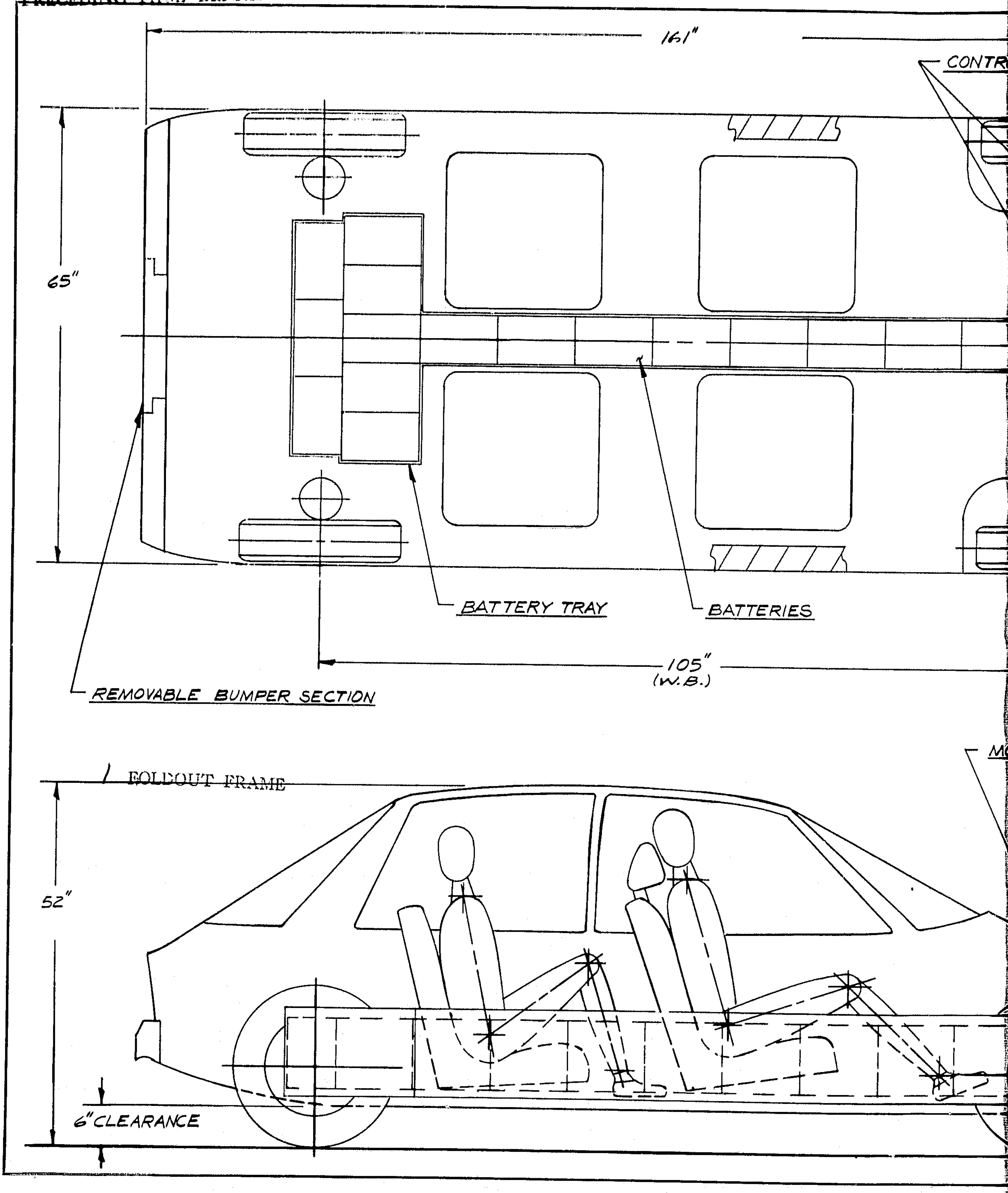

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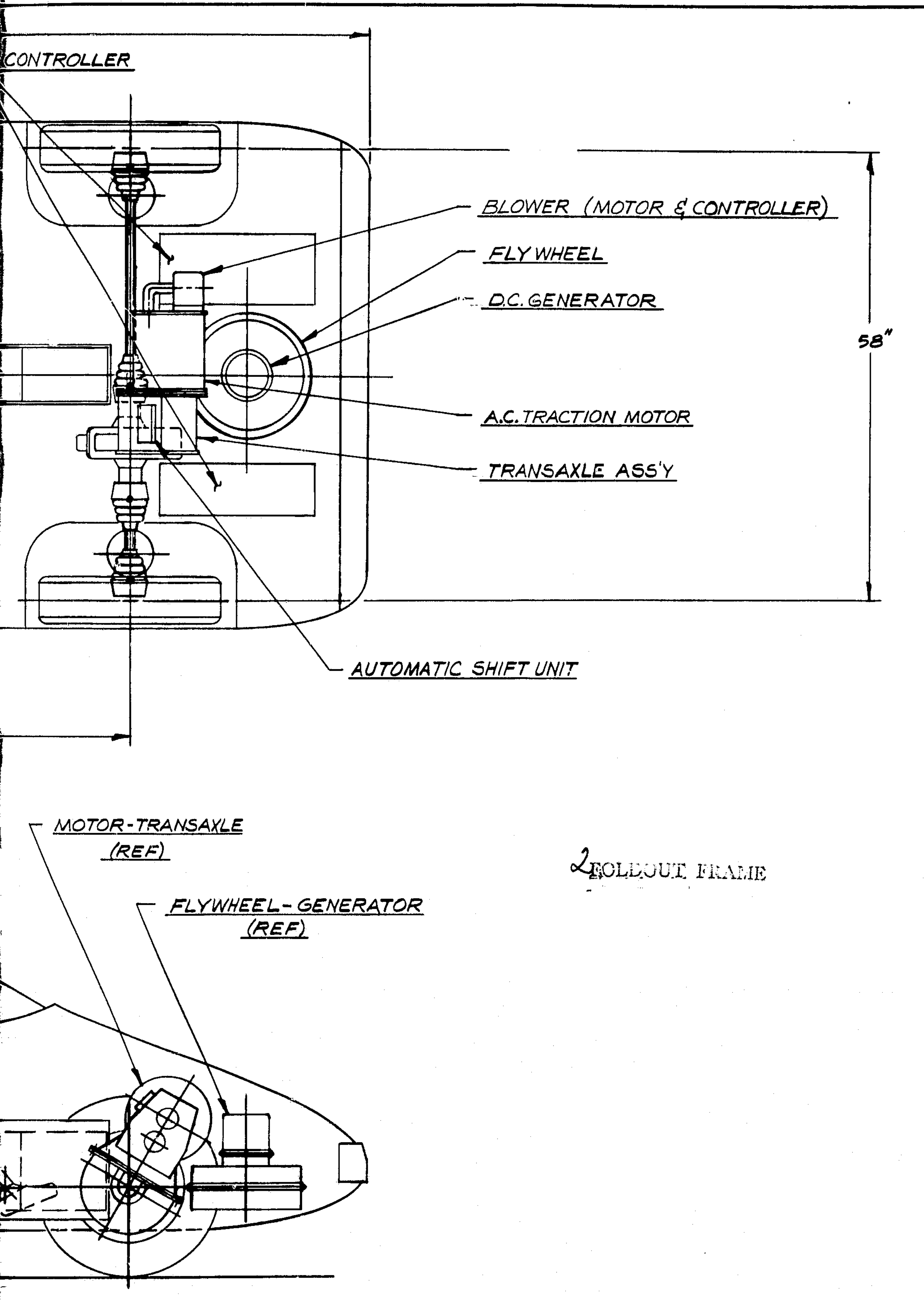

2 FOLDOUT FRAME

UNLESS OTHERWISE SPECIFIED: TOLERANCE ON FRACTIONS ± / FINISH ON MACHINE SURFACES √ / BREAK SHARP EDGES 1/64 MAX. / REMOVE BURRS / 30° CHAMFER ENDS OF ALL SCREW THREADS / DO NOT SCALE DRAWING	MATERIAL ~ / SURFACE TREATMENT ~		
NAME	DATE		
DRAWN T. Pickett	6-28-79	ADVANCED E.V. PROPULSION SYSTEM	WILLIAM M. BROBECK AND ASSOCIATES / 1235 TENTH ST. BERKELEY, CALIF. 94710 / TELEPHONE 415-524-8664
CHECKED [illegible]	7-15-79	CONCEPT "A6"	SCALE 1/8
SUPERV. [illegible]	7-15-79	GENERAL ARRANGEMENT	DRG. NO. 131D057
RELEASED [illegible]	11-15-79		JOB 131-3.3

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APPENDIX B

ADVANCED ELECTRIC VEHICLE PROPULSION SYSTEM

DESIGN CONCEPT: D2

GENERAL DESCRIPTION:

Propulsion system using an advanced design dc motor with electronic commutation which functions as chopper for voltage control and voltage boost for regenerative braking. Extra power for acceleration and braking is provided by a flywheel using a continuously variable transmission.

GENERAL PROPULSION SYSTEM DESCRIPTION

DESIGN CONCEPT D2

Curb weight	1474 kg (3250 lbs)
Battery weight	544 kg (1199 lbs)
Propulsion system weight without battery	205 kg (452 lbs)
Traction Motor	
Electronically commutated brushless dc	
Rated power	26 kW
Base speed	5400 rpm
Maximum speed	7800 rpm
Efficiency	90.4%
Voltage	96 Vdc
Weight	43 kg (95 lbs)
Fiber-Composite Flywheel	
Total stored energy	2.44 MJ (678 Wh)
Maximum speed	46300 rpm
Total weight	16 kg (35.3 lbs)
CVT	
Planetary cone type	
Maximum power	34 kW
Maximum/minimum speed input	46300/15400 rpm
Full load efficiency	94%
Weight	71 kg (157 lbs)
Magnetic Coupling	
Maximum power	36 kW
Base speed	23200 rpm
Weight	9 kg (20 lbs)
Transaxle - 3-Speed	
Weight	50 kg (109 lbs)
Controller	
9-phase chopper	
Rated power	29 kW
Weight	16 kg (34.8 lbs)
Battery - Lead-Acid	
Specific energy	40 Wh/kg (18 Wh/lb)
Specific power	100 W/kg (45 W/lb)
Efficiency	60%
Propulsion System Performance	
Range for steady 45 mph cruise	223.7 km (139 mi)
Range for SAE J227a Schedule D	160.9 km (100 mi)
Acceleration 0 to 55 mph	15 sec

TRACTION MOTOR

DESIGN CONCEPT D2

TYPE: Electronically commutated brushless dc, four pole design with field excitation provided through slip rings.

Rating

Power continuous	26,000 Watts
Base speed	5,400 rpm
Maximum speed	7,800 rpm
Efficiency	90.4%
Voltage	96 Vdc
Current	300 Adc

Number of phases of armature 9

Dimensions

	mm	in
Armature stack length	85.7	3.375
slot depth	22.9	.90
slot width	6.4	.25
Rotor diameter	138.7	5.46
Rotor length	85.7	3.375
Air gap diameter	138.9	5.469
Housing I.D.	220.7	8.69
Housing O.D.	246.1	9.69
Housing length	292.1	11.5
Bearing O.D.	88.9	3.5
Drive shaft O.D.	38.1	1.5

Weights

	kg	lbs
Armature iron	10.66	23.5
Armature copper	10.43	23.
Field copper	4.99	11.
Rotor iron	8.39	18.5
Shaft	2.49	5.5
Housing	2.72	6.
End bells	2.49	5.5
Miscellaneous	1.04	2.3
Total unit weight	43.21	95.3

Resistance

Armature winding	.1098 Ω
Field winding	204.1323 Ω

Winding description

Armature	Lap winding - 36 Slots
Field	Wound rotor, supplied by slip rings

Losses at continuous power (26,000 W)

Total	2761 W
Ohmic	1849 W
Hysteresis	138 W
Eddy current	221 W
Bearing friction	359 W
Windage	193 W

Cooling

Air cooling provided by thermostatically controlled blower

Cost, weight and power of blower is included in motor/controller cost, weight and losses.

CONTROLLER FOR ELECTRONICALLY COMMUTATED DC MOTOR

DESIGN CONCEPT D2

TYPE: Variable voltage, 9-phase electronic commutation with chopper field and armature control.

Ratings

kVA rating, continuous	29 kW
Input voltage	96 V
Output voltage	96 V
Output current, maximum continuous	350 Adc

Power Loss

At full oad	1180 W
Efficiency at full load	96.1%

Cooling

*Forced air cooling

Field Control

Maximum current	1.34 Adc
Maximum voltage	96. Vdc

Weight — 15.79 kg (34.8 lbs)

Control Method

Shaft position sensor for commutation
Armature current chopper below base speed
Field current chopper above base speed

*Cost, weight and power of blower is included in motor/controller cost, weight and losses.

FLYWHEEL

DESIGN CONCEPT D2

TYPE: Bi-annulate rim fiber-composite

Maximum speed	46316 rpm	
Maximum stored energy	2.44 MJ (679 Wh)	
Available energy for a 3:1 speed range	2.17 MJ (603 Wh)	
Specific energy	64.3 Wh/kg (29.18 Wh/lb)	
Flywheel dimensions	mm	in
Inner ring, S-2 glass/epoxy		
I.D.	253.7	9.99
O.D.	303.	11.93
Outer ring, Kevlar 49/epoxy		
I.D.	303.	11.93
O.D.	362.	14.26
Height	98.6	3.88
Hub - aluminum with kevlar reinforcement		
Kevlar O.D.	146.1	5.75
I.D.	121.7	4.79
Aluminum hub I.D.	111.5	4.39
Weights	kg	lbs
Rings	8.4	18.52
Spokes	.47	1.03
Hub	1.60	3.53
Balancing weights	.09	.19
Total	10.56	23.27
Housing	5.44	12.
Total	16.00	35.27
Vacuum		
Bearings	Ball bearings	
Seals - hermetically sealed		

CONTINUOUSLY VARIABLE TRANSMISSION (CVT)

DESIGN CONCEPT D2

TYPE: Planetary cone type with magnetic coupling for peak torque limiting and declutching capability.

Rating

Maximum power	34,000 W
Maximum/minimum speed input	46,316-15,439 rpm
Maximum/minimum speed output	7,800-1,158 rpm
Full load efficiency @ (33,302 W)	94%
Ratio	12:1

Torque

(0 to 55 mph in 15 seconds)	
Maximum input @ 21,007 rpm	16.12 Nm
Maximum output @ 4,333 rpm	73.39 Nm

Loss coefficients

Viscous drag	2 %
Spin torque	4 %
Creep	3 %

Bearing types	Ball bearing
Weight including magnetic coupling	80.5 kg (177.5 lbs)

TRANSAXLE

DESIGN CONCEPT D2

TYPE: 3-speed with electronically controlled gear changing mechanism

Differential	
Ratio	5.444
Bearing type	Ball bearing
Maximum torque input	460 Nm (340 lb-ft)
Maximum torque output	2508 Nm (1850 lb-ft)
Weight	17.7 kg (39 lbs)
Axle	
Axle Weight	9.1 kg (20 lbs)
Transmission	
Gear ratios	1, 1.74, 3.86
Bearing type	Ball bearing
Synchromesh type	
Maximum torque input	119 Nm (88 lb-ft)
Maximum torque output	460 Nm (340 lb-ft)
Maximum speed input	9000 rpm
Weight	20.4 kg (45 lbs)
Gear shift mechanism	
Weight	2.2 kg (5 lbs)
Weight of Complete Transaxle	49.4 kg (109 lbs)

BATTERIES

DESIGN CONCEPT D2

TYPE: Lead-acid (nickel-zinc)

Battery characteristics

Specific energy	40 (80) Wh/kg
Specific power	100 (150) W/kg
Cycle life (80% discharge)	800 (500)
Cost	50 (75) $/kWh
Efficiency	60 (70) %

Total installed battery weight (lead-acid) 544 kg (1199 lbs)

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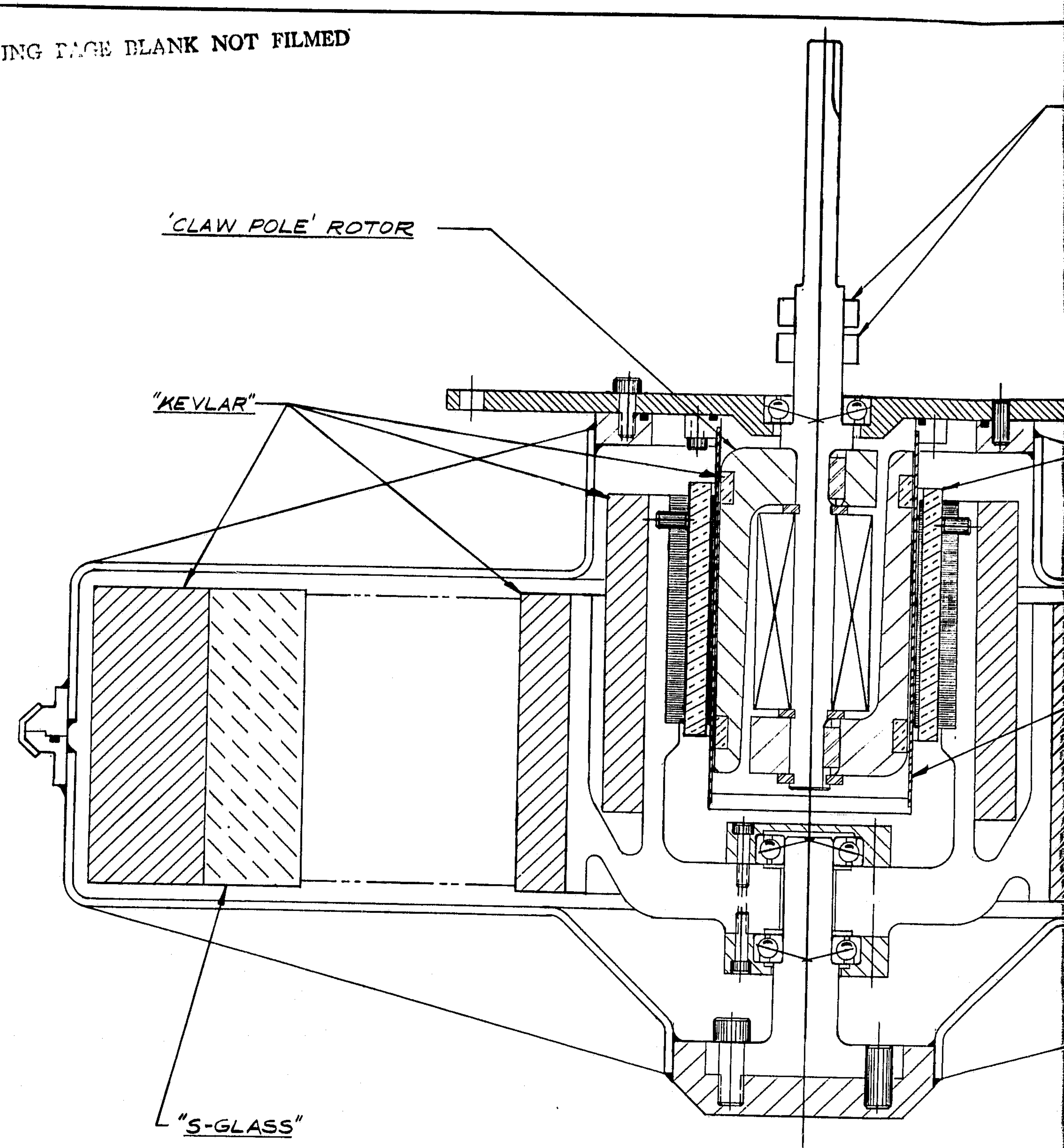

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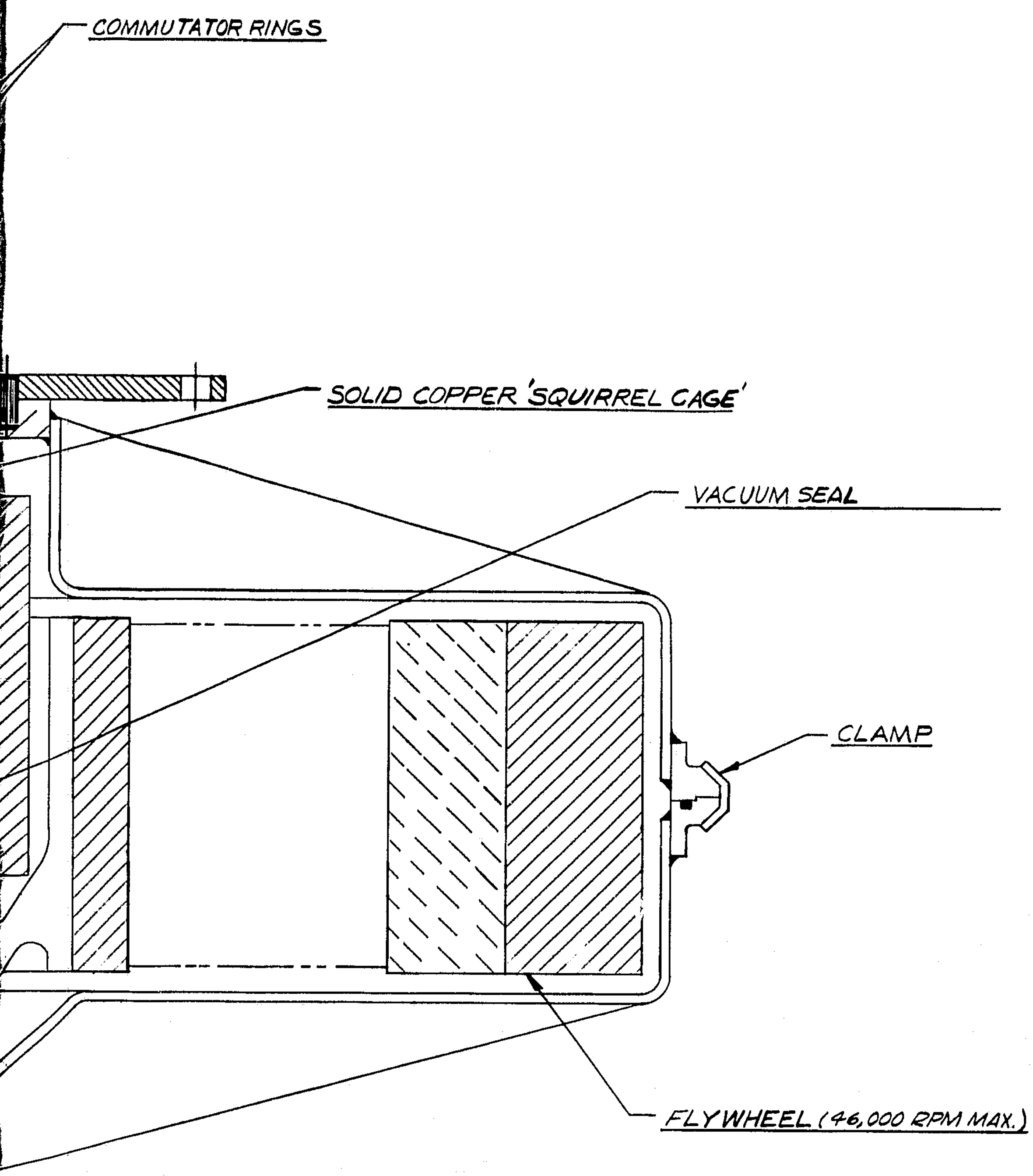

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WILLIAM M. BROBECK AND ASSOCIATES
1235 TENTH ST., BERKELEY, CALIF. 94710
TELEPHONE 415-524-[illegible]

ADVANCED E.V. PROPULSION SYSTEM
CONCEPT D2
FLYWHEEL W/MAG. COUPLING

SCALE NONE
JOB 131-3.3
DRG. NO. 131D081

	NAME	DATE
DRAWN	T Pickett	[illegible] 15 79
CHECKED	[illegible]	7-15-79
SUPERV.	[illegible]	7-15-79
RELEASED	[illegible]	11-15-79

MATERIAL ~
SURFACE TREATMENT ~

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES ✓
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

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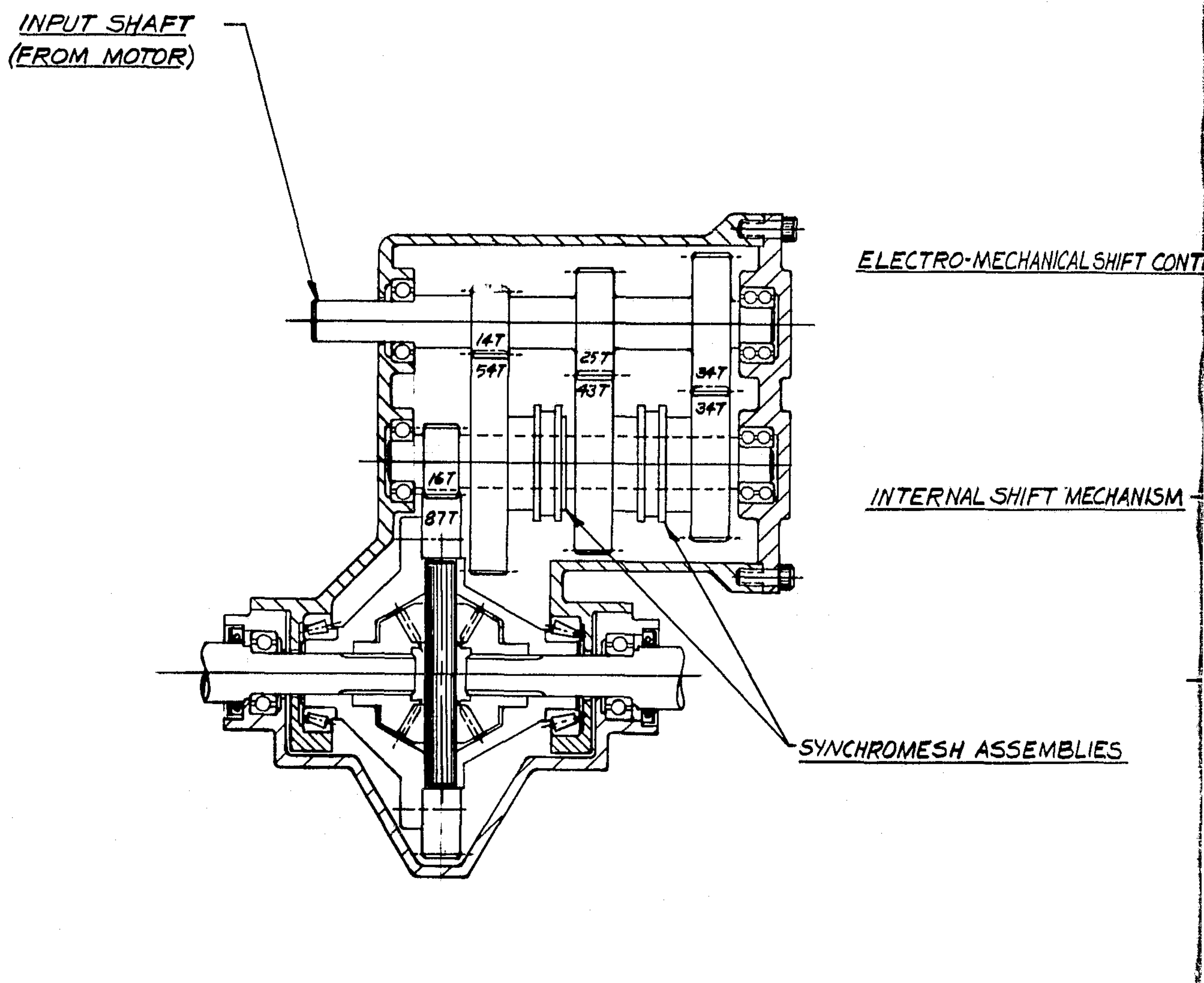

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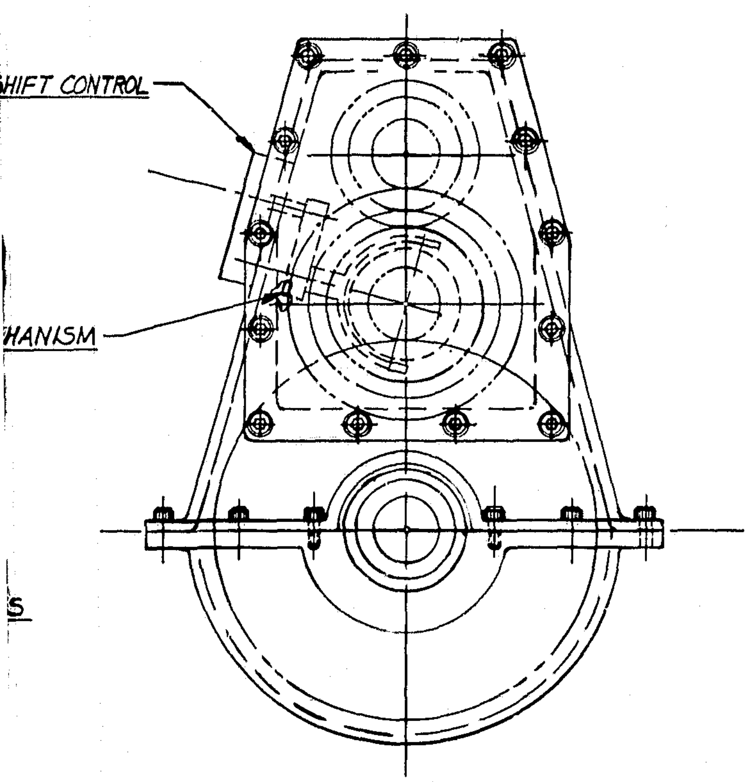


GEAR RATIOS:

1ST GEAR : 3.8571
2ND GEAR : 1.7200
3RD GEAR : 1.0000
AXLE RATIO : 5.4444

INPUT RATINGS:

MAXIMUM RPM-6000
MAXIMUM H.P.-67

2 FOLDOUT FRAME

WILLIAM M. BROBECK AND ASSOCIATES
1235 TENTH ST., BERKELEY, CALIF. 94710
TELEPHONE 415-524-8664

ADVANCED E.V. PROPULSION SYSTEM
CONCEPT 'D2'
3 SPEED TRANSAXLE

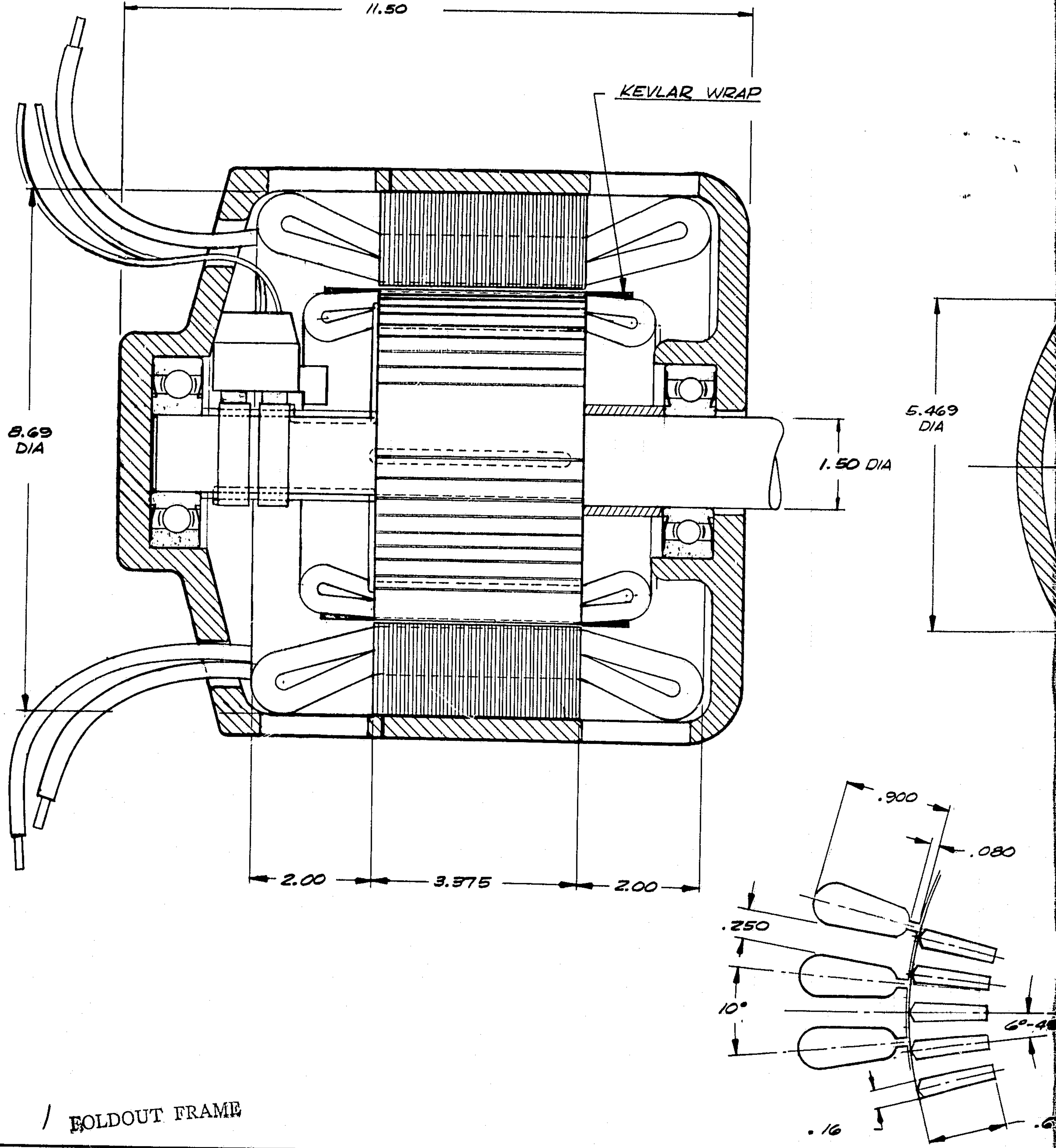
	NAME	DATE
DRAWN	T. Pickett	5-23-79
CHECKED	[illegible]	7-15-79
SUPERV.	[illegible]	7-15-79
RELEASED	[illegible]	11-15-79

SCALE 1/2
JOB 131-3.3
DRG. NO. 131D082

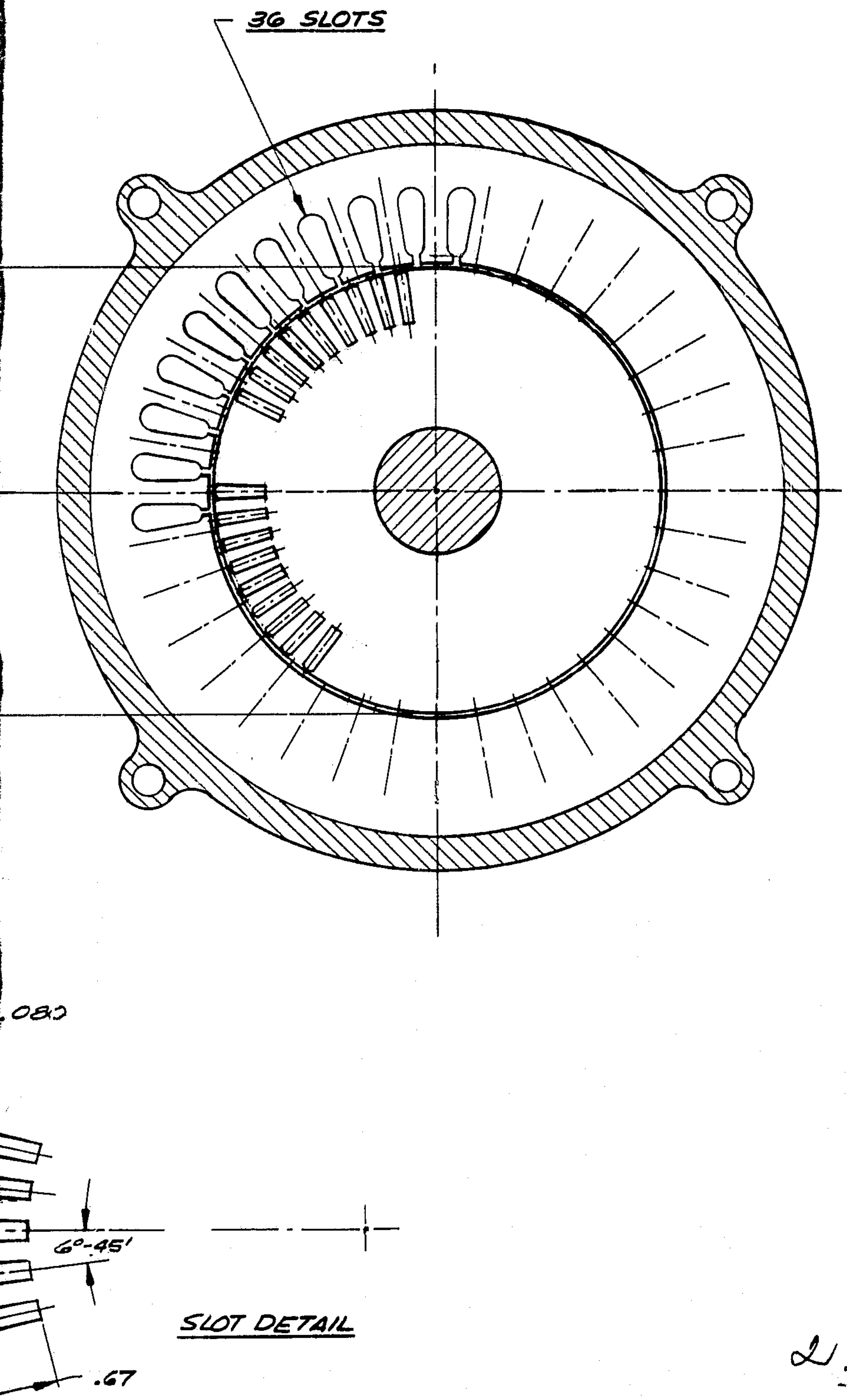
MATERIAL ~
SURFACE TREATMENT ~

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES ✓
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

PRECEDING PAGE BLANK NOT FILMED



/ FOLDOUT FRAME



2 FOLDOUT FRAME

WILLIAM M. BROBECK AND ASSOCIATES
1235 TENTH ST., BERKELEY, CALIF. 94710
TELEPHONE 415-524-8664

SCALE FULL & NOTED
JOB 131-3-3
DRG. NO. 131D084

ADVANCED E.V. PROPULSION SYSTEM.
CONCEPT 'D2'
D.C. MOTOR

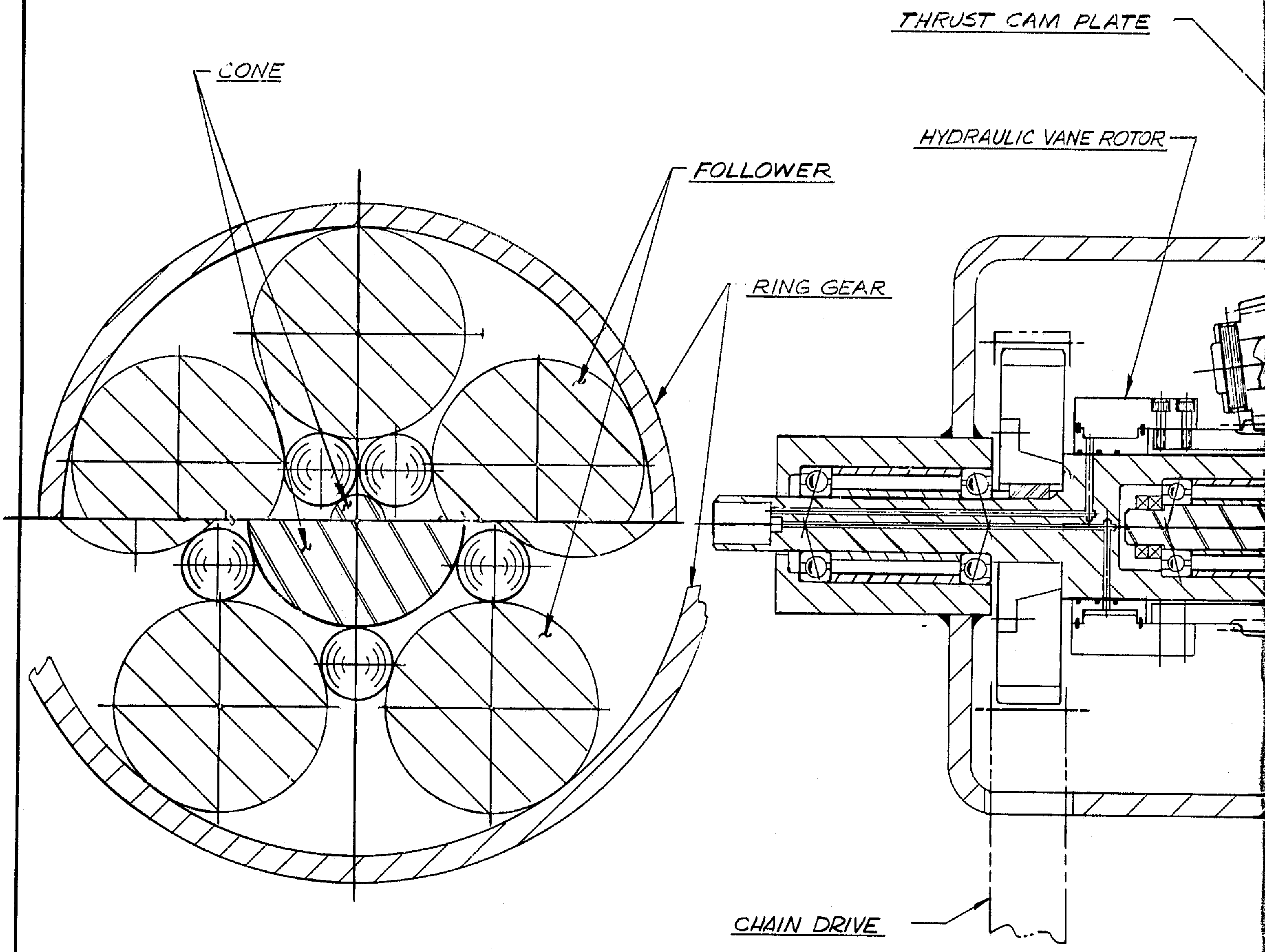
	NAME	DATE
DRAWN	MEL MARTER	6-18-79
CHECKED	H. Vail	7-15-79
SUPERV.	H. Vail	
RELEASED		

MATERIAL ~

SURFACE TREATMENT ~

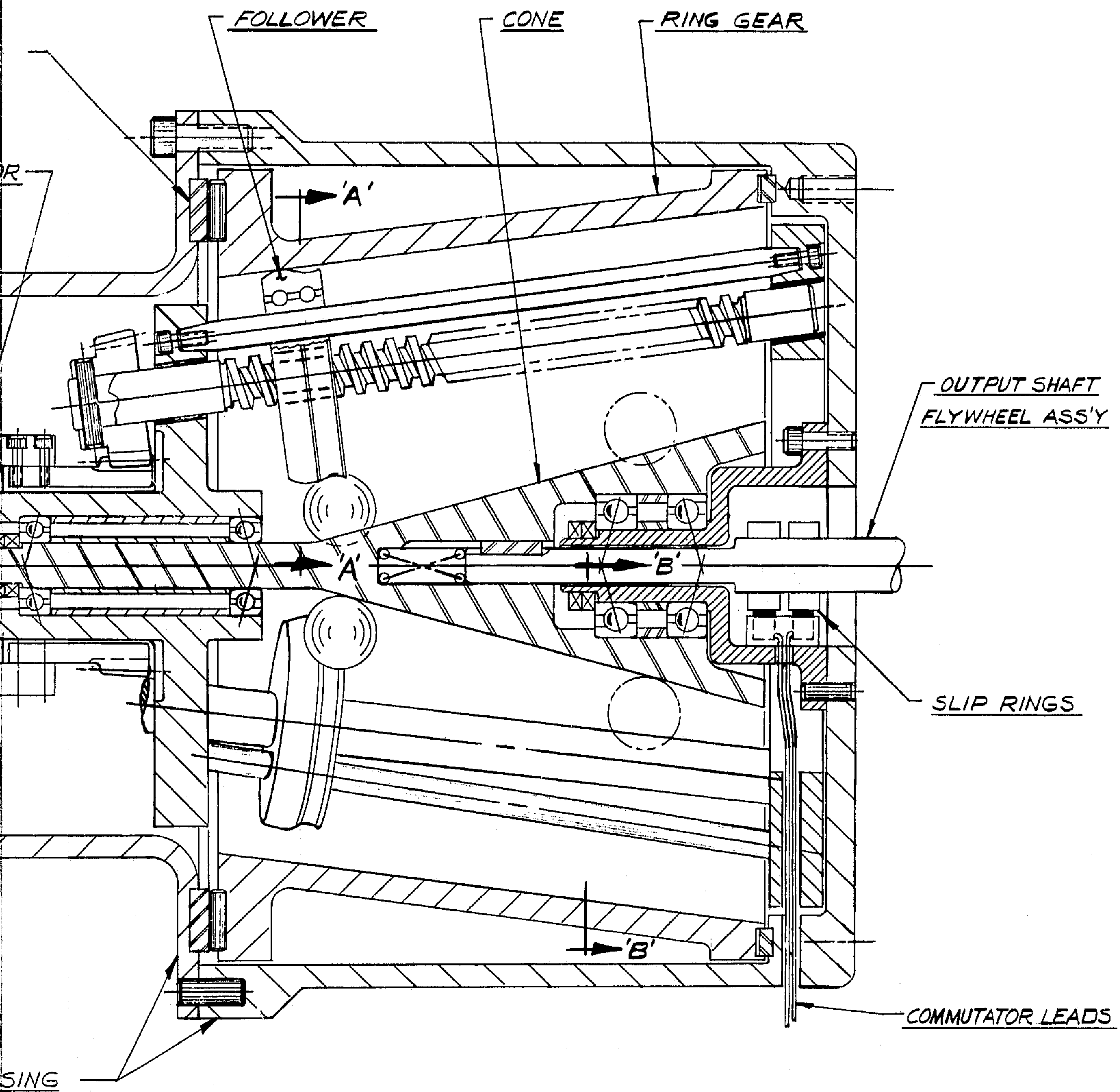
UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES ✓
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

PRECEDING PAGE BLANK NOT FILMED



PARTIAL SECTIONS: 'A'-'A' (TOP HALF)
'B'-'B' (BOTTOM HALF)

FOLDOUT FRAME



2 FOLDOUT FRAME

WILLIAM M. BROBECK AND ASSOCIATES 1235 TENTH ST., BERKELEY, CALIF. 94710 TELEPHONE 415-524-8664	DRG. NO. 131D085
SCALE FULL	JOB 131-3.3
ADVANCED E.V. PROPULSION SYSTEM CONCEPT D2 CONTINUOUSLY VARIABLE XMISS.	

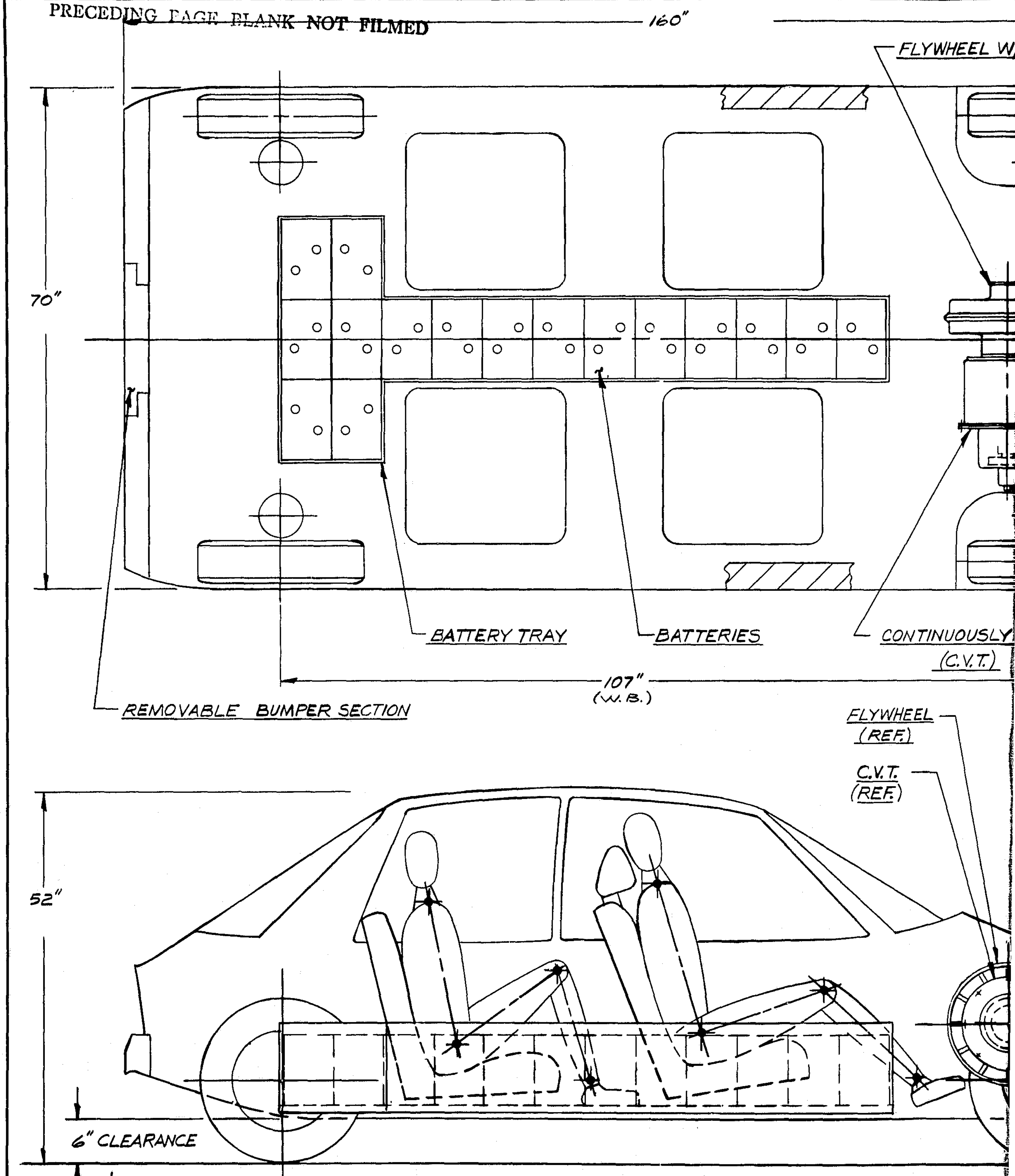
	NAME	DATE
DRAWN	T Pickett	June 26 79
CHECKED		7-15-79
SUPERV.		7-15-79
RELEASED		11-15-79

MATERIAL ~

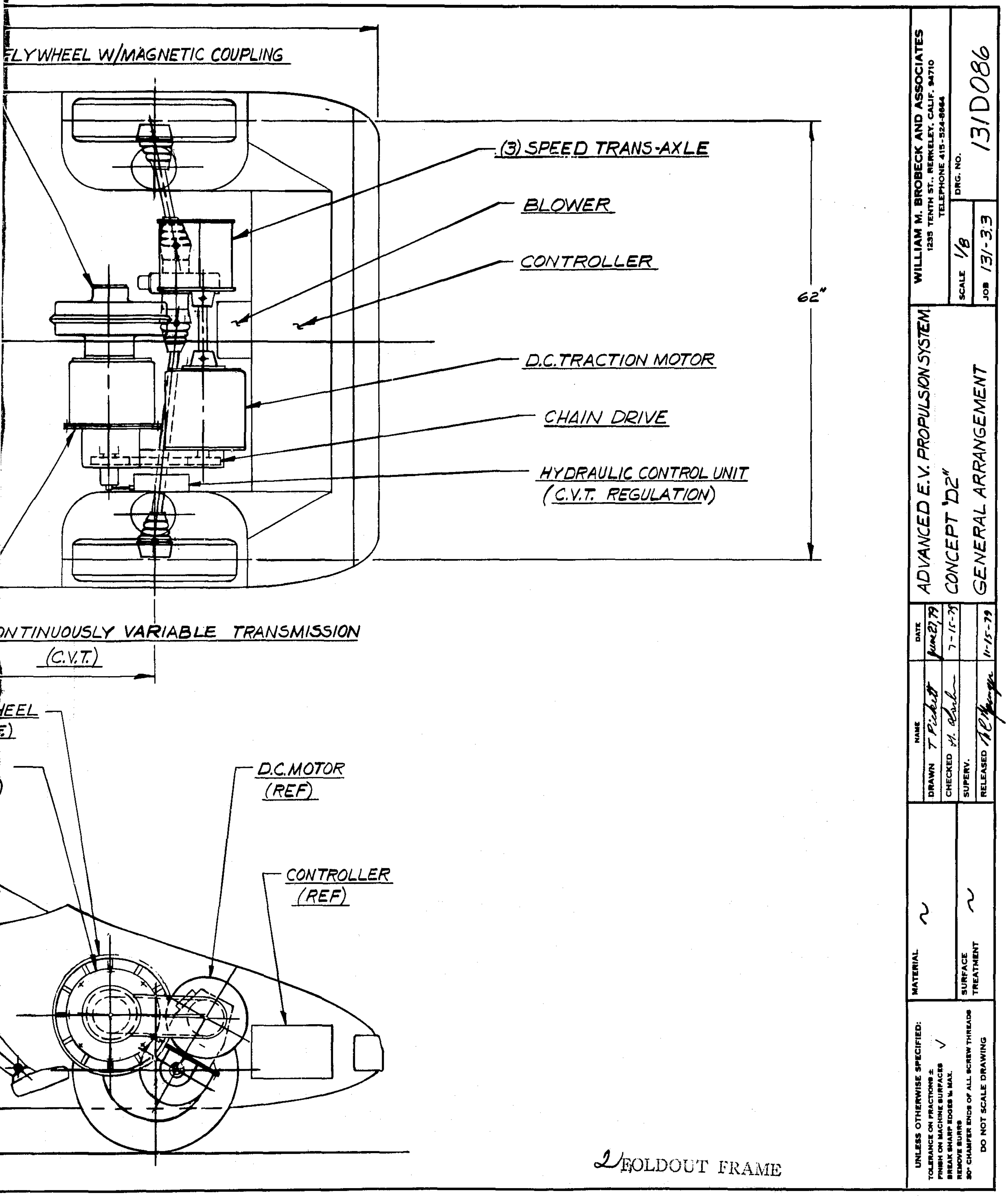
SURFACE TREATMENT ~

UNLESS OTHERWISE SPECIFIED:
TOLERANCE ON FRACTIONS ±
FINISH ON MACHINE SURFACES
BREAK SHARP EDGES 1/64 MAX.
REMOVE BURRS
30° CHAMFER ENDS OF ALL SCREW THREADS
DO NOT SCALE DRAWING

PRECEDING PAGE BLANK NOT FILMED



FOLDOUT FRAME



2 FOLDOUT FRAME

APPENDIX C

MODELS FOR PROPULSION SYSTEM COMPONENTS

A brief description of the models for the battery, transaxle, motor and controller follows. A typical page of computer printout showing that portion of the computation of the power and losses at each time step is given in Table C1.

Table C1-A

ADVANCED EV PROPULSION SYSTEM CONCEPT A6 SINGLE MOTOR /DR.AXLE W/TRANS. WF AC1

VEHICLE CHARACTERISTICS

BASE WEIGHT.	MAX.PAYLOAD	TEST LOAD	WT.PROPAGATION F.	AIR DRAG CDA	AIR DENSITY	ROT.INER.FACT.
718.67	600.00	300.00	1.2990	6.0000	.23800E-02	1.0400

TIRE FACTORS

RADIUS INCH	ROLLING RESIST.COEFFICIENTS			SHIFT POINTS FT/SEC		
11.5	.80000E-02	.10970E-04	.96300E-07	19.00	31.00	76.00

AXLE FACTORS

RATIO	WEIGHT	TORQUE CAP.	COST	LOSS COFF.A0,	A1	A2
7.2666	59.0	250.	1.50	.12480E+00	.24950E-04	.66000E-02

DRIVE MOTOR FACTORS

RATED POWER	MIN SPEED	MAX SPEED	OVERLOAD PERCENT	RATED VOLTS	RATED CURRENT	SPECIFIC WEIGHT	EFFICIENCY
36000.	7200.0	9000.0	375.00	96.000	194.00	.50000E-02	91.000

LOSS DISTRIBUTION FACTORS

OHMIC HEATING	HYSTERESIS	EDDY CURRENT	BEARING FRICT.	WINDAGE	FREQUENCY	COST	POWER FACTOR
67.000	5.0000	10.000	9.0000	9.0000	240.00	.20000E-01	.84000

CONTROLLER FROM BATTERY TO MOTOR CHARACTERISTICS

RATED POWER	INPUT VOLTAGE	OUTPUT VOLTAGE	RATED CURRENT	FREQUENCY	SPEC.WEIGHT
45000.	240.00	238.00	388.00	240.00	.12000E-02

LOSS COEFF.A0,	A1	A2	COST
.10000E+02	.24000E+00	.25800E-01	.21E+03

CONTROLLER FROM GENERATOR TO MOTOR CHARACTERISTICS

RATED POWER	INPUT VOLTAGE	OUTPUT VOLTAGE	RATED CURRENT	FREQUENCY	SPEC.WEIGHT
40000.	241.00	238.00	388.00	240.00	.15000E-02

LOSS COEFF.A0,	A1	A2	COST
.12300E+03	.37500E+01	.60000E-02	.25E+03

BATTERY CHARACTERISTICS

VOLTAGE	SPEC.ENERGY	SPEC.POWER	BATT.WEIGHT	COST	EFFICIENCY
96.00	15.00	20.00	1239.	2.500	65.00

FLYWHEEL CHARACTERISTICS

SPEC.ENERGY	FLYWEEL WEIGHT	MAX SPEED	RUNDOWN PERCENT/HR	COST
29.180	45.780	30000.	4.0000	500.00

GENERATOR FACTORS

RATED POWER	MIN SPEED	MAX SPEED	OVERLOAD PERCENT	RATED VOLTS	RATED CURRENT	SPECIFIC WEIGHT	EFFICIENCY
45000.	20000.	40000.	200.00	241.00	196.00	.83000E-02	92.000

LOSS DISTRIBUTION FACTORS

OHMIC HEATING	HYSTERESIS	EDDY CURRENT	BEARING FRICT.	WINDAGE	FREQUENCY	COST
45.000	5.0000	5.0000	5.0000	40.000	666.60	5.5000

TRANSMISSION CHARACTERISTICS

HIGH GEAR RATIO	SEC.GEAR RATIO	LOW GEAR RATIO	LOSS COEFFICIENTS			TRANS.WEIGHT	COST
1.0000	1.7400	3.8600	.55500E-01	.11100E-05	.22200E-01	50.00	275.00

Table C1-B

ADVANCED EV PROPULSION SYSTEM CONCEPT A6 SINGLE MOTOR /DR.AXLE W/TRANS. WF AC1

THE PROPULSION SYSTEM CURRENT IS FROM THE BATTERY AND A FLYWHEEL BUFFER.

```
VEHICLE TEST WEIGHT  =   3575.80 POUNC
BATTERY WEIGHT       =   1239.00 POUNDS
AXLE RATIO           =    7.2666
TRANS.    HIGH GEAR  =    1.0000
RATIO     SEC. GEAR  =    1.7400
          LOW  GEAR  =    3.8600
MOTOR RATED POWER    =   36000.0
  CANDICATE NO. 3 POLYPHASE INDUCTION MOTOR - 3 PH.
THIS SUBROUTINE DATED MAR. 28, 1979.  FCY
```

CIRCLE DIAGRAM VECTORS.

I1 21	I0	I2	E2	AB	BC	CD	DE
256.872	94.9936	217.446	57.6055	2.91293	1.36295	4.07854	207.418

CIRCUIT CONSTANTS, OHMS PER LEG.

R1	R2	R3	X1	X2	X3
.827341E-02	.527162E-02	18.6403	.266201E-01	.265821E-01	.606735

LEG CURRENTS AND VOLTAGE.

I1	I2	I0	E1	E2	PF
256.872	217.446	94.9936	61.1144	57.6055	.840000

MOTOR CHARACTERISTICS.
CANDIDATE NO. 3 THREE PHASE INDUCTION MOTOR

RATED POWER	VOLTAGE	LEG CURRENT	ROTOR CURRENT	SPEED RPM	LEG RESIST	ROTOR RESIST	REACTANCE X3
36000.0	61.1144	256.872	217.446	7200.00	.827341E-02	.527162E-02	.606735

BEARING FRICTION	EDDY CURRENT	HYSTERESIS	WINDAGE	LEAKAGE REACTANCE	POWER FACTOR	SLIP
320.440	356.044	178.022	320.440	.266201E-01	.840000	.200000E-01

SLIP	RPM	TORQUE	POWER	VOLTAGE	CURRENT	POWER FACTOR	EFFICIENCY
-.107701	8138.21	-148.483	-126541.	61.1144	918.391	-.547693	.728780
-.979095E-01	8066.27	-148.914	-125788.	61.1144	877.283	-.586690	.750197
-.881186E-01	7994.34	-147.575	-123545.	61.1144	828.960	-.627436	.771868
-.783276E-01	7922.41	-143.931	-119410.	61.1144	772.421	-.669273	.793749
-.685367E-01	7850.47	-137.413	-112967.	61.1144	706.774	-.711165	.815761
-.587457E-01	7778.54	-127.495	-103853.	61.1144	631.411	-.751566	.837770
-.489547E-01	7706.61	-113.800	-91840.3	61.1144	546.243	-.788206	.859522
-.391638E-01	7634.67	-96.2453	-76948.2	61.1144	451.999	-.817575	.880503
-.293728E-01	7562.74	-75.1691	-59531.6	61.1144	350.612	-.833026	.899503
-.195818E-01	7490.81	-51.3885	-40310.9	61.1144	246.034	-.815816	.912911
-.979087E-02	7418.87	-26.1348	-20304.2	61.1144	148.017	-.675682	.903097
.979096E-07	7346.94	-.858418	-660.440	61.1144	96.4966	.442237E-01	1.18467
.979106E-02	7275.00	23.0385	17551.9	61.1144	148.422	.715191	.901862
.195820E-01	7203.07	44.4454	33525.3	61.1144	238.253	.841677	.911853
.293730E-01	7131.14	62.6741	46803.2	61.1144	329.535	.861442	.899257
.391640E-01	7059.20	77.4714	57269.8	61.1144	414.819	.854321	.881417
.489549E-01	6987.27	88.9325	65072.4	61.1144	492.088	.836832	.861888
.587459E-01	6915.34	97.3794	70519.4	61.1144	560.949	.814492	.841848
.685368E-01	6843.40	103.246	73990.3	61.1144	621.714	.789878	.821787
.783278E-01	6771.47	106.993	75869.4	61.1144	675.025	.764435	.801939
.881188E-01	6699.54	109.053	76508.4	61.1144	721.660	.739044	[illegible]
.979097E-01	6627.60	109.804	76208.6	61.1144	762.419	.714252	[illegible]
.107701	6555.67	109.565	75216.9	61.1144	798.064	.690388	.7445[illegible]

Table C1-C

ADVANCED EV PROPULSION SYSTEM CONCEPT A6 SINGLE MOTOR /DR.AXLE W/TRANS. WF AC1

THE PROPULSION SYSTEM CURRENT IS FROM THE BATTERY AND A FLYWHEEL BUFFER.

SAE J227 DRIVING CYCLE 45 MPH CRUISE CONDITION APPROX. CONST. POWER ACCEL.

VEHICLE TEST WEIGHT = 3575.80 POUND
BATTERY WEIGHT = 1239.00 POUNDS
AXLE RATIO = 7.2666
TRANS. HIGH GEAR = 1.0000
RATIO SEC. GEAR = 1.7400
LOW GEAR = 3.8600
MOTOR RATED POWER = 36000.0

ACCUM. DIST MILES	VEHICLE SPEED FT/SEC	GEAR	ROAD POWER WATTS	MOTOR POWER WATTS	MOTOR SPEED RPM	MOTOR AC VOLTS	MOTOR AC AMPS	PWR FAC TOR	MOTOR I*I*R WATTS	EDDY CURR WATTS	HYST LOSS WATTS	WINDAGE LOSS WATTS	FRICT LOSS WATTS	CNTR. LOSS WATTS	BATTERY POWER WATTS	BATT CURR AMPS	MOTOR EFFIC PERCT	OVERL EFFIC PERCT	ACCUM ENERGY W*HRS
.0003	1.770	1	1050.	1126.	495.	6.8	264.4	.5857	656.	4.	22.	2.	22.	440.	2272.	23.7	61.48	46.23	.63
.0013	5.310	1	3154.	3383.	1484.	15.7	248.1	.6091	618.	22.	49.	14.	66.	399.	4551.	47.4	81.47	69.29	1.90
.0030	8.850	1	5262.	5646.	2474.	24.6	246.9	.6179	622.	56.	77.	38.	110.	396.	6945.	72.3	86.21	75.77	3.82
.0054	12.390	1	7379.	7919.	3463.	33.5	247.2	.6236	628.	105.	104.	74.	154.	397.	9382.	97.7	88.13	78.65	6.43
.0084	15.930	1	9506.	10205.	4452.	42.3	247.9	.6282	635.	170.	132.	123.	198.	399.	11860.	123.5	89.03	80.15	9.73
.0121	19.470	1	11647.	12506.	5442.	51.2	248.8	.6325	641.	249.	159.	183.	242.	401.	14382.	149.8	89.45	80.98	13.72
.0164	23.010	1	13805.	14826.	6431.	60.0	249.8	.6365	648.	344.	187.	256.	286.	403.	16950.	176.6	89.60	81.44	18.43
.0215	26.550	1	15981.	17167.	7421.	67.7	250.7	.6516	659.	439.	208.	340.	330.	405.	19549.	203.6	89.67	81.75	23.86
.0272	30.090	1	18178.	19532.	8410.	67.7	254.4	.7277	718.	436.	192.	437.	374.	415.	22105.	230.3	90.05	82.24	30.00
.0335	33.630	2	20400.	21275.	4237.	41.0	404.3	.8281	1976.	150.	122.	111.	189.	867.	24690.	257.2	89.31	82.63	36.86
.0405	36.578	2	15487.	16192.	4608.	44.0	311.2	.7550	1100.	179.	135.	131.	205.	567.	18509.	192.8	90.24	83.67	42.00
.0478	38.865	2	15682.	16403.	4897.	46.5	302.4	.7430	1029.	202.	143.	148.	218.	542.	18685.	194.6	90.41	83.93	47.19
.0556	41.024	2	15890.	16630.	5169.	48.9	295.3	.7327	973.	224.	150.	165.	230.	522.	18895.	196.8	90.51	84.10	52.44
.0637	43.076	2	16084.	16840.	5427.	51.2	289.4	.7232	928.	247.	158.	182.	242.	506.	19101.	199.0	90.56	84.20	57.74
.0723	45.033	2	16284.	17057.	5674.	53.4	284.4	.7148	890.	269.	165.	199.	253.	493.	19325.	201.3	90.57	84.27	63.11
.0812	46.909	2	16484.	17272.	5910.	55.5	280.2	.7072	859.	291.	171.	216.	263.	481.	19554.	203.7	90.56	84.30	68.54
.0904	48.712	2	16696.	17502.	6137.	57.5	276.7	.7006	834.	313.	178.	233.	273.	472.	19804.	206.3	90.53	84.31	74.04
.0999	50.451	2	16895.	17717.	6356.	59.5	273.6	.6944	811.	336.	184.	250.	283.	464.	20043.	208.8	90.48	84.29	79.61
.1098	52.132	2	17105.	17942.	6568.	61.3	270.9	.6889	792.	358.	190.	267.	292.	457.	20297.	211.4	90.43	84.27	85.25
.1200	53.760	2	17325.	18179.	6773.	63.2	268.7	.6842	776.	380.	196.	284.	301.	451.	20566.	214.2	90.37	84.24	90.96
.1305	55.341	2	17528.	18398.	6972.	64.9	266.6	.6796	761.	402.	201.	300.	310.	445.	20819.	216.9	90.31	84.20	96.75
.1412	56.877	2	17745.	18631.	7166.	66.7	264.8	.6756	748.	424.	207.	317.	319.	441.	21087.	219.7	90.24	84.15	102.60
.1523	58.373	2	17971.	18873.	7354.	67.7	263.3	.6779	741.	438.	209.	334.	327.	437.	21360.	222.5	90.20	84.14	108.54
.1636	59.831	2	18183.	19100.	7538.	67.7	262.1	.6892	740.	438.	206.	351.	335.	434.	21605.	225.0	90.22	84.16	114.54
.1752	61.255	2	18420.	19355.	7718.	67.7	261.4	.7002	742.	437.	203.	368.	343.	432.	21880.	227.9	90.24	84.18	120.62
.1871	62.647	2	18629.	19579.	7893.	67.7	260.7	.7102	744.	437.	200.	385.	351.	430.	22126.	230.5	90.24	84.19	126.76
.1992	64.008	2	18870.	19836.	8064.	67.7	260.5	.7200	749.	436.	197.	402.	359.	430.	22409.	233.4	90.25	84.20	132.99
.2116	65.341	2	19095.	20077.	8232.	67.7	260.5	.7290	753.	436.	194.	419.	366.	430.	22676.	236.2	90.25	84.21	139.29
.2241	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	141.37
.2366	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	143.45
.2491	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	145.53
.2616	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	147.61
.2741	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	149.69
.2866	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	151.77
.2991	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	153.85
.3116	66.000	3	5711.	6087.	4779.	45.0	209.1	.4376	402.	196.	142.	141.	213.	309.	7490.	78.0	84.77	76.25	155.93

FLYWHEEL ENERGY = .17744E+07
FLYWHEEL RPM = 20462.

Table C1-D

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ADVANCED EV PROPULSION SYSTEM CONCEPT A6 SINGLE MOTOR /DR.AXLE W/TRANS. WF AC1
  SAE J227 DRIVING CYCLE  45 MPH CRUISE CONDITION APPROX. CONST. POWER ACCEL.
THE PROPULSION SYSTEM CURRENT IS FROM THE BATTERY AND A FLYWHEEL BUFFER.

RMS AVERAGING FOR PBAR
      PBAR           EBAR
     8.238          17.40
     8.238          39.46
WITH REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        107.65      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        244.06      MILES
 ENERGY CONSUMED PER MILE =       200.30      W-H/MILE
     8.554          17.19
     8.554          39.40
WITHOUT REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        99.680      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        228.50      MILES
 ENERGY CONSUMED PER MILE =       213.65      W-H/MILE


 ARITHMETIC AVERAGING FOR PBAR
      PBAR           EBAR
     6.706          18.46
     6.706          39.71
WITH REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        114.21      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        245.66      MILES
 ENERGY CONSUMED PER MILE =       200.30      W-H/MILE
     8.082          17.51
     8.082          39.48
WITHOUT REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        101.54      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        228.97      MILES
 ENERGY CONSUMED PER MILE =       213.65      W-H/MILE


 ARITHMETIC AVERAGING FOR PBAR
      PBAR           EBAR
AVERAGING OVER TIME OF FULL CYCLE
     4.782          19.85
     4.782          40.03
WITH REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        122.78      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        247.64      MILES
 ENERGY CONSUMED PER MILE =       200.30      W-H/MILE
     5.101          19.62
     5.101          39.98
WITHOUT REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        113.75      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        231.86      MILES
 ENERGY CONSUMED PER MILE =       213.65      W-H/MILE

 STEP BY STEP CALCULATION OF BATTERY FRACTION USED.
WITH REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        103.36      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        242.57      MILES
 ENERGY CONSUMED PER MILE =       200.30      W-H/MILE
WITHOUT REGENERATION
 RANGE WITH LEAD-ACID BATTERY =        97.336      MILES
 RANGE WITH NICKEL-ZINC BATTERY =        227.97      MILES
 ENERGY CONSUMED PER MILE =       213.65      W-H/MILE
```

Battery Model

For a vehicle in normal operation the power level fluctuates from the high values for acceleration to much lower values for steady driving. With the fluctuating power of stop and go driving the range of an electric vehicle will be substantially less than for constant speed driving on a level road. Part of this difference is due to the fact that the available energy from the battery when operated at high power is less than that available at low power. (Ref. 19)

The available energy from a battery is dependent upon the manner and rate of discharge. A steady discharge at low power extracts more energy than a steady discharge at high power. Figure C1 shows the variation in available energy from an ISOA lead-acid battery for various steady power levels, with energy and power normalized to the values per pound of battery. For a variable rate of discharge the total available energy may be estimated by a variety of ways with differing degrees of accuracy. (Ref. 33, 34)

One scheme used an accumulation of increments of fractional discharge in which a period of high power provides a disproportionately greater percent of discharge than a period of low power. The extent of the disproportionality is calculated from the curve in Figure C1. Some other schemes use models that attempt to relate to the physical characteristics of the battery using a few well-chosen parameters. Still other schemes involve using the average power over the driving cycle to compute the available energy. A root mean square (RMS) average and a simple arithmetic average have been used.

In an earlier study on the benefits of regenerative braking, (Ref. 30) it was found that the difference in available energy using the different methods of calculation was small and that the available data on battery performance with fluctuating power levels did not provide a strong support for any one calculational method. The method using RMS averaging appears to give the lowest range and, therefore, was considered to give an appropriately conservative value of power to use in range calculations.

The battery energy vs. power curve of Figure C1 was represented by a mathmatical equation which was incorporated into the subroutine used to calculate specific energy as a function of specific power. Two such equations were used; one for ISOA lead-acid and one for Ni/Zn.

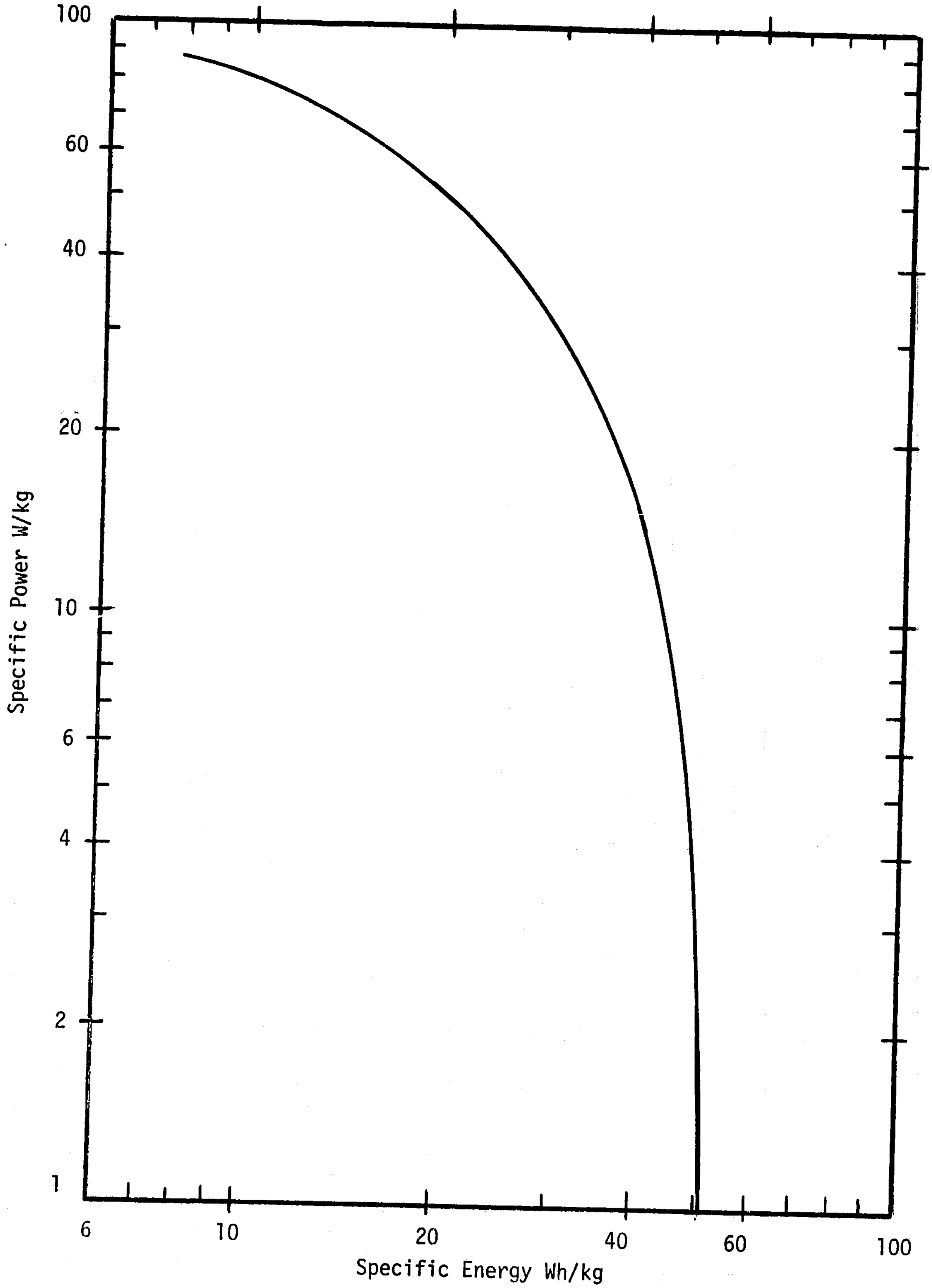


Figure C1. Ragone Chart for ISOA Lead-Acid Battery

For the ISOA lead-acid the relationship is as follows:

$$*\overline{E} = 23.543 - .81 \times \overline{P} + .784 \times 10^{-2} \overline{P}^{\,2}$$

Where

$\overline{E}$ = specific energy Wh/lb

$\overline{P}$ = specific power W/lb

The relationship for Ni/Zn is as follows: (for positive values of $\overline{P}$)

$$**\overline{E} = 20.4 + \sqrt{\frac{64.3 - \overline{P}}{.1544}}$$

Unless $\overline{P}$ is greater than 64.3, in which case $\overline{E}$ is set to 21.8.

Trans/axle Model

The subroutines for the propulsion system include the calculation of energy losses in the transmission and axle gearing and the calculation of the speed and torque multiplication associated with the various gear ratios. Loss coefficients and gear ratios are input to the program from data cards. The tire rolling radius is also an input value. From the vehicle velocity and tire radius the axle speed is calculated.

$$RPM_A = V \times \frac{60 \times 12}{2\pi R}$$

The pinion gear speed is then calculated from the axle speed by multiplying by the axle ratio.

$$RPM_{Pinion} = Ratio \times RPM_{Axle}$$

And the motor speed is calculated from the final drive pinion by multiplying by the appropriate transmission ratio, which is selected to satisfy the shift point criteria which in turn is based on the vehicle speed and power requirement.

$$RPM = RPM_{Pinion} \times \text{Transmission Ratio}$$

---

*Numerical fit of curve provided by NASA Lewis.
**Numerical fit of curve (ref. 19, p. 200).

The final drive pinion power is found by adding to the drive axle power an increment of power due to an increment of pinion torque found from the following:

$$\Delta T = a_0 + a_1 RPM_{Pinion} + a_2 T_{Pinion}$$

Where a_0, a_1 and a_2 are loss coefficients from data cards.

The increment of power ΔP is found from:

$$\Delta P = \Delta T \times RPM_{Pinion} \times 2\pi$$

The losses in the transmission are added to the final drive pinion power to obtain the motor power. The increment of frictional torque for the transmission is found from the following:

$$T_T = \frac{1}{2}\left(1 + \frac{RPM}{RPM_P}\right) \times (B_0 + B_1 \times RPM + B_2 \times Torque)$$

Where B_0, B_1 and B_2 are read from input cards.

Torque is the motor torque for a frictionless transmission

RPM is the motor speed

RPM_{Pinion} is the final drive pinion speed.

The increment of power loss associated with the increment of torque is added to obtain the motor power.

Motor Models

Two motor models were used to represent the two types of motors. The dc motor is modeled in terms of the known torque/current and speed/voltage relationships for a separately excited dc motor. The three-phase induction motor is modeled in terms of its equivalent circuit. The calculated losses for each motor type included the following:

Windage
Bearing Friction
Eddy current
Hysteresis
Copper I^2R

Model for DC Motor

For the dc motor the torque and generated voltage are dependent upon the air-gap flux in addition to the armature current and rotor speed. The air-gap flux at the design point is assumed to be high enough to just start to saturate the iron and that flux would be a function of field current as shown in Figure C2. The curve can be represented by the following equation:

*Flux = 5.7 tanh (.18226 * x) + .1033 * x + .5

Where x is a non-dimensional ampere turns of the field coils and Flux is the non-dimensional air-gap flux. At the design point x = 6 and Flux = 5.67. The flux can be raised or lowered by changing the field current; but since saturation effects limit the amount of flux that can be obtained, the field current is limited to values below some reasonable overload current.

The required flux and armature current of the motor is found from the required generated counter emf and motor torque by iteration. First the flux is found from the relationship that the counter emf is proportional to the product of the speed and flux and that the required counter emf is the terminal voltage minus the IR drop of the armature. Thus

$$\text{Flux} = K_1 (E - IR)/\text{rpm}$$

Where K_1 is a proportionality constant dependent upon the motor design

E = terminal voltage
I = armature current (trial value used)
R = armature resistance

RPM = rotor speed

Then the armature current is found using the relationship that rotor torque is proportional to product of flux and current. Thus

$$I = K_2 * \text{Torque}/\text{Flux}$$

The range through which the Flux may change is limited by the magnetic properties of the iron and the limiting current of the field coils. At low speeds where excessive flux would be required to produce the counter emf, the method of avoiding excessive field current is to reduce the effective motor terminal voltage by using the armature current controller.

The eddy current losses are calculated from the air-gap flux and motor speed using the following relationship: (Ref. 3)

$$\Delta P_{ec} = K_3 (\text{RPM} * \text{Flux})^2$$

* Numerical fit of curve from Ref. 15, p. 123.

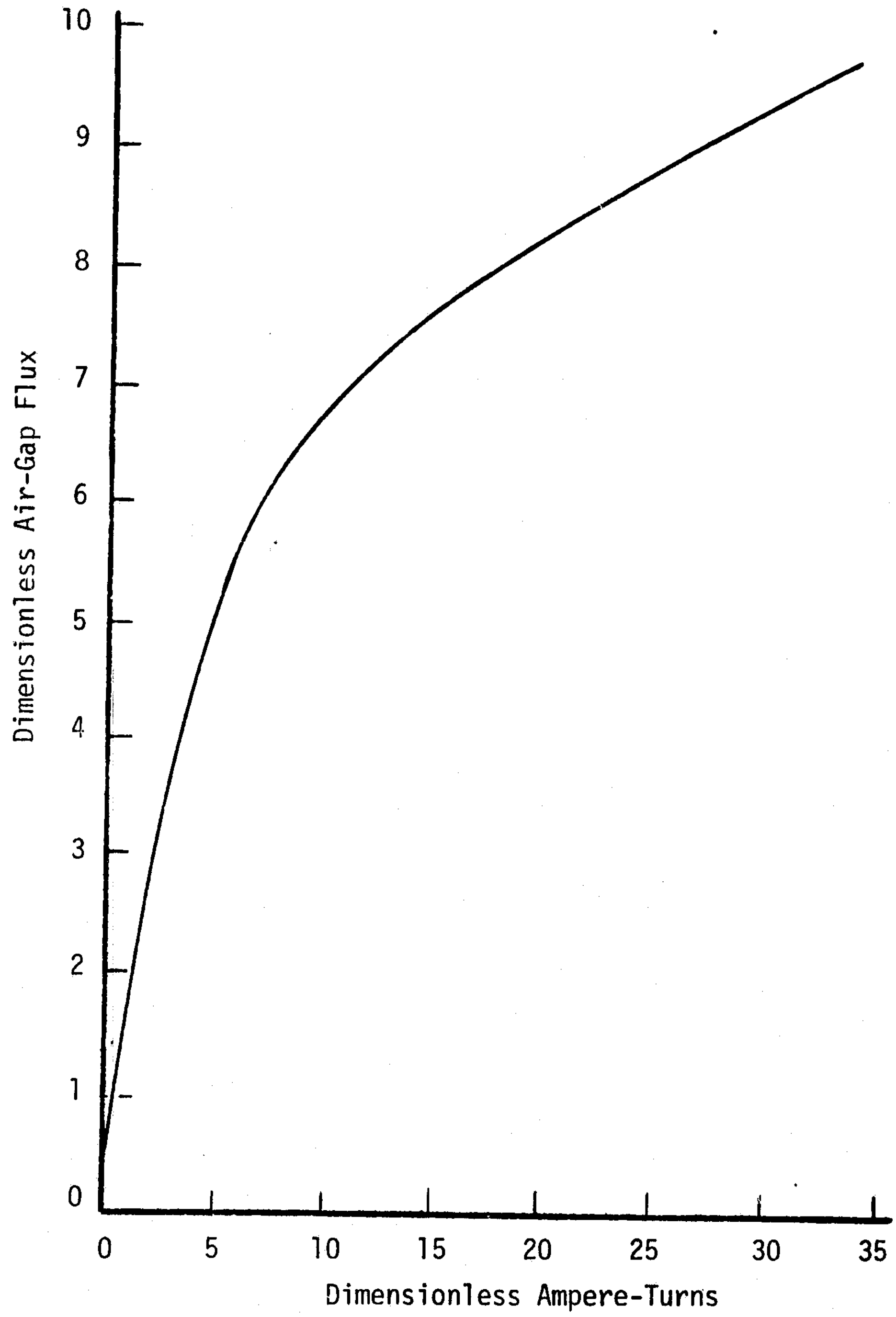


Figure C2. Air-Gap Flux vs. Field Current

The hysteresis losses are also calculated from air-gap flux and speed. The relationship is the following (Ref. 3):

$$\Delta P_{Hyst} = K_4 \text{ RPM } (\text{Flux})^{1.6}$$

The bearing losses are taken as increasing linearly with speed and the windage losses as quadratic with speed.

The copper I^2R losses are simply the sum of the field I^2R loss and the armature I^2R. Field currents and armature currents are both calculated to satisfy the flux and torque relationships.

Three-Phase Induction Motor

The model for the induction motor is based on the equivalent circuit shown in Figure C3 for a single leg. One third of the power is developed in each leg of a three-phase motor. The motor is assumed to be delta connected so that full-line voltage is applied to each leg. The circuit constants R_1, R_2, R_3, X_1, X_2 and X_3 are calculated in the subroutine from the input characteristics of the motor. The input characteristics are the efficiency, power factor and percent slip at rated power and speed and distribution of losses. At speeds less than the base speed the terminal voltage is reduced to be a linear function of input frequency and at speeds above base speed this voltage is set at a constant value.

The currents in the various elements in the equivalent circuit are calculated by first assuming a value of E_2 from which preliminary values of I_2, I_3 and I_4 are calculated as follows:

$$I_2 = E_2/Z_2$$

$$I_3 = E_2/Z_3$$

$$I_4 = E_2/Z_4$$

Where

$$Z_2 = \frac{R_2}{s} + j\, X_2$$

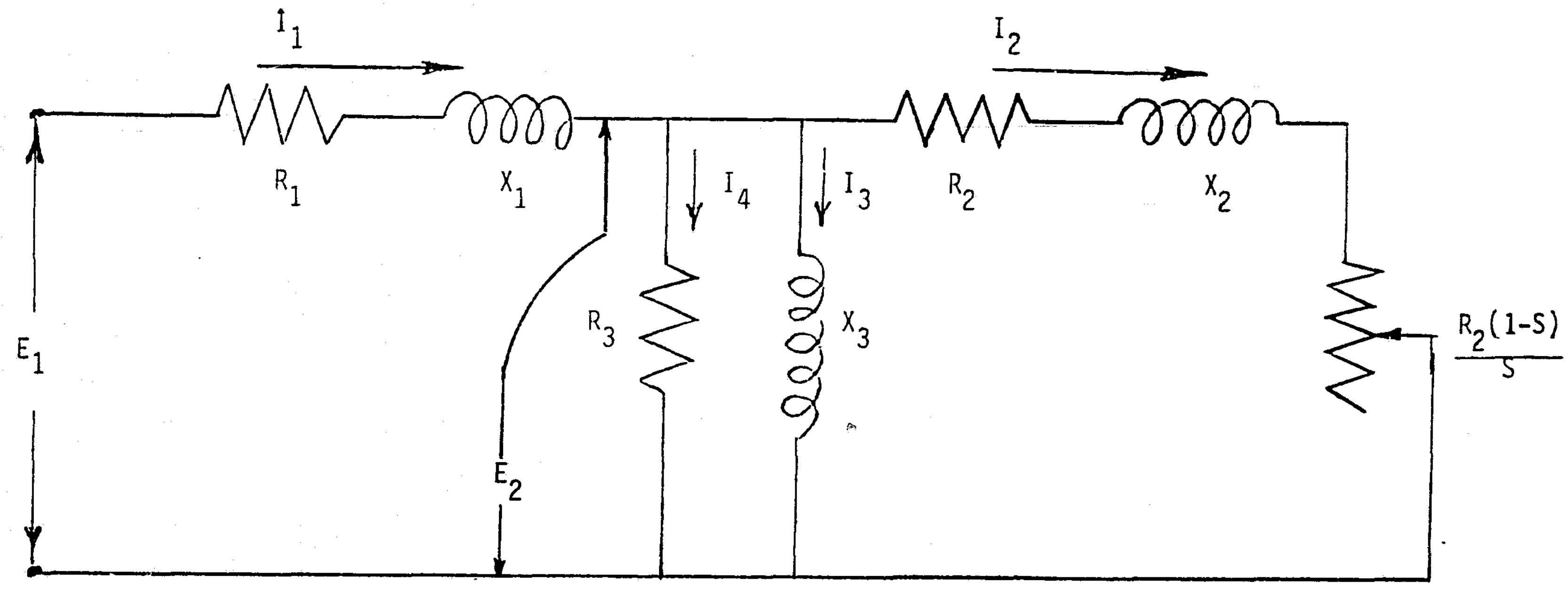
$$Z_3 = j\, X_3$$

$$Z_4 = R_3$$

Summing these preliminary values of current gives the I_1 vector

$$\vec{I}_1 = \vec{I}_2 + \vec{I}_3 + \vec{I}_4$$

Using this value of I_1 and the assumed value of E_2 a new value of the E_1 vector is calculated by vector addition.



S	=	Slip	
E_1	=	Phase voltage	V/phase
I_1	=	Stator current	A/phase
I_2	=	Rotor current	A/phase
I_M	=	$I_4 + I_3$ = Exciting current	A/phase
R_1	=	Stator resistance	Ω/phase
R_2	=	Rotor resistance	Ω/phase
R_3	=	Iron loss equivalent resistance	Ω/phase
X_1	=	Stator leakage reactance	Ω/phase
X_2	=	Rotor leakage reactance	Ω/phase
X_3	=	Magnetizing reactance	Ω/phase

Figure C3. Equivalent Circuit of Induction Motor

$$E_{1N} = E_2 + I_1 Z_1$$

Where

$$Z_1 = R_1 + j X_1$$

This value of E_{1N} will differ slightly from E_1 due to the error in assumed value of E_2. The value of E_2 and the current vectors are readjusted by the ratio of the correct value of E_1 to the calculated value E_{1N}. A reiteration confirms that the correct value of E_2 and the current vectors are obtained.

The windage, bearing friction, hysteresis and eddy current losses are calculated for the induction motor in the same way as they are for the dc motor. The air-gap flux is calculated as that required to produce the necessary counter emf at the operating speed using the following relationship

$$\text{Flux} = K_1 E_2/\text{RPM}_s$$

Where K_1 is a proportionality constant

E_2 = counter emf

RPM_s = synchronous speed

The counter emf E_2 and the currents in each of the elements of the equivalent circuit are found by iteration by starting from a guessed at value of slip. The starting value is based on a linearization of the slip torque curve using

Slipx = Slip * Tor/Torrt

Where

Slipx = trial slip
Slip = rated slip
Tor = motor torque
Torrt = rated motor torque

The trial slip is substituted into the equations for the circuit and the values of current vectors are solved after the reactances are adjusted for the input frequency. The power output of the motor with the trial slip is compared with the desired power and the slip is readjusted to raise or lower the power output as required.

The iteration process converges rapidly to the required slip and torque if the torque is less than the breakaway torque of the motor. The breakaway torque and slip are also calculated; and if the repaired torque exceeds this maximum torque, this factor is printed out.

Controller Model

The subroutines for the various types of motors calculate the controller losses as a function of the idealized battery current using three input parameters used as loss coefficients to characterize the controller. The power loss is in the following form:

$$\Delta P = C_0 + C_1 I + C_2 I^2$$

Where C_0, C_1 and C_2 are input values

I = idealized battery current.

The idealized battery current is simply the average current required to satisfy the power and losses of the motor using a lossless controller. The loss coefficients C_0, C_1 and C_2 are separately calculated from the nature of the controller and its elements.

At the rated power condition with a certain input current, there will be RMS currents through diodes, and SCRs or transistors. For a specific distribution of current there will be an identifiable distribution of losses. The losses in the diodes and SCRs are principally due to their forward voltage drop and this value influences the coefficient C_1 in proportion to the diode current fraction. The rate of change in the voltage drop influences C_2. An additional loss for the diodes and SCRs is due to their reverse leakage current times their reverse voltage. The losses in transistors are due mainly to the collector-emitter saturation voltage, the base-emitter saturation voltage and to the collector-emitter leakage current.

Using catalog values of voltage and leakage currents for probable diodes and transistor types and numbers of units in series and parallel estimates of the loss coefficients were made. These result in overall efficiencies of the controller from about 93 to 96 percent with the higher efficiencies at higher loads.

The model does not take into account the different modes of operation of the controllers. When the motors are above their base speeds the effective voltage at their terminals are the maximum value. When the motors are below their base speeds the effective voltage is reduced by use of a current chopper. The switching losses of the chopper will increase as the effective voltage is decreased. A more sophisticated model would account for the variations in switching losses, perhaps by readjusting the loss coefficients as a function of the effective voltage.

In addition to the switching losses in the semiconductor switches, there will be differences in the distribution of current in the circuit elements and changes in the current waveforms as the chopping frequencies and on-off ratios change. The waveforms and distribution of current in the transactions and diodes were calculated for several load conditions for the induction motor operated above the base speed. The current (RMS) through the free-wheel diodes is approximately equal to the out-of-phase component of current and the current through the transistors is approximately equal to the vector sum of the in-phase and out-of-phase current. These values were used for estimating the loss coefficients.

For a more sophisticated model, the current distribution and waveforms during chopper operation should be calculated, and used for estimating losses.

APPENDIX D

GUIDELINES AND BACK-UP INFORMATION FOR COST CALCULATIONS

Guidelines for Life Cycle Cost Calculations

* Costs shall be calculated only for the propulsion system plus the battery, therefore other vehicle costs, insurance, taxes, etc. are not included.

* Use 1976 dollars

* Acquisition cost is the sum of the OEM cost (manufacturing cost plus corporate level costs such as general and administrative, required return on investments of facilities and tooling, cost of sales,...) of components plus the cost of assembling the components plus the dealer markup (assume 17%).

* Annual production is 100,000 units

* Operating cost is the sum of maintenance costs plus repair costs plus electricity cost plus battery replacement costs.

* Electricity cost is 4 cents/kWh from the wall plug.

* Vehicle lifetime is 10 years and 100,000 miles.

* A constant non-inflating dollar should be assumed. No inflation factor is included in the discount rate since it is assumed that personal disposable income tracks inflation. A 2% discount rate for personal cars shall be used as it represents only time preference (opportunity cost).

* Cost of finance is not included in this procedure since it is assumed that the discounted present value of the sequence of total payments would approximately equal the original purchase price.

* All expenses are assumed to be costed at the end of each year. Year "Zero" is reserved for those costs which must be incurred <u>before</u> the vehicle is operated.

* Assume chassis (propulsion system) salvage value is 2% of the purchase price, depleted battery salvage value is 10% of the purchase price, and used battery salvage is 50% of the purchase price pro-rated over the remaining life of the battery.

* In determining battery life assume the vehicle is driven 10,000 miles per year. For convenience in calculation assume the mileage is accumulated through successive SAE J227a Schedule D driving cycles from 400 - 10 mile trips per year, 150 - 30 mile trips, and 30 - 50 mile trips, charging after each trip. The battery cycle life shall be determined based on these trip profiles, field environmental effects, and the degradation due to the actual conditions imposed on the battery by the propulsion system and vehicle.

* The calculation of life cycle cost shall follow the format shown on Worksheets 1 and 2 using the following instructions.

1) The purchase price is entered on the appropriate line of the life cycle cost worksheet as a year "Zero" cost.

2) Operating costs: electricity, maintenance and repair, and battery replacement costs are copied from the operating cost worksheet to the same position on the life cycle cost worksheet.

3) Discount factor - $1/(1 + i)^t$ is computed for each year (where t = year 0 to 10 and i equals the discount rate).

4) For each year, the discount factor times the cost gives the present value of the cost for that year. These are summed to provide the discounted present value of the life cycle cost.

5) The value computed in step 4 is divided by the total miles driven to provide the life cycle cost per mile and is expressed in cents per mile.

Table D1

Operating/Life Cycle Cost Analysis
of AEVA Propulsion System

Concept:	A6 - AC Induction Motor with Flywheel Buffer
Battery Weight:	1226 lbs lead-acid
Energy used over "D" Cycle	212 Wh/mile
Battery Characteristics:	As listed in Table 4
Vehicle Life:	10 years
Distance driven annually:	16100 km (10000 mi)
Energy cost from wall plug:	.04 $/kWh
Salvage Value	
Chassis	2% of purchase
Battery	10% of purchase if depleted 50% of purchase prorated over remaining battery life

Battery Cost = ($/kWh x Battery Weight x Specific Energy/2204)

$\doteq$ $1112

Energy Cost = Energy Consumed/mile x Miles x Price/kWh/Battery Efficiency

= $141/yr

Table D2

Propulsion System Acquisition Cost Analysis
Concept A6 with Lead-Acid Batteries

	Unit Price	Unit	Weight (lbs)	Cost ($)
Axle	2.	$/lb	59	118
Drive Motor	2.1	$/lb	90	189
*Controllers:				
Battery to Motor	7.38	$/kVA	65	464
Generator to Motor	7.38	k/kVA	50	354
Flywheel	6.	$/lb	35	210
Motor/Generator	2.5	$/lb	43	107
Transmission	2.	$/lb	50	100
Subtotal:			392	1542
Assembly and Test:				
Two manhours at $30 per hour				60
Batteries			1226	1112
Total:			1631	2714

Acquisition Cost = Total + 17% Dealer Markup
= $3175

*Controllers are rated at 63 and 48 kVA each.

Table D3

Worksheet 1
Operating Cost Worksheet

Concept A6 with Lead-Acid Batteries

	YEAR									
	1	2	3	4	5	6	7	8	9	10
Mile Dependent Costs										
COSTS IN CENTS PER MILE										
Maintenance										
Electric	.10	.10	.35	.10	.10	.35	.10	.10	.35	.10
Mechanical	.10	.10	.30	.10	.10	.30	.10	.10	.30	.10
Energy Buffer	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10
A TOTAL	.30	.30	.75	.30	.30	.75	.30	.30	.75	.30
Repair										
Electric				1.				1.		
Flywheel										
Transmission					.5					
D TOTAL				1.	.5			1.		
Electricity										
E TOTAL	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41	1.41
F TOTALS A+D+E	1.71	1.71	2.16	2.71	2.21	2.16	1.71	2.71	2.16	1.71
G Mileage Each Year	10000									10000
H TOTAL DOLLARS (F/100) x G	171	171	216	271	221	216	171	271	216	171
Battery Replacement						1112				
YEAR TOTALS $	171	171	216	271	221	1328	171	271	216	171

Total Operating Cost = $\boxed{\$3207}$ Operating Cost Per Mile = $\boxed{3.207}$ cents/mile

Table D4

Worksheet 2
Life Cycle Cost Worksheet

Concept A6 with
Lead-Acid Batteries

	YEAR										
	"0"	1	2	3	4	5	6	7	8	9	10
1 Purchase Price	3175										
2 Electricity		141	141	141	141	141	141	141	141	141	141
3 Repair and Maintenance		30	30	75	130	80	75	30	130	75	30
4 Battery Replacement							1112				
5 Chassis Salvage (Minus)											-41
6 Battery Salvage (Minus)							-111				-185
7 TOTAL (1 - 6)	3175	171	171	216	271	221	1217	171	271	216	-55
8 Discount Factor	1.0	.98	.962	.942	.924	.906	.888	.87	.853	.837	.82
9 Present Value (7 x 8)	3175	168	165	203	250	201	1081	149	231	181	-45

10 Present Value of Life Cycle Cost (Sum of 9) = $\boxed{\$5759}$

11 Present Value of Life Cycle Per Mile Driven (10/Total Miles) = $\boxed{5.76}$ cents/mile

C-8

Table D5

Operating/Life Cycle Cost Analysis
of AEVA Propulsion System

Concept:	D2 - Brushless dc Motor with CVT Flywheel Buffer
Battery Weight:	1199 lbs lead-acid
Energy used over "D" Cycle:	210.45 Wh/mi
Battery Characteristics:	As listed in Table 4
Vehicle Life:	10 years
Miles driven annually:	16,100 km (10,000 mi)
Energy cost from wall plug:	.04 $/kWh
Salvage Value	
Chassis:	2% of purchase
Battery:	10% of purchase if depleted 50% of purchase prorated over remaining battery life

Battery Cost = ($/kWh x Battery Weight x Specific Energy/2204)

= $1088

Energy Cost = Energy Consumed/mile x Miles x Price/kWh/Battery Efficiency

= $140/yr

Table D6

Propulsion System Acquisition Cost Analysis
Concept D2 with Lead-Acid Batteries

	Unit Price	Unit	Weight (lbs.)	Cost ($)
Axle	2	$/lb	59	118
Drive Motor	2.3	$/lb	95	219
Controller	7.37	$/kVA	35	214
Flywheel	6	$/lb	35	210
*CVT		$/lb	178	661
Transmission	2	$/lb	50	100
Subtotal:			452	1522
Assembly and Test:				
Two manhours @ $30 per hour				60
Batteries				1088
Total:				2670
Acquisition Cost = Total + 17% Dealer Markup =				3123

*Includes magnetic coupling and hydraulic pump motor.

Table D7

Worksheet 1
Operating Cost Worksheet

	YEAR 1	2	3	4	5	6	7	8	9	10
Mile Dependent Costs										
Maintenance										
Mechanical	.62	.82	.87	.82	.62	1.07	.62	.82	.87	.82
Energy Buffer	.10	.10	.10	.10	.10	.10	.10	.10	.10	.10
A TOTAL	.72	.92	.97	.98	.72	1.17	.72	.92	.97	.92
Repair										
Electric				.5				.5		
Differential					.6					.6
Hydraulic Pump			.1			.1			.1	
D TOTAL			.1	.5	.6	.1	-	.5	.1	.6
Electricity										
E TOTAL	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
F TOTALS A+D+E	2.12	2.32	2.47	2.82	2.72	2.67	2.12	2.82	2.47	2.38
G MILAGE EACH YEAR	10000	10000	10000	10000	10000	10000	10000	10000	10000	10000
H TOTAL DOLLARS (F/100) x G	212	232	247	282	272	267	212	282	247	238
Battery Replacement						1088				
YEAR TOTALS $	212	232	247	282	272	1355	212	282	247	238

Total Operating Cost = $\boxed{\$3207}$ Operating Cost Per Mile = $\boxed{3.207}$ (cents/mile)

Table D8

Worksheet 2

Life Cycle Cost Worksheet

	YEAR										
	"0"	1	2	3	4	5	6	7	8	9	10
1 Purchase Price	3123										
2 Electricity		140	140	140	140	140	140	140	140	140	140
3 Repair and Maintenance		72	92	107	142	132	127	172	142	107	152
3 Battery Replacement							1088				
5 Chassis Salvage (Minus)											-41
6 Battery Salvage (Minus)							-109				-181
7 TOTAL (1 - 6)	3123	212	232	247	282	272	1106	212	282	247	70
8 Discount Factor	1.0	.98	.962	.942	.924	.906	.888	.87	.853	.837	.82
9 Present Value (7 x 8)	3123	208	223	233	261	246	982	184	241	207	57

10 Present Value of Life Cycle Cost (Sum of 9) = $\boxed{\$5965}$

11 Present Value of Life Cycle Per Mile Driven (10/Total Miles) = $\boxed{5.965}$ cents/mile

Table D9

OPERATING/LIFE CYCLE COST ANALYSIS
OF AEVA PROPULSIONS SYSTEM WITH NICKEL-ZINC BATTERIES

Concept/A6--Ac induction motor with flywheel buffer.

UNIT	WEIGHT (lbs.)	COST ($)
Axle	59	118
Drive Mount	63	131
Controllers		
BM	45	333
GM	35	256
Flywheel	35	210
Motor Generator	30	75
Transmission	50	100
Subtotal	317	1223
Assembly and Test		60
Subtotal		1283
Batteries (Ni-Zn)	490	1334
TOTAL	807	2617
Acquisition Cost (17% Markup)		3062
Energy Cost: 102 Wh/km (165 Wh/mi)		94

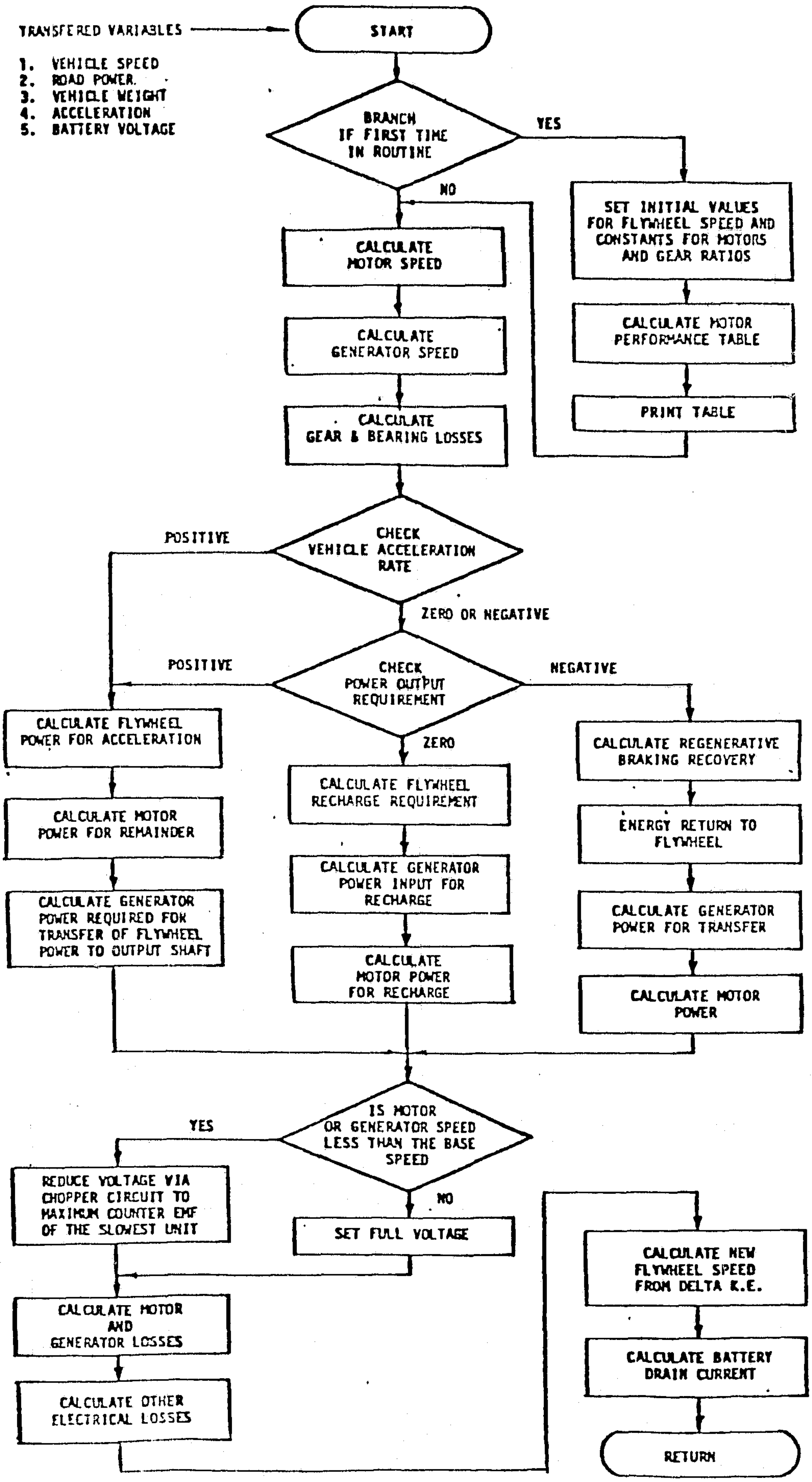
Assuming same repair and maintenance cost as in lead acid case:

CANDIDATE (A6)	LEAD ACID (A6)	Ni-Zn (A6)
Acquisition Cost	3175	3062
Annualized Acquisition Cost	317.5	306.2
Discounted Annual Cost @ 2% Discount Rate		
Electricity	126.6	94.0
Repair and Maintenance	61.5	61.5
Battery Replacement	99.8	239.6
Drive Train Salvage	-3.7	-3.5
Battery Salvage	-26.6	-33.5
Discounted Annual Operating Costs	257.6	358.1
Present Value Life Cycle, $/Yr	575	664.3
Present Value Life Cycle, $/km ($/mi)	.0357 (.0575)	.0413 (.0664)

APPENDIX E

COMPUTER FLOW CHART AND PROGRAM

FLYWHEEL/BATTERY HYBRID CANDIDATE SUBROUTINE FLOW CHART



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*USEFPR
MNF4,L=0.
LGO,LC=20000.
EXIT.
DUMP,0.
GRUMP.
      PROGRAM AEVA(INPUT,OUTPUT,TAPE4=INPUT,TAPE16=OUTPUT,TAPE5,TAPE6)
      COMMON /A/ A,AF,BSL,BV,CD,    DT,FC(20,150),FSE,JFLAG,MHP,P,
     1PPMAX,PD,RPMAX,SUMBFR,SUMFC,SUMFFR,VA,VN,VT
     2,SUMBE,SUMFEP,SUMFEN,PICE,PDB,PFY,PB,HPD,FQ,EHD,DELFC ,PBAR
      COMMON /B/ IX1,IX2,NTS,RANGE,SUMD,VC,TOTE,XMPG
      COMMON /C/ WBAS,WPAY,WTEST,WPROP,WAX,WMOT,WTCBM,WTCGM,WB,WV,WF,
     1WGLN,WTXM,WGROS,WCURB,TESTW,WPS,ROTI,WCBM,WCGM
      COMMON /D/ CDA,RHOA,RADIUS,C0,C1,C2,RATIO,TAXL,A0,A1,A2,RPR,SPEEDI
     1,SPEEDA,OLOAD,RVT,CURDM,WBAR,EFFDM,RI2,HYSTI,EDI,BFI,WNDI,FREQ,
     2PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,CBMO,CBM1,CBM2,PCGM,VCGMIN,VCGMOT
     3,CGMCUR,CGMFRQ,CGMO,CGM1,CGM2,EBARM,PBARM,EFFB,XFSM,RUND,GRPR,
     4GSPD1,GSPD2,GOLD,GRVT,GCUR,GBAR,EFFCG,GRI2,GHYSTI,GEDI,GBRI,GWNDI
     5,GFREQ,TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,TXBAR,TXMTQ
      COMMON /E/ COSTDM,COSTAX,COSTB,COSTF,COSTCB,COSTCG,COSTG,COSTXM
      COMMON /F/ PSA(1390),NFLAG,IX3,FAMP(1390),VLG,VSG,VHG
      DIMENSION         IX1(16),IX2(16),IX3(16),V1(1390),BAMP(1390)
      DIMENSION BLW(4)
      WRITE(16,800)
  800 FORMAT(*1*,73H PROGRAM MODIFIED TO USE AEPS BUFFERING ROUTINE. COP
     1Y MADE 3/28/79 FCY.   /22H SHIFT POINTS READ IN.    )
  610 CONTINUE
C     READ TITLE
      READ(4,10) IX1
   10 FORMAT(16A5)
      WRITE (16,114) IX1
  114 FORMAT (1H1,1X,16A5)
      READ(4,11) WBAS,WPAY,WTEST,WPROP,CDA,RHOA,ROTI
      WRITE(16,205) WBAS,WPAY,WTEST,WPROP,CDA,RHOA,ROTI
      READ(4,11) RADIUS,C0,C1,C2,VLG,VSG,VHG
      WRITE(16,207) RADIUS,C0,C1,C2,VLG,VSG,VHG
      READ(4,11) RATIO,WAX,TAXL,COSTAX,A0,A1,A2
      WRITE(16,209) RATIO,WAX,TAXL,COSTAX,A0,A1,A2
      READ(4,11) RPR,SPEEDI,SPEEDA,OLOAD,RVT,CURDM,WBAR,EFFDM
      WRITE(16,211) RPR,SPEEDI,SPEEDA,OLOAD,RVT,CURDM,WBAR,EFFDM
      READ(4,11)     RI2,HYSTI,EDI,BFI,WNDI,FREQ,COSTDM,TOTE
      IF(TOTE.LE.0.) TOTE = .80
      WRITE(16,213) RI2,HYSTI,EDI,BFI,WNDI,FREQ,COSTDM,TOTE
      READ(4,11)       PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,WCBM
      WRITE(16,215) PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,WCBM
      READ(4,11) CBMO,CBM1,CBM2,COSTCB
      WRITE(16,217) CBMO,CBM1,CBM2,COSTCB
      READ(4,11) PCGM,VCGMIN,VCGMOT,CGMCUR,CGMFRQ,WCGM
      WRITE(16,219) PCGM,VCGMIN,VCGMOT,CGMCUR,CGMFRQ,WCGM
      READ(4,11) CGMO,CGM1,CGM2,COSTCG
      WRITE(16,221) CGMO,CGM1,CGM2,COSTCG
      READ(4,11) BV,EBARM,PBARM,WB,COSTB,EFFB
      WRITE(16,223) BV,EBARM,PBARM,WB,COSTB,EFFB
      READ(4,11) FSE,WF,XFSM,RUND,COSTF
      WRITE(16,225) FSE,WF,XFSM,RUND,COSTF
      READ(4,11) GRPR,GSPD1,GSPD2,GOLD,GRVT,GCUR,GBAR,EFFOG
      WRITE(16,227) GRPR,GSPD1,GSPD2,GOLD,GRVT,GCUR,GBAR,EFFOG
      READ(4,11) GRI2,GHYSTI,GEDI,GBRI,GWNDI,GFREQ,COSTG
      WRITE(16,229) GRI2,GHYSTI,GEDI,GBRI,GWNDI,GFREQ,COSTG
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REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

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      READ(4,11) TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,WTXM,TXCOST
      WRITE(16,231) TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,WTXM,TXCOST
   11 FORMAT(8F10.3)
  112 FORMAT (1X,6G14.4)
  205 FORMAT(/24H VEHICLE CHARACTERISTICS /
     14X,12HBASE WEIGHT,4X,11HMAX.PAYLOAD,4X,9HTEST LOAD,1X,17HWT.PROPAG
     2ATION F.,1X,12HAIR DRAG CDA,3X,11HAIR DENSITY,1X,14HROT.INER.FACT.
     3/7G15.5)
  207 FORMAT(/14H TIRE FACTORS /5X,11HRADIUS INCH,12X,27HROLLING RESIST.
     2COEFFICIENTS ,3X,21HSHIFT POINTS FT/SEC   /1G15.3,3E15.5,3F15.2 )
  209 FORMAT(/14H AXLE FACTORS   /7X,5HRATIO,9X,6HWEIGHT,8X,11HTORQUE CA
     1P.,6X,4HCOST,2X,13HLOSS COFF.A0,13X,2HA1,13X,2HA2/ 1G15.5,
     23G15.3,3F15.5)
  211 FORMAT(/21H DRIVE MOTOR FACTORS   /5X,11HRATED POWER,4X,9HMIN SPEE
     1D,5X,9HMAX SPEED,3X,16HOVERLOAD PERCENT,3X,11HRATED VOLTS,1X,13HRA
     2TED CURRENT,1X,15HSPECIFIC WEIGHT,2X,10HEFFICIENCY     /
     38G15.5 )
  213 FORMAT (26H LOSS DISTRIBUTION FACTORS /3X,13HOHMIC HEATING,5X,10HH
     1YSTERESIS,3X,12HEDDY CURRENT,1X,14HBEARING FRICT.,4X,7HWINDAGE,6X,
     39HFREQUENCY,11X,4HCOST,6X,12HPOWER FACTOR/ 8G15.5 )
  215 FORMAT (/50H CONTROLLER FROM BATTERY TO MOTOR CHARACTERISTICS /
     14X,11HRATED POWER,2X,13HINPUT VOLTAGE,1X,14HOUTPUT VOLTAGE,2X,13HR
     2ATED CURRENT,6X,9HFREQUENCY,4X,11HSPEC.WEIGHT /6G15.5 )
  217 FORMAT(2X,14HLOSS COEFF.A0,13X,2HA1,13X,2HA2,11X4HCOST /
     13E15.5,1G15.2 )
  219 FORMAT  (/50HCONTROLLER FROM GENERATOR TO MOTOR CHARACTERISTICS/
     14X,11HRATED POWER,2X,13HINPUT VOLTAGE,1X,14HOUTPUT VOLTAGE,2X,13HR
     2ATED CURRENT,6X,9HFREQUENCY,4X,11HSPEC.WEIGHT /6G15.5 )
  221 FORMAT(2X,14HLOSS COEFF.A0,13X,2HA1,13X,2HA2,11X4HCOST /
     13E15.5,1G15.2 )
  223 FORMAT (/24H BATTERY CHARACTERISTICS     /
     15X,7HVOLTAGE,4X,11HSPEC.ENERGY,5X,10HSPEC.POWER,4X,11HBATT.WEIGHT,
     211X,4HCOST,5X,10HEFFICIENCY/6G15.4)
  225 FORMAT (/26H FLYWHEEL CHARACTERISTICS /
     12X,11HSPEC.ENERGY,1X,14HFLYWEEL WEIGHT,4X,9HMAX SPEED,1X,18HRUNDOW
     2N PERCENT/HR,8X,4HCOST /5G15.5)
  227 FORMAT (/19H GENERATOR FACTORS /
     12X,11HRATED POWER,6X,9HMIN SPEED,5X,9HMAX SPEED,1X,16HOVERLOAD PER
     2CENT,3X,11HRATED VOLTS,2X,13HRATED CURRENT,1X,15HSPECIFIC WEIGHT,4
     3X,10HEFFICIENCY/8G15.5)
  229 FORMAT (26H LOSS DISTRIBUTION FACTORS /3X,13HOHMIC HEATING,5X,10HH
     1YSTERESIS,3X,12HEDDY CURRENT,1X,14HBEARING FRICT.,4X,7HWINDAGE, 6X
     3,9HFREQUENCY,11X,4HCOST   /7G15.5 )
  231 FORMAT (/29H TRANSMISSION CHARACTERISTICS /
     21X,15HHIGH GEAR RATIO,1X,14HSEC.GEAR RATIO,1X,14HLOW GEAR RATIO,14
     2X,17HLOSS COEFFICIENTS,17X,12HTRANS.WEIGHT,11X,4HCOST/
     33G15.5,3E15.5,2F15.2)
      WMOT = WBAR*RPR/SPEED1*3600.
      WTCBM = WCBM*PCBM
      WTCGM = WCGM*PCGM
      WGEN = GBAR*GRPR/GSPD1*3600.
      BSE =  EBARM
      CALL VEHWT
  600 CONTINUE
      WRITE (16,114) IX1
      WRITE (16,233) WV,WGROS,WCURB
  233 FORMAT(/16H VEHICLE WEIGHTS ,10H  TEST WT ,10H GROSS WT  ,
     110H  CURB WT./ 11X,3F16.2)
      XMPG=0.
      DT=1.
      NFLAG =0
      SUMD = 0.
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      PBMAX = 0.
      PRMAX = 0.
      BCMA=0.
      SEIN=0.
      SEOUT=0.
      BCMI=0.
      SBI=0.
      SBD=0.
      JFLAG=0
      READ(4,10) IX2
      DO 49 I=1,15
      IX3(I)=IX2(I)
   49 CONTINUE
      READ(4,11)XNTS,DT,SL
      IF(DT.LE.0.) DT = 1.
      WRITE (16,116) IX2
  116 FORMAT (1X,16A5)
      WRITE(16,136) DT
  136 FORMAT(//1X,40H VEHICLE SPEED AT END OF EACH TIME STEP     ,
     112H DELTA T =    ,F7.4,5H SEC     )
      NTS=XNTS
      DO 15 I=1,NTS,10
         J=I-1
      READ(4,16) (V1(L+J),L=1,10)
      WRITE(16,16) (V1(L+J),L=1,10)
   15 CONTINUE
   16 FORMAT(10(1X,F7.3))
      IL=NTS
      NL=0
      VT=0
   33 NL=NL+1
      NC=0
      SUMD=0.
      VN=0.
      VT=0.
C     ENTER CALCULATIONAL LOOP
      DO 60 I=1,NTS
         NC=NC+1
         II=I-1
         L=II-(II/IL)*IL+1
   44    VN=V1(L)
   48    A=(VN-VT)/DT
         VA=(VN+VT)/2.
      JFLAG = 0
   57 RA=ROTI*WV*A/32.2
      RD = 0.5*RHOA*CDA*(VA**2)
      RR=WV*(C0+C1*VA+C2*VA**2)
         RS=WV*SL/100.
         RSUM=RA+RD+RR+RS
         P=RSUM*VA
C     CONVERT TO WATTS FROM FT*LBS/SEC
      PD = (745./550.)*P
      CALL AEPS(BCUR,I)
      IF (JFLAG.GT.4)    GO TO 62
         IF(JFLAG.EQ.1) GO TO 57
   62 CONTINUE
      IF(PD.GT.PRMAX) PRMAX=PD
      IF(PD.LT.PBMAX) PBMAX=PD
      IF(PD.GT.0.) SEIN = SEIN +PD*DT/3600.
      IF(PD.LT.0.)SEOUT = SEOUT+PD*DT/3600.
      CALL BAR(PBAR,BSE,EBAR)
      BAMP(I) = BCUR
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      IF(BCUR.GT.BCMA)BCMA=BCUR
      IF(BCUR.LT.BCMI) BCMI=BCUR
      IF(BCUR.GT.0.) SBI=SBI+BCUR*DT/3600.
      IF(BCUR.LT.0.)SBO=SBO+BCUR*DT/3600.
        NT=NT+1
 59     VT=VN
 60   CONTINUE
      WRITE(16,126) IX1,IX2,IX3
126   FORMAT(1H1,1X,16A5/1X,16A5/1X,16A5)
      WRITE(16,120) PRMAX,PBMAX
      WRITE(16,122) SEIN,SEOUT
      WRITE(16,124) SBI,SBO
      WRITE(16,130) BCMA,BCMI
      WRITE (16,132) SUMD
120   FORMAT(1X,22H MAX DRIVE POWER =      ,G14.5 ,6H WATTS/
     11X,22H MAX BRAKING POWER =    ,G14.5,6H WATTS )
122   FORMAT(1X,22H DRIVING ENERGY IN =      ,G14.5,11H WATT-HOURS/
     11X,22H BRAKING ENERGY =         ,G14.5,11H WATT-HOURS )
124   FORMAT(1X,22H DISCHARGE ENERGY   =    ,G14.5,10H AMP-HOURS /
     11X,22H RECHARGE ENERGY   =       ,G14.5,10H AMP-HOURS )
130   FORMAT(1X,22H MAX CURRENT OUT =       ,G14.5,5H AMPS /
     11X,22H MAX CURRENT IN    =       ,G14.5,5H AMPS )
132   FORMAT (1X,23H DISTANCE TRAVELED     =  , G14.5,6H MILES )
      IF(NFLAG.EQ.0) GO TO 710
      WRITE(16,250) DT
250   FORMAT(//119H PROPULSION SYSTEM CURRENT AT END OF EACH TIME STEP I
     1S EQUAL TO BATTERY CURRENT PLUS BUFFER CURRENT.    DELTA TIME   =
     2,F8.4,4H SEC)
      WRITE (16,118)(PSA(I),I=1,NTS)
710   CONTINUE
      WRITE(16,128) DT
128   FORMAT(//54H BATTERY CURRENT AT END OF EACH TIME STEP.   DELTA T =
     1    ,F8.4,  4H SEC   )
      WRITE (16,118) (BAMP(I),I=1,NTS)
      WRITE(16,260)DT
260   FORMAT(// 54H FLYWHEEL BUFFER CURRENT AT  END OF EACH TIME STEP. DE
     1LTA TIME = ,F8.4,4H SEC)
      WRITE(16,118)(FAMP(I),I=1,NTS)
118   FORMAT (1X,10F11.4)
C   SUM ENERGY AND CALCULATE RANGE
 70   RANGE = .8*SUMD*(WB*13.)/((BV*(SBI + SBO)))
      RANGWO= .8*SUMD*(WB*13.)/((BV*(SBI)))
       RANGE = RANGE/.8
       RANGWO = RANGWO/.8
C   LEAD LEVEL BATTERY OVER TIME OF CURRENT DRAIN.
      TIME = 0.
      TIME2 = 0.
      TIME3 = 0.
      RMS1 = 0.
      RMS2 = 0.
      DO 154 J1 = 1,4
      BLW(J1) = 0.
154   CONTINUE
      X = BV/WB
      E = 0.
      DO 150 I=1,NTS
      TIME3 = TIME3+ DT
      IF(ABS(BAMP(I)).GT.5.) TIME = TIME + DT
      IF(BAMP(I).GT.5.) TIME2 = TIME2 + DT
      RMS1 = RMS1 +(BAMP(I)**2)
      IF(BAMP(I).GT.0.) RMS2 = RMS2 + BAMP(I)**2
      PR = X*BAMP(I)
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      PWD = PR
      IF(PWD.LT.0.) PWD = 0.
      PRX = PR
      CALL BAR(PRX,13.,E)
C     E= 1.126*E
      BLW(1) = BLW(1) + PR/E
      BLW(2) = BLW(2) + PWD/E
      CALL BAR(PRX,40.,E)
      BLW(3) = BLW(3) + PR/E
      BLW(4) = BLW(4) + PWD/E
  150 CONTINUE
      DO 156 J1 = 1,4
      BLW(J1) = BLW(J1)*DT/3600.
  156 CONTINUE
      RMS1 = SQRT(RMS1/TIME)
      RMS2 = SQRT(RMS2/TIME2)
      L = 1
      WRITE(16,126) IX1,IX2,IX3
      WRITE(16,168)
  168 FORMAT(/1X,23H RMS AVERAGING FOR PBAR  /8X,4HPBAR ,8X,4HEBAR   )
  170 CONTINUE
      PBAR = BV*RMS1/WB
      IF(L.EQ.2) PBAR = 3600.*BV*(SBI+SBO)/WB/TIME
      IF(L.EQ.3) PBAR = 3600.*BV*(SBI+SBO)/WB/TIME3
      CALL BAR(PBAR,13.,EBAR)
C     EBAR = 1.126*EBAR
      WRITE(16,112) PBAR,EBAR
      RANGEL= RANGE*EBAR/13.
      CALL BAR(PBAR,40.,EBAR)
      WRITE(16,112) PBAR,EBAR
      RANGEN = RANGE*EBAR/13.
      EXX = BV*(SBI + SBO)/SUMD
      WRITE(16,164)
  164 FORMAT(19H WITH REGENERATION   )
      WRITE(16,160) RANGEL,RANGEN,EXX
  160 FORMAT(33H  RANGE WITH LEAD-ACID BATTERY =    ,G14.5,6H MILES   /
     135H  RANGE WITH NICKEL-ZINC BATTERY =   ,G14.5,6H MILES  /
     229H  ENERGY CONSUMED PER MILE =   ,G14.5,10H W-H/MILE     )
      PBAR = BV*RMS2/WB
      IF(L.EQ.2)  PBAR= 3600.*(BV*SBI/WB/TIME2)
      IF(L.EQ.3) PBAR = 3600.*(BV*SBI/WB/TIME3)
      CALL BAR(PBAR,13.,EBAR)
C     EBAR = 1.126*EBAR
      WRITE(16,112) PBAR,EBAR
      RANGEL= RANGWD *EBAR/13.
      CALL BAR(PBAR,40.,EBAR)
      WRITE(16,112) PBAR,EBAR
      RANGEN= RANGWD *EBAR/13.
      WRITE(16,166)
  166 FORMAT(22H WITHOUT REGENERATION  )
      EXX = BV*SBI/SUMD
      WRITE(16,160) RANGEL,RANGEN,EXX
      L = L+1
      IF(L.GT.3) GO TO 172
      WRITE(16,169)
      IF(L.EQ.3) WRITE(16,138)
  138 FORMAT( 38H AVERAGING OVER TIME OF FULL CYCLE        )
      GO TO 170
  172 CONTINUE
  169 FORMAT(//32H  ARITHMETIC AVERAGING FOR PBAR  /8X,4HPBAR,8X,4HEBAR)
      WRITE(16,162)
  162 FORMAT(//52H  STEP BY STEP CALCULATION OF BATTERY FRACTION USED. )
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      WRITE(16,164)
       RANGEL = SUMD*.8/BLW(1)
       RANGEN = SUMD*.8/BLW(3)
      RANGEL = RANGEL/.8
      RANGEN = RANGEN/.8
      EXX = BV*(SBI + SBO)/SUMD
      WRITE(16,160) RANGEL,RANGEN,EXX
      WRITE(16,166)
       RANGEL = SUMD*.8/BLW(2)
       RANGEN = SUMD*.8/BLW(4)
      RANGEL = RANGEL/.8
      RANGEN = RANGEN/.8
      EXX = BV*SBI/SUMD
      WRITE(16,160) RANGEL,RANGEN,EXX
      READ(4,11) X
      IF(X.GT.0.) GO TO 600
      READ (4,11) X
      IF (X.GT.0.) GO TO 610
      CALL EXIT
      END
      SUBROUTINE BAR(PBAR,BSE,EBAR)
C  THIS IS A NEW ROUTINE FOR FCY 8/1/77.
      X = ABS(PBAR)
      IF(BSE.EQ.13.) GO TO 10
      IF(BSE.EQ.40.) GO TO 20
      EBAR = 1.E-06
      GO TO 90
C FOR BSE = 13. USE LEAD-ACID BATTERY VALUES.
   10 EBAR = 25.543 - .81*X + .784E-02*X**2
      GO TO 90
C  FOR BSE = 40. USE NI.-ZN. BATTERY VALUES.
   20 IF(X.GT.64.3) X=64.
      EBAR = 20.4 +SQRT((64.3-X)/.1544)
      IF(PBAR.LT.0.) EBAR = 40.807
   90 RETURN
      END
      SUBROUTINE  VEHWT
C  THIS SUBROUTINE CALCULATES VEHICLE WEIGHTS
      COMMON /C/ WBAS,WPAY,WTEST,WPROP,WAX,WMOT,WTCBM,WTCGM,WB,WV,WF,
     1WGEN,WTXM,WGROS,WCURB,TESTW,WPS,ROTI,WCBM,WCGM
      COMMON /D/ CDA,RHOA,RADIUS,CO,C1,C2,RATIO,TAXL,A0,A1,A2,RPR,SPEEDI
     1,SPEEDA,DLOAD,RVT,CURDM,WBAR,EFFDM,RI2,HYSTI,EDI,BFI,WNDI,FREQ,
     2PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,CBMO,CBM1,CBM2,PCGM,VCGMIN,VCGMOT
     3,CGMCUR,CGMFRQ,CGMO,CGM1,CGM2,EBARM,PBARM,EFFB,XFSM,RUND,GRPR,
     4GSPD1,GSPD2,GOLD,GRVT,GCUR,GBAR,EFFOG,GRI2,GHYSTI,GEDI,GBRI,GWNDI
     5,GFREQ,TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,TXBAR,TXMTQ
      COMMON /E/ COSTDM,COSTAX,COSTB,COSTF,COSTCB,COSTCG,COSTG,COSTXM
      WPS = WAX + WMOT + WTCBM + WTCGM + WB + WF + WGEN + WTXM
      WGROS = WPROP*(WPS + WBAS + WPAY)
      WCURB = WGROS - WPAY
      TESTW = WCURB + WTEST
      WV = TESTW
      RETURN
      END
      SUBROUTINE AEPS(BCUR,I)
C THIS ROUTINE GIVE CURRENT OUT OF FLYWHEEL BUFFER AND SUBRRACTS IF FROM BATTER
CURRENT,DURING DOWN TIME BATTERY RECHARGES FLYWHEEL.BRAKING ALSO CHARGES
C   FLYWHEEL.
      COMMON /A/ A,AF,BSE,BV,CD,    DT,FC(20,150),FSE,JFLAG,MHP,P,
     1PBMAX,PD,RPMAX,SUMBFR,SUMFC,SUMFFR,VA,VN,VT
     2,SUMBE,SUMFEP,SUMFEN,PICF,PD3,PFY,PB,HPD,FQ,EHD,DELFC  ,PBAR
      COMMON /B/IX1,IX2,NTS,RANGE,SUMD,VC,TOTE,XMPG
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      COMMON /C/ WBAS,WRAY,WTEST,WPROP,WAX,WMOT,WTCBM,WTCGM,WB,WV,WF,
     1WGEN,WTXM,WGKOS,WCURD,TESTW,WPS,ROTI,WCBM,WCGM
      COMMON /D/ CDA,RHOA,RADIUS,C0,C1,C2,RATIO,TAXL,A0,A1,A2,RPR,SPEEDI
     1,SPEEDA,DLDAD,RVT,CURDM,WBAR,EFFDM,RI2,HYSTI,EDI,BFI,WNDI,FREQ,
     2PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,CBM0,CBM1,CBM2,PCGM,VCGMIN,VCGMOT
     3,CGMCUR,CGMFRQ,CGM0,CGM1,CGM2,EBARM,PBARM,EFFB,XFSM,RUND,GRPR,
     4GSPD1,GSPD2,GDLD,GRVT,GCUR,GBAR,EFFOG,GRI2,GHYSTI,GEDI,GBRI,GWNDI
     5,GFREQ,TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,TXBAR,TXMTQ
      COMMON /E/ COSTDM,COSTAX,COSTB,COSTF,COSTCB,COSTCG,COSTG,COSTXM
      COMMON /F/ PSA(1390),NFLAG,IX3,FAMP(1390),VLG,VSG,VHG
      DIMENSION        IX1(15),IX2(16),IX3(16),V1(1390),BAMP(1390)
      IF(NFLAG.NE.0) GO TO 100
      NNP=0
      WRITE(16,504)
      IX3(1)=5H THE
      IX3(2)=5HPROPU
      IX3(3)=5HLSION
      IX3(4)=5H SYST
      IX3(5)=5HEM CU
      IX3(6)=5HRRENT
      IX3(7)=5H IS F
      IX3(8)=5HROM T
      IX3(9)=5HHE BA
      IX3(10)=5HTTERY
      IX3(11)=5H AND
      IX3(12)=5HA FLY
      IX3(13)=5HWHEEL
      IX3(14)=5H BUFF
      IX3(15)=5HER.
      WRITE(16,500)
      WRITE(16,501)
      WRITE(16,502)
      WRITE(16,503)
  500 FORMAT( 54H THIS ROUTINE GIVES CURRENT OF THE FLYWHEEL BUFFER AND)
  501 FORMAT( 54H SUBTRACTS IT FROM CURRENT. DURING DOWN TIME          )
  502 FORMAT( 54H BATTERY RECHARGES FLYWHEEL. BRAKING ALSO CHARGES     )
  503 FORMAT( 54H FLYWHEEL.                                            )
  504 FORMAT( 54H AEPS SUBROUTINE VERSION 2                            )
      RECMAX=    GRPR*.1
      NFLAG=1
      PI=3.14159265
C INITIALIZE  VARIABLE FOR FIRST TIME IN ROUTINE
C  SET FLYWHEEL MOMENT OF INERTI+ IN MKS UNITS. F+CTOR .66   IS TO
C  COMPENSATE FOR FLYWHEEL HOUSING WEIGHT.
      FIN=2.*WF*FSE/(XFSM*2.*PI/60.)**2*3600*.66
      BUFFER=.85*WV*ROTI*746./550./32.2
      FER=WF*FSE*3600.
      XIFS=.7453*XFSM*2.*PI/60.
      XFS=XIFS
      XFSMAX=XFS
      XFSMIN=XFS
      FE=.5*FIN*(XFS**2)
  100 CONTINUE
      IF(A.LE.0.) GO TO 120
      PBUF=(A*VA*BUFFER)
      GO TO 130
  120 PBUF=0.
      IF(PD.LT.0.) PBUF=PD
  130 CONTINUE
      RPM=XFS*60./2./PI
      IF(MOD(NNP,36).NE.0) GO TO 190
      WRITE(16,260) FE,RPM
```

```
190 NNP=NNP+1
260 FORMAT(/20H FLYWHEEL ENERGY =    ,G15.5/15H FLYWHEEL RPM =,G15.5)
    CALL PMDC(BCUR)
    PSA(I)=BCUR
    IF(BCUR.LT.0.) GO TO 140
    BUFFI = BCUR*PBUF/ABS(PD)
150 BCUR=BCUR-BUFFI
    IF(BUFFI.GE.0.) FE=FE-BV*BUFFI/EFFOG*DT*100.
    IF(BUFFI.LT.0.) FE=FE-BV*BUFFI*EFFOG*DT/100.
    FE=FE-(FER*RUND/100./3600.*DT*(FE/FER)**2)
    IF( A.NE.0.) GO TO 170
    RECH=.2*(XIFS**2-XFS**2)*FIN/2./DT
    B=1.
    IF (VA.EQ.0.) B  =3.
    IF(ABS(RECH).GT.B*RECMAX)RECH=RECH*RECMAX/ABS(RECH)*B
    BCUR=RECH/(BV*EFFOG)*100.+BCUR
    FE=FE+RECH*DT
170 XFS=(2.*FE/FIN)**.5
    IF(XFS.GT.XFSMAX)XFSMAX=XFS
    IF(XFS.LT.XFSMIN)XFSMIN=XFS
    IF(XFS.LT.XIFS/10.) GO TO 180
    IF(I.EQ.NTS) WRITE(16,260)FE,RPM
    IF(I.EQ.NTS)XFSMAX=XFSMAX*60./2./PI
    IF(I.EQ.NTS)XFSMIN=XFSMIN*60./2./PI
    IF(I.EQ.NTS) WRITE(16,270)XFSMAX,XFSMIN
270 FORMAT(/18HMAX.FLYWHEEL RPM =,G15.5,5X,17HMIN.FLYWHEEL RPM=,G15.5)
    FAMP(I)=PSA(I)-BCUR
    RETURN
140 BUFFI=BCUR
    GO TO 150
180 WRITE(16,250) FIN ,XIFS,XFS
    CALL EXIT
250 FORMAT(/// 43H***FLYWHEEL RAN DOWN.CALLED EXITIN AEPS,***,3E15.5)
    END
    SUBROUTINE PMDC(BCUR)
    COMMON /A/ A,AF,BSE,BV,CD,    DT,FC(20,150),FSE,JFLAG,MHP,P,
   1PBMAX,PD,RPMAX,SUMBFR,SUMFC,SUMFFR,VA,VN,VT
   2,SUMBS,SUMFEP,SUMFFN,PICF,PDB,PFY,PB,HPD,FQ,EHD,DELFC,PBAR
    COMMON /B/IX1,IX2,NTS,RANGE,SUMD,VC,TOTE,XMPG
    COMMON /C/ WBAS,WPAY,WTEST,WPROP,WAX,WMOT,WTCBM,WTCGM,WB,WV,WF,
   2WGEN,WTKM,WGROS,WCURB,TESTW,WPS,ROTI,WCBM,WCGM
    COMMON /D/ CDA,RHOA,RADIUS,C0,C1,C2,RATIO,TAXL,A0,A1,A2,RPR,SPEEDI
   1,SPEEDA,GLOAD,RVT,CURDM,BBAR,EFFDM,RI2,HYSTI,EDI,BFI,WNDI,FREQ,
   2PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,CBM0,CBM1,CBM2,PCGM,VCGMIN,VCGMOT
   3,CGMCUR,CGMFRQ,CGM0,CGM1,CGM2,EBARM,PBARM,EFFB,XFSM,RUND,GRPR,
   4GSPD1,GSPD2,GLOD,GRVT,GCUR,GBAR,EFFOG,GRI2,GHYSTI,GEDI,GBRI,GWNDI
   5,GFREQ,TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,TXBAR,TXMTQ
    COMMON /E/ COSTDM,COSTAX,COSTB,COSTF,COSTCB,COSTCG,COSTG,COSTXM
    COMMON /F/ PSA(1390),NFLAG,IX3,FAMP(1390),VLG,VSG,VHG
    DIMENSION          IX1(16),IX2(16),IX3(16),V1(1390),BAMP(1390)
C   THIS ROUTINE CALCULATES THE CURRENT AND POWER FOR AN INDUCTION MOTOR
C   SET INITIAL VALUES OF CIRCUIT AND MOTOR CONSTANTS
    DIMENSION GRA(4)
    REAL I0,I1,I2,I3,I4
    REAL IOX,IOY,IOX1,IOY1
    REAL I2X,I2Y,I4Y,I1Y,I1X,I3X
    FLUF(X) = (5.7*(TANH(.18226*X))+ .1033*X + .5)
    AX1(X,Y)=(SQRT((X**4.*.1033*6./Y)+38.44) -6.2)*Y/1.2396
    AX2(X,Y)  =  (SQRT((X**4.*5.85309/Y)+.25) -.5)*Y/13.7062
    AX3(X,Y,Z)  =  (X/3600.)*((Y/Z)**1.6)
    AX4(X,Y,Z)  =  ((X*Y)/(3600.*Z))**2
    IF(VA.EQ.0.) GO TO 1000
```

```
      IF(SUMD.NE.0.) GO TO 40
      NMP = 0
      WRITE(16,134) IX1
      WRITE(16,126)  IX3
  134 FORMAT (1H1,1X,13A5)
      WRITE(16,140)TESTW,WB,RATIO,TXMR1,TXMR2,TXMR3,RPR
  140 FORMAT(/1X,23HVEHICLE TEST WEIGHT    =    ,F8.2,7H POUND
     1/1X,23HBATTERY WEIGHT         =    ,F8.2,7H POUNDS
     2/1X,23HAXLE RATIO              =   ,F8.4
     3/1X,23HTRANS.     HIGH GEAR   =    ,F8.4
     4/1X,23H RATIO    SEC. GEAR    =    ,F8.4
     5/1X,23H           LOW  GEAR   =    ,F8.4
     6/1X,23HMOTOR RATED POWER      =    ,F8.1)
C  PUT WRITE ROUTINE HERE FOR CANDIDATES
      WRITE(16,136)
  136 FORMAT(2X,51H CANDIDATE NO. 3 POLYPHASE INDUCTION MOTOR - 3 PH.   ,
     1/51H THIS SUBROUTINE DATED MAR. 28, 1979.  FCY                    )
      X = 6.
      ACCUM = 0.
      GRA(3) =   60./(2.*3.14159*RADIUS/12.)
      GRA(3) = GRA(3) * RATIO
      GRA(2) = GRA(3) * TXMR2
      GRA(1) = GRA(3) * TXMR3
      GRA(3) = GRA(3) * TXMR1
      GRA(4) = 15.
      FLX = .44643E-02
      FLUX = FLX*FLUF(X)
      FLXD = FLUX
C   SET SHIFT POINT
C SHIFT POINTS READ IN AS DATA.
CC    VLG = 19.
CC    VSG = 35.
C  PER LEG CURRENTS AND LOSSES FOR THREE PHASE INDUCTION MOTOR
      ACVT=BV*(.5**.5)*.9003
      E1  = ACVT
      SLIP=COSTOM
      SPEEDB  = SPEEDI / (1. - SLIP )
      TORRT = RPR / SPEEDI
      XLOSS = RPR*(100./EFFDM - 1.)
      CURDM = (RPR+XLOSS)/RVT
      ACX = CURDM
      FQ = ACX
      AMAX = OLOAD*FQ / 100./(3.)**.5
      WND1=XLOSS*WNDI/100.
      HYS1=XLOSS*HYSTI/100.
      ED1= XLOSS*EDI/100.
      BF1 =XLOSS*BFI/100.
      WNDX = (XLOSS*WNDI/100.)/((SPEEDI/3600.)**2)
      BFX = (XLOSS*BFI/100.)/(SPEEDI/3600.)
      HYSX = (XLOSS*HYSTI/100.)/AX3(SPEEDB,FLUX,FLXD)
      EDX = (XLOSS*EDI/100.)/AX4(SPEEDB,FLUX,FLXD)
      PF  = TOTE
      SN  = (1.- PF**2)**.5
      I1  = RPR / (E1*(EFFDM/100.)*PF*3.)
      SNI1 =   I1 * SN
C PER LEG LOSSES
      XLOSS = RPR*(100./EFFDM - 1.) /3.
      ABRT = (HYSTI + EDI)*XLOSS / (100.*E1)
      BDRT = (RI2 / 100.)*XLOSS / E1
      DERT = ((RPR / 3.) + ((WNDI + BFI) / 100.)*XLOSS) / E1
      PH4 = 1. - (SLIP/(1. - SLIP))*DERT/BDRT
      IF(PH4.LE.0.) GO TO 690
```

```
      BCRT = PH4 * BDRT
      CDRT = BDRT - BCRT
      CSI2 = BDRT + DERT
      SNI2 = CSI2 * (2.5 - (2.5**2 -1.)**.5)
      SNI0 = SNI1 - SNI2
      R1 = BCRT * E1/ I1**2
      R3 = E1/ABRT
C     TRY ITERATIVE SCHEME FOR I2,I0,R2,R3,X1,X2,X3,AND E2
      PH1 = .04
      PH2 = .04
      WRITE(16,981)
      I2 = (SNI2**2 + CSI2**2)**.5
      R2S = E1 * (CDRT + DERT)/ I2**2
      X3 = E1/(SNI0*(1.+PH1))
      X1 = PH1 * X3
      X2 = PH2 * X3
      N = 0
      PF1 = PF
      CSI0 =ABRT
      YI1 = I1*PF
      XI1 = I1*SN
      YI0 = CSI0
      XI0 = SNI0
      I0 = (CSI0**2 + SNI0**2)**.5
      I2 = (CSI2**2 + SNI2**2)**.5
      X3 = E1 /SNI0
      X1 = PH1 * X3
      X2 = PH2 * X3
      SNA=SNI2 / I2
      CSA = CSI2 /I2
  610 CONTINUE
      X2 = X1
      E2 = I2 *((X2**2 + R2S**2)**.5)
      R3 = E2**2/(ABRT*E1)
      I4 = E2/R3
      I3 = (I0 **2 - I4**2)**.5
      X3 = E2 / I3
      SNB = X2/((R2S**2 + X2**2)**.5)
      CSB = (1.-SNB**2)**.5
      SNG = SNA*CSB - SNB * CSA
      CSG = CSA * CSB + SNA *SNB
      E2E1 = ((E1 - E2 *CSG)**2 + (E2*SNG)**2)**.5
      X1 = E2E1**2 - (I1*R1)**2
      IF(X1.GT.0.) X1 =(X1**.5)/I1
      IF(X1.LT.0.) X1 = .5*ABS(X1)
      N = N + 1
      IF(N.GT.20) GO TO 622
      IF(ABS(X2-X1).GT.1.E-06) GO TO 610
      GO TO 620
  981 FORMAT(/25H  CIRCLE DIAGRAM VECTORS.  /
     1           8X,2HI1,12X,3HI0 ,13X,2HI2,13X,2HE2,13X,3HAB ,11X,3HBC ,
     211X,3HCD ,11X,3HDE   )
  690 WRITE(16,920) SLIP
  920 FORMAT(15HSLIP EXCESSIVE   ,G15.5 )
      CALL EXIT
  622 WRITE(16,986) N
  986 FORMAT (1X,I5)
  620 CONTINUE
      I0 = (YI0**2 + XI0**2)**.5
      PF = PF1
      R2 = R2S * SLIP
      ABRT = YI0
```

```
      BCRT = YI0*XI1/XI0 - ABRT
      CORT = R2*I2**2/F1
      DERT = YI1-ABRT-BCRT-CORT
      WRITE (16,984) I1,I0,I2,E2,ABRT,BCRT,CORT,DERT
      EX = E2
      WRITE(16,988) R1,R2,R3,X1,X2,X3,I1,I2,I0,E1,E2,PF
  988 FORMAT(/37H CIRCUIT CONSTANTS, OHMS PER LEG.          /
     1             10X,5HR1      ,10X,5HR2      ,10X,5HR3      ,10X,5HX1      ,10X,
     1 5HX2     ,10X,5HX3      /1X,6G15.6 /
     428H LEG CURRENTS AND VOLTAGE.  /
     5                                       10X,5HI1      ,10X,5HI2      ,10X,5HI0
     3      ,10X,5HE1      ,10X,5HE2      ,10X,5HPF      /1X,6G15.6 )
C
C  PRINT MOTOR CHARACTERISTICS.
      WRITE(16,980)
      WRITE(16,982)
  980 FORMAT(///23H MOTOR CHARACTERISTICS. /24H   CANDIDATE NO. 3 THREE
     1,22HPHASE INDUCTION MOTOR    / )
  982 FORMAT(3X,15H  RATED POWER     ,17H          VOLTAGE       ,15H  LEG CURRE
     1NT   ,17H ROTOR CURRENT    ,15H SPEED   RPM     ,15H  LEG RESIST
     2, 15H ROTOR RESIST    , 15H REACTANCE X3       )
      AVT= ACVT
      RCUR = I1
      RFC = I2
      RESA = R1
      BASS = SPEEDI
      RESF = R2
      WRITE(16,984) RPR,AVT,RCUR,RFC,BASS,RESA,RESF,X3
      WRITE(16,989)
  989 FORMAT(// 19H BEARING FRICTION   ,16H EDDY CURRENT          ,
     115H   HYSTERESIS    ,11H WINDAGE    ,19H LEAKAGE REACTANCE
     2 15H   POWER FACTOR    ,13H          SLIP         )
      WRITE(16,984)BF1,ED1,HYS1,WND1,X1,PF,SLIP
  984 FORMAT(1X,8G15.6 )
C  ADD TO SUBROUTINE A PORTION TO CALCULATE POWER AND TORQUE AND EFF.
C  AT VARIOUS AMOUNTS OF SLIP AT RATED FREQUENCY.
      TWOPI  = 6.283185
      SX = R2/((R1**2 + (X1 + X2)**2)**.5)
       DELS = SX / 10.
      SLIPX = .00001*DELS - DELS*2. - SX
      WRITE(16,910)
  910 FORMAT(/3X,4HSLIP,12X,3HRPM,9X,6HTORQUE,10X,5HPOWER,8X,7HVOLTAGE,
     1 8X,
     1 7HCURRENT,4X,12HPOWER FACTOR,12H  EFFICIENCY )
      DO 650 J = 1,24
      SLIPX = SLIPX + DELS
      R2S = R2 / SLIPX
      Z2  = (R2S**2 + X2**2)**.5
      I2 = E2 / Z2
      I2X = I2 * X2 / Z2
      I2Y = I2 * R2S / Z2
      I3X = E2 / X3
      I4Y = E2 / R3
      I1Y = I2Y + I4Y
      I1X = I2X + I3X
      I1 = (I1Y**2 + I1X**2)**.5
      SNB = I1X / I1
      CSB = I1Y / I1
      E1Y = E2 + I1Y * R1 + I1X * X1
      E1X = I1X * R1 - I1Y * X1
      E1N = (E1Y**2 + E1X**2)**.5
      SNG = E1X / E1N
```

```
      CSG = E1Y / E1N
      CSA = CSB * CSG + SNB * SNG
      PF1 = CSA
      FAC = E1 /E1N
      I2 = I2 * FAC
      I3 = I3X * FAC
      I4 = I4Y * FAC
      I1 = I1 * FAC
      E2 = E2 * FAC
      IO = (I3**2 + I4**2)**.5
      RPM = SPEEDS*(1.-SLIPX)
      POWER = I2**2*R2*(1.-SLIPX)* 3./SLIPX-WNDX*(RPM/3600.)**2-BFX*RPM/
     13600.
      TOR = POWER/(TWOPI*RPM/60.)
      EFF = POWER / (3.*E1*PF1 * I1 )
      IF(POWER.LT.0.) EFF = 1./EFF
      WRITE(16,984 ) SLIPX,RPM,TOR,POWER,E1,I1,PF1,EFF
      E2 = I3*X3
  660 CONTINUE
  125 FORMAT (/1X,16A5)
  132 FORMAT (//1X,50HACCUM. VEHICLE GEAR ROAD  MOTOR  MOTOR MOTOR MOTOR
     1,62H  PWR  MOTOR  EDDY  HYST  WINDAGE FRICT CNTR. BATTERY BATT  MO
     2,18HTOR   OVERL  ACCUM /
     31X,60HDIST   SPEED          POWER POWER  SPEED AC    AC      FAC  I*I
     4,60H*R   CURR  LOSS   LOSS   LOSS   LOSS   POWER   CURR  EFFIC EF
     5,11HFIC  ENERGY /
     61X,60HMILES  FT/SEC         WATTS WATTS  RPM   VOLTS AMPS   TOR  WAT
     6,1HT
     7,60HS  WATTS WATTS  WATTS  WATTS  WATTS  WATTS.  AMPS  PERCT PER
     8,9HCT  W*HRS   )
   40 CONTINUE
      N= 1
      IF(VA.GT.VHG) GO TO 10
      IF(VA.GT.VSG)  GO TO 20
      NG=1
      GO TO 30
   10 NG=3
      GO TO 30
   20 NG=2
C UPSHIFT IF ACCELERATION IS EQUAL TO ZERO, OR SMALL.
      IF(ABS(A).LT.0.90) NG = 3
   30 CONTINUE
C   SET RPM AND DRIVE LINE MECHANICAL LOSSES
      NX=NG
      RPM=VA*GRA(3)/TXMRI
      PA = PD
      DTOR = A0 + (RPM*A1) + ((ABS(PD))*60.0/(1.356*2.*3.14159*RPM)*A2)
      AXPR = (DTOR*RPM*2.*3.14159/60.)*1.356
      PDI = PA + AXPR
      RPMX = RPM
      RPM=VA*GRA(NG)
      TMPR=TXA0+(RPM*TXA1)+(ABS(PDI)*60./(1.356*2.*3.14159*RPM)*TXA2)
      TMPR = TMPR*(1.+RPM/RPMX)*.5
      TMPR=(TMPR*RPM*2.*3.14159/60.)*1.356
      PDI=PDI+TMPR-XMPG
      PDIM = PDI
      PDX=BFX*RPM/3600.
      BFXM = PDX
      PDX =PDX + (WNDX*((RPM/3600.)**2))
      WNDXM = PDX - BFXM
      PDI=PDI+PDX
      BVB=(BV - CBM1 )*(.5**.5)
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```
C  FIND ELECTRICAL MOTOR CURRENT AND IRON LOSSES
C  ITERATIVE SCHEME FOR MOTOR CURRENT PER LEG AND FOR POWER FACTOR.
      BVX = BV3
      PPL = PDI / 3.
      TOR = PDI / RPM
      SLIPX = SLIP*TOR/TORRT
      N = 0
       NXX=0
       SX= 0.
      SX=   S(SX)
      DO 648 I=1,8
      SX2=SX
      IF(PPL.LT.0.)SX=-SX
      IF( SX.LT.-.45) SX=-.45
      Q=R2**2/(R1**2+2.*R1*R2+(((X1+X2)*RPM/SPEEDB)**2)*(1.+2.*SX)
     1/(1.-SX)**2)
      Q2=(Q**2+Q)**.5
      IF(PPL.LT.0.)SX=Q2+Q
      IF(PPL.GT.0.)SX=Q2-Q
      IF((ABS(SX)).GT.0.1)  SX=.1*SPEEDB/RPM
      IF(SX.GT.0.6)SX=.6
      IF(ABS(SX-SX2).LT.1.E-07)GO TO 630
  648 CONTINUE
  630 CONTINUE
      N = N + 1
      IF(ABS(SLIPX).GT.SX)  SLIPX=(1.-.1**N)*SIGN(SX,PPL)
      RPA = RPM/(1. - SLIPX)
      XRPM=RPA/SPEEDB
      IF (RPA.LT.SPEEDB) BVX=BV3*((1.-.03)*XRPM+.03)
      E1 = BVX
      IF(N.EQ.1) E2 = E1
      R2S = R2 / SLIPX
      Z2 = (R2S**2 +(X2*XRPM)**2)**.5
      I2 = E2 / Z2
      I2X = I2*(X2*XRPM)/Z2
      I2Y = I2 * R2S / Z2
      I3X = E2/(X3*XRPM)
      I4Y = E2 / R3
      I1Y = I2Y + I4Y
      I1X = I2X + I3X
      I1 = (I1Y**2 + I1X**2)**.5
      SNB = I1X / I1
      CSB = I1Y / I1
      E1X = I1X * R1 - I1Y *(X1*XRPM)
      E1Y = E2 + I1Y * R1 + I1X *(X1*XRPM)
      E1N = (E1Y**2 + E1X**2)**.5
      SNG = E1X / E1N
      CSG = E1Y / E1N
      CSA = CSB * CSG + SNB * SNG
      PF1 = CSA
      FAC = E1 /E1N
      I2 = I2 * FAC
      I3 = I3X * FAC
      I4 = I4Y * FAC
      I1 = I1 * FAC
      E2 = E2 * FAC
      I0 = (I3**2 + I4**2)**.5
      RAT = (I2**2)*R2/PPL
      RAT2 = RAT*(1.-SLIPX)/SLIPX
      IF(RAT2.GT.1.)GO TO 632
      IF(NXX.GT.0) GO TO 634
      SLIPX=(1.-.5**(N+1))*SIGN(SX,PPL)
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REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

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      GO TO 636
  632 NXX=1
  634 SLIPX=SLIPX/RAT2
  636 CONTINUE
      IF( ABS(RAT2 -1.).LT.1.E-06) GO TO 640
      IF(ABS(RAT2-RATX).LT.1.E-08)GO TO 642
      RATX=RAT2
      IF(N.GT.25) GO TO 642
      IF(ABS(SLIPX).LT.1.E-06) GO TO 644
      GO TO 630
  644 I2 = 0.
      I1 = I0
  642 CONTINUE
      PMMX=3.*RAT2*PPL-WNDXM-BFXM
      WRITE(16,901)PDIM,PMMX
  901 FORMAT(1X,45H********* EXCESSIVE POWER REQUIRED ********* ,
     13X,23HREQUIRED MOTOR POWER = ,F12.2,21H   AVAILABLE POWER = ,
     2F12.2)
  640 CONTINUE
      F2 = I3*X3*XRPM
      PFX = PF1
      PF3 = PF1
      FLUX = F2*SPEED0*FLXD/(RPA*FX)
      XLUX = ABS(FLUX)
      HYST = HYSX*AX3(RPA,XLUX,FLXD)
      EDDY=EDX*AX4(RPA,XLUX,FLXD)
      IF(ABS(I1).GT.(AMAX/2.))I1= I1*AMAX/(2.*ABS(I1))
      BCUR=(3.)**.5*I1*BVX*PFX/(BV-CBM1)
      IF(ABS(BCUR).GT.AMAX) BCUR = BCUR*AMAX/ABS(BCUR)
  500 CONTINUE
      IF((BCUR.GT.0.).AND.(PD.LT.1.0)) BCUR = 0.
      XI2R = ((I1**2)*R1 + (I2**2)*R2)*3.
      ACUR=3.**.5*I1
      IF (ACUR.LE.AMAX) GO TO 530
      WRITE(16,930)ACUR,AMAX
      ACUR=AMAX
      XI2R=(I2R-3.*(I1**2-(AMAX/3.))*R1
  530 CONTINUE
      PB = PDIM + XI2R + EDDY + HYST + WNDXM + BFXM
      PBA = PB
C  SET POWER LOSS FOR CONTROLLER
C     PBX=JUNCTION LOSS,PBASE=BASE JUNCTION LOSS,PSWT=SWITCHING LOSS
      PBX=CBM0+ABS(CBM1*ACUR)+((CBM2*ACUR**2)/9)
      PBASE=(.8+.02*(ACUR/90))*ACUR/5
      PSWT=ACUR*BV*1.6/1000.
      PBX=(PBX+PBASE+PSWT)*11./9.
      PB = PB + PBX
      BCUR = PB/BV
      PBMAX = 1.2*OLOAD*RPR / EFFDM
      IF(ABS(PB).GT.PBMAX) PB = PB*PBMAX / ABS(PB)
      IF(ABS(BCUR).GT.AMAX) BCUR = BCUR*AMAX/ABS(BCUR)
      PBAR = PB / WB
      IF(PB.EQ.0.) PB =1.E-08
      IF(PD.EQ.0.) PD =1.E-08
      IF(ACUR.GT.AMAX) WRITE(16,930) ACUR, AMAX
  930 FORMAT(1X,45H********* EXCESSIVE CURRENT REQUIRED ******* ,
     13X,23HREQUIRED CURRENT      =,F11.3,21H   AVAIL. CURRENT   = ,
     2F11.3)
         SUMD=SUMD+VA*DT/5280.
      IF(PDIM.EQ.0.) PDIM = 1.E-08
      IF(PBA.EQ.0.) PBA = 1.E-08
      XMEFF = 100.*PDIM/PBA
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      XMEFF = 100.*PD/P3
      IF (PD.LT.0.) XOEFF = 100.*PB/PD
      IF(PDIM.LT.0.) XMEFF=100.*PBA/PDIM
      ACCUM = ACCUM + PB*DT/3600.
      IF(MOD(NNP,36).NE.0) GO TO 248
      WRITE(16,134) IX1
      WRITE(16,126)  IX3
      WRITE(16,126) IX2
      WRITE(16,140)TESTW,WB,RATIO,TXMR1,TXMR2,TXMR3,RPR
      WRITE (16,132)
  248 CONTINUE
      NNP = NNP + 1
      WRITE (16,138) SUMD,VA,NX,PD,PDIM,RPM,BVX,ACUR,PF3,
     1                                                XI2R,EDDY,HYST,
     2WNDXM,BFXM,PBX,PB,BCUR,XMEFF,XOEFF,ACCUM
  138 FORMAT(1X,1F6.4,1F7.3,I2,3F7.0,2F7.1,F7.4,1X, 6F6.0,1F8.0,1F7.1
     1     ,2F6.2,1F9.2 )
  950 RETURN
 1000 BCUR=0.
      RPM = 0.
      ACUR =0.
      PDIM = 0.
      BVX = 0.
      XI2R = 0.
      EDDY = 0.
      HYST = 0.
      I1  = 0.
      I2 = 0.
      WNDXM = 0.
      BFXM = 0.
      GO TO 500
        END
      SUBROUTINE AEPS(BCUR,I)
C  THIS SUBROUTINE CALCULATES THE POWER FROM THE FLYWHEEL VIA A CVT
C  TO PROVIDE ACCELERATION AND BRAKING. RECHARGE OF THE FLYWHEEL OCCURS
C  WHEN THE ACCELERATION EQUALS ZERO.
      COMMON /A/ A,AF,BSE,BV,CD,    DT,FC(20,150),FSE,JFLAG,MHP,P,
     1PBMAX,PD,RPMAX,SUMBFR,SUMFC,SUMFFR,VA,VN,VT
     2,SUMBE,SUMFEP,SUMFEN,PICT,PDB,PFY,PB,HPD,FQ,EHD,DELFC  ,PBAR
      COMMON /B/IX1,IX2,NTS,RANGE,SUMD,VC,TOTE,XMPG
      COMMON /C/ WBAS,WPAY,WTEST,WPROP,WAX,WMOT,WTCBM,WTCGM,WB,WV,WF,
     1WGEN,WTXM,WGROS,WCURB,TESTW,WPS,ROTI,WCBM,WCGM
      COMMON /D/ CDA,RHOA,RADIUS,C0,C1,C2,RATIO,TAXL,A0,A1,A2,RPR,SPEEDI
     1,SPEEDA,ULOAD,RVT,CURDM,WBAR,EFFDM,RI2,HYSTI,EDI,BFI,WNDI,FREQ,
     2PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,CBM0,CBM1,CBM2,PCGM,VCGMIN,VCGMOT
     3,CGMCUR,CGMFRQ,CGM0,CGM1,CGM2,EBARM,PBARM,EFFB,XFSM,RUND,GRPR,
     4GSPD1,GSPD2,GOLD,GRVT,GCUR,GBAR,EFFOG,GRI2,GHYSTI,GEDI,GBRI,GWNDI
     5,GFREQ,TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,TXBAR,TXMTQ
      COMMON /E/ COSTDM,COSTAX,COSTB,COSTF,COSTCB,COSTCG,COSTG,COSTXM
      COMMON /F/ PSA(1390),NFLAG,IX3,FAMP(1390),VLG,VSG,VHG
      DIMENSION          IX1(16),IX2(16),IX3(16),V1(1390),BAMP(1390)
      IF(SUMD.NE.0) GO TO 100
      NFLAG = 1
      WRITE(16,210)
      WRITE(16,202)
  202 FORMAT( //45H SUBROUTINE VERSION OF JAN. 9, 1979. FCY          )
  210 FORMAT(1X,51HTHIS PROPULSION SYSTEM USES A FLYWHEEL AND CVT FOR  ,
     151HACCELERATION AND BRAKING, FLYWHEEL RECHARGE OCCURS WHEN A=0.  )
C  INITIALIZE VARIABLE THE FIRST TIME IN THIS SUBROUTINE.
      PI = 3.14159265
      XKC = 2.*PI/ 60.
      RECMAX = GRPR* .07
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REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

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      NNP=0
      SPEED =  XFSM*XRC
      TORRAT = GRPR/(XFSM*XRC)
      WRITE(16,270) TORRAT,GHYSTI,GEDI,GBRI
  270 FORMAT(/1X,15HRATED TORQUE =    ,G15.5/1X,15HSPIN TORQUE =    ,G15.
     15,8H PERCENT  /1X,15HPERCENT CREEP =  ,G15.5/1X,15HWINDAGE TOR. =
     2  ,G15.5   )
C  SET FLYWHEEL MOMENT OF INERTIA IN MKS UNITS. FACTOR .66   IS TO
C  COMPENSATE FOR FLYWHEEL HOUSING WEIGHT.
      FIN=2.*WF*FSE/(XFSM*2.*PI/60.)**2*3600*.66
      FER = WF * FSE * 3600.
C     .70 =SMALLER FLYWHEEL
      BUFFAC =   .70*WV*ROTI*746./550./32.2
      XIFS = .7453 * XFSM * XRC
      XFS = XIFS
      FE = .5 * FIN *(XFS**2)
      GRAX = (RADIUS/12.)*RATIO/XPC
      CXR2 = GSPD1 / SPEEDA
      IX3(1) = 5H THIS
      IX3(2) = 5H PROG
      IX3(3) = 5HRAM U
      IX3(4) = 5HSES A
      IX3(5) = 5H SUBR
      IX3(6) = 5HOUTIN
      IX3(7) = 5HE TC
      IX3(8) = 5HMODEL
      IX3(9) = 5H THE
      IX3(10) = 5HCVT T
      IX3(11) = 5HO TRA
      IX3(12) = 5HNSFER
      IX3(13) = 5H POWE
      IX3(14) = 5HR OF
      IX3(15) = 5HA FLY
      IX3(16) = 5HWHEEL
  100 CONTINUE
      IF(A.LE.0.) GO TO 120
      PBUF = A * VA * BUFFAC
      GO TO 130
  120 PBUF = 0.
      IF(PD.LT.0.) PBUF = PD
  130 CONTINUE
      CXR = GRAX * TXMR2
      IF(VA.LT.30.) CXR = GRAX*TXMR3
      IF(VA.GT.70.)  CXR = GRAX * TXMR1
      XPSS = VA * CXR
      XPRS = XPSS * XRC * CXR2
      RAT1 = XPRS / XFS
      RECH = 0.
      IF(VA.EQ.0.) GO TO 170
      IF(A.NE.0.) GO TO 170
      RECH = .2*(XIFS**2 - XFS**2)*FIN/2./DT*1.5
      IF(ABS(RECH).GT.RECMAX) RECH = RECH*RECMAX/ABS(RECH)
  170 CONTINUE
      PBUF = PBUF-RECH
      CVTIT = PBUF/ XFS
      TREFF = CVTEF(XFS,RAT1,CVTIT,TORRAT,GHYSTI,GEDI,GBRI,SPEED)
      IF(PBUF.GT.0.) PFLY = PBUF / TREFF
      IF(PBUF.LE.0.) PFLY = PBUF * TREFF
      XMPG=PBUF
      RPM = XFS/XRC
      IF(MOD(NNP,36).NE.0) GO TO 190
      WRITE(16,260) FE,RPM
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  190 NNP=NNP+1
      CALL PMDC(BCUR)
      WRITE(16,220) RPM,FE,PBUF,PFLY,TREFF
  220 FORMAT(1X,7HRPM =   ,G15.5,7H  FE =   ,G15.5,8H PBUF =   ,G15.5,
     19H PFLY =   ,G15.5,9H TREFF =   ,G15.5 )
      PSA(I) = BCUR
      FE = FE - PFLY*DT -((FER*RUND/100.)*DT/3600.)*(FE/FER)**2
      FE = FE + PECH * DT
      IF(I.EQ.NTS)WRITE(16,260)FE,RPM
  260 FORMAT(/20H FLYWHEEL ENERGY =   ,G15.5/15H FLYWHEEL RPM =,G15.5)
      XFS = (2.*FE / FIN)**.5
      RETURN
      END
      FUNCTION CVTEF(RPS,RATIO,TORQUE,TORRAT,SPINT,CREEP,VISC,SPEED)
C   THIS FUNCTION GIVES THE EFFICIENCY OF A CONTINUOUSLY VARIABLE
C   TRANSMISSION.
C   RPS IS SPEED OF INPUT IN RADIANS PER SECOND.
C   TORQUE IS IN NEWTON-METERS.
C  TORRAT IS RATED TORQUE.
C   SPINT IS SPIN TORQUE IN PERCENT OF RATED TORQUE.
C   CREEP IS PERCENT CREEP AT RATED TORQUE.
C   VISC IS DRAG PROPORTIONAL TO SPEED AS PERCENT OF RATED TORQUE AT MAX
C   SPEED
C   SPEED IS RATED SPEED IN RADIAN PER SECOND
C   MAX TORQUE IS 2.* RATED TORQUE.
      IF(TORQUE.EQ.0.) GO TO 100
      DET = VISC*TORRAT/100./SPEED
      B = (2./RATIO)/(2.-SPINT/100.)
      TORQUA = ABS(TORQUE)
      TORQA=(TORQUA - DET*RPS - SPINT*TORRAT/100.)*B
      TORQI = TORQUA / RATIO
      IF(TORQA.LE.0.) TORQA = .25*TORQI
      TOREF = TORQA/TORQI
      CREEPA = CREEP*TORQUA/(TORRAT*100.)
      SPEFF = 1.-CREEPA
      CVTEF=TOREF*SPEFF
      RETURN
  100 CVTEF = 1.
      RETURN
      END
      SUBROUTINE PMDC(BCUR)
      COMMON /A/ A,AF,BSE,BV,CD,    DT,FC(20,150),FSE,JFLAG,MHP,P,
     1PDMAX,PD,RPMAX,SUMBER,SUMFC,SUMFER,VA,VN,VT
     2,SUMBE,SUMFEP,SUMFEN,PICE,PDD,PFY,PB,HPD,FQ,EHD,DELFC,PBAR
      COMMON /B/ IX1,IX2,NTS,RANGE,SUMD,VC,TOTE,XMPG
      COMMON /C/ WBAS,WPAY,WTEST,WPROP,WAX,WMOT,WTCBM,WTCGM,WB,WV,WF,
     1WGEN,WTXM,WGRDS,WCURB,TESTW,WPS,ROTI,WCBM,WCGM
      COMMON /D/ ODA,RHOA,RADIUS,C0,C1,C2,RATIO,TAXL,A0,A1,A2,RPR,SPEEDI
     1,SPEEDA,DLOAD,RVT,CURDM,WBAR,EFFDM,RI2,HYSTI,EDI,BFI,WNDI,FREQ,
     2PCBM,VCBMIN,VCBMOT,CBMCUR,CBMFRQ,CBMO,CBM1,CBM2,PCGM,VCGMIN,VCGMOT
     3,CGMCUR,CGMFRQ,CGMO,CGM1,CGM2,EBARM,PBARM,EFFB,XFSM,RUND,GRPR,
     4GSPD1,GSPD2,GOLD,GRVT,GCUR,GBAR,EFFDG,GRI2,GHYSTI,GEDI,GBRI,GWNDI
     5,GFREQ,TXMR1,TXMR2,TXMR3,TXA0,TXA1,TXA2,TXBAR,TXMTQ
      COMMON /E/ COSTDM,COSTAX,COSTB,COSTF,COSTCB,COSTCG,COSTG,COSTXM
      COMMON /F/ PSA(1390),NFLAG,IX3,FAMP(1390),VLG,VSG,VHG
      DIMENSION         IX1(16),IX2(16),IX3(16),V1(1390),BAMP(1390)
C   THIS ROUTINE CALCULATES THE CURRENT AND POWER FOR A SHUNT WOUND
C   SEPARATELY EXCITED DC MOTOR.
C   SET INITIAL VALUES OF CIRCUIT AND MOTOR CONSTANTS
      DIMENSION GRA(4)
      FLUF(X) = (5.7*(TANH(.18226*X))+ .1033*X + .5)
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      AX1(X,Y) =(SQRT((X*4.*.1033*6./Y)+38.44) -6.2)*Y/1.2396
      AX2(X,Y) = (SQRT((X*4.*6.85309/Y)+.25) -.5)*Y/13.7062
      AX3(X,Y,Z) = (X/3600.)*((Y/Z)**1.6)
      AX4(X,Y,Z) = ((X*Y)/(3600.*Z))**2
      IF(VA.EQ.0.) GO TO 1000
      IF(SUMO.NE.0.) GO TO 40
      NNP = 0
C  PUT WRITE ROUTINE HERE FOR CANDIDATES
      WRITE(26,134) IX1
  134 FORMAT (1H1,1X,16A5)
      WRITE(26,140)TESTW,WB,RATIO,TXMR1,TXMR2,TXMR3,RPR
  140 FORMAT(/1X,23HVEHICLE TEST WEIGHT    =   ,F8.2,7H POUND
     1/1X,23HBATTERY WEIGHT         =   ,F8.2,7H POUNDS
     2/1X,23HAXLE RATIO              =  ,F8.4
     3/1X,23HTRANS.    HIGH GEAR    =   ,F8.4
     4/1X,23H RATIO    SEC. GEAR    =   ,F8.4
     5/1X,23H          LOW   GEAR =     ,F8.4
     6/1X,23HMOTOR RATED POWER      =   ,F8.1)
      WRITE(36,136)
  136 FORMAT(2X,45H CANDIDATE NO. 2 SEPARATELY EXCITED DC MOTOR.     ,
     127H VERSION OF JAN. 4, 1979.     ,3HECY   )
      X = 6.
      ACCUM = 0.
      GRA(3) =   60./( 2.*3.14159*RADIUS/12.)
      GRA(3) = GRA(3) * RATIO
      GRA(2) = GRA(3) * TXMR2
      GRA(1) = GRA(3) * TXMR3
      GRA(3) = GRA(3) * TXMR1
      GRA(4) = 15.
      RESFL= 7.018
      BRES = CBM2
      XLOSS = RPR*(100./EFFDM - 1.)
C  SET FIELD RESISTANCE TO GIVE FIELD I**2*R LOSSES OF .15 OF TOTAL I2R
      XR = .15
      RES = (XLOSS*RI2/100.)
      FIR = XR*RES/RVT
      CURDM =  (RPR+XLOSS)/RVT
      ACX = CURDM - FIR
      RES =  (1.-XR)*RES/(ACX**2)
      XCUR = ACX
      BVX = EV-RES*ACX-CBM1
      FLX =  BVX/(SPEEDI*FLUF(X))
      FLUX = FLX*FLUF(X)
      FLXD = FLUX
      FLX2 = FLX*SQRT(.250026)
      FQ = ACX
      AMAX = OLOAD*FQ/100.
      RESFL = RVT/FIR
      HYSX = (XLOSS*HYSTI/100.)/AX3(SPEEDI,FLUX,FLXD)
      WNDX = (XLOSS*WNDI/100.)/((SPEEDI/3600.)**2)
      EDX =  (XLOSS*EDI/100.)/AX4(SPEEDI,FLUX,FLXD)
      BFX = (XLOSS*BFI/100.)/(SPEEDI/3600.)
      FIRX = 1.8*FIR
      FCRZ = 3.*FIR
C  FIND SHIFT POINT
C
C  PRINT MOTOR CHARACTERISTICS.
C
      WRITE(16,980)
      WRITE(16,982)
  980 FORMAT(///23H MOTOR CHARACTERISTICS. /17H  CANDIDATE NO. 2    /)
  982 FORMAT(3X,15H  RATED POWER     ,17H       VOLTAGE      ,15H ARM. CURRE
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     1NT    ,17H FIELD CURRENT    ,15H SPEED   RPM     ,15H ARM. RESIST
     2, 15H FIELD RESIST   , 15H FLUX FACTOR       )
      KVT=BV
      KCUR = FQ
      REC = FIR
      RESA = RES
      BASS = SPEEDI
      RESF = RESFL
      RX = X
      WRITE(16,984) FPK,KVT,KCUR,REC,BASS,RESA,RESF,RX
      WRITE(16,989)
  989 FORMAT(// 19H BEARING FRICTION   ,16H EDDY CURRENT      ,
     115H   HYSTERESIS    ,11H WINDAGE    ,19H    FLUX CONSTANT
      WND1=XLOSS*WNDI/100.
      HYS1=XLOSS*HYSTI/100.
      ED1= XLOSS*EDI/100.
      BF1 =XLOSS*BFI/100.
      WRITE(16,984)BF1,ED1,HYS1,WND1,FLX
  984 FORMAT(1X,8F15.6 )
      WRITE(16,126) IX2
  126 FORMAT (/1X,16A5)
      WRITE(16,132)
  132 FORMAT (//1X,50HACCUM. VEHICLE GEAR ROAD   MOTOR   MOTOR  MOTOR
     1,62HARMTR  MOTOR   EDDY   HYST  WINDAGE FRICT CNTR. BATTERY BATT  MO
     3,18HTOR    OVERL  ACCUM /
     31X,60HDIST    SPEED          POWER  POWER   SPEED  VOLTAGE CURR   I*I
     4,60H*R  CURR  LOSS   LOSS    LOSS    LOSS    POWER    CURR   EFFIC EF
     5,11HFIC   ENERGY /
     61X,60HMILES   FT/SEC         WATTS   WATTS    RPM     VOLTS    AMPS    WAT
     6,1HT
     7,60HS  WATTS WATTS   WATTS   WATTS   WATTS   WATTS    AMPS   PERCT PER
     8,9HCT   W*HRS     )
   40 CONTINUE
      N= 1
      IF(VA.GT.VHG) GO TO 10
      IF(VA.GT.VSG)  GO TO 20
      NG=1
      GO TO 30
   10 NG=3
      GO TO 30
   20 NG=2
C UPSHIFT IF ACCELERATION IS EQUAL TO ZERO.
      IF(A.EQ.0.) NG = 3
   30 CONTINUE
C   SET RPM AND DRIVE LINE MECHANICAL LOSSES
      NX=NG
      RPM=VA*GRA(3)/TXMR1
      PA  = PD
      DTOR = A0 + (RPM*A1) + ((ABS(PD))*60.0/(1.356*2.*3.14159*RPM)*A2)
      AXPR = (DTOR*RPM*2.*3.14159/60.)*1.356
      PDI  = PA + AXPR
      RPMX = RPM
      RPM=VA*GRA(NG)
      TMPR=TXA0+(RPM*TXA1)+(ABS(PDI)*60./(1.356*2.*3.14159*RPM)*TXA2)
      TMPR = TMPR*(1.+RPM/RPMX)*.5
      TMPR=(TMPR*RPM*2.*3.14159/60.)*1.356
      PDI=PDI+TMPR-XMPG
      PDIM = PDI
      PDX=BFX*RPM/3600.
      BFXM = PDX
      PDX =PDX + (WNDX*((RPM/3600.)**2))
      WNDXM = PDX - BFXM
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      PDI=PDI+PDX
      BVX =BV - CBM1
      IF ( RPM.LT.SPEEDI) BVX = 1.1*BVX*RPM/SPEEDI
      PMMX = 2.1 * RPR
      IF (RPM.LT.SPEEDI) PMMX = 2.1*RPM/SPEEDI*RPR
      IF(PDI.GT.PMMX) WRITE(16,901) PDI,PMMX
C   FIND ELECTRICAL MOTOR CURRENT AND IRON LOSSES
      IF(PDI.LT.0.) GO TO 200
C   TRIAL VALUE OF FIELD CURRENT AND ITERATION FOR ARMATURE CURRENT
  270 FLUX = ABS(BVX-((RES+BRES)*PDI/BVX))/RPM
      N=1
  260 FCR = FCUR(FLUX,FIR,FLX)
      IF(FCR.GT.FCRZ) FCR = 1.001*FCRZ
      IF(FCR.GT. CRZ) FLUX = FLX*(FLUF(6.*FCR/FIR))
      XLUX = ABS(FLUX)
      HYST = HYSX*AX3(RPM,XLUX,FLXD)
      EDDY = EDX *AX4(RPM,XLUX,FLXD)
      PDX = PDI + HYST + EDDY
      N=N+1
      IF(N.GT.30) GO TO 245
      IF(FLUX.GT.0.) XCUR = PDX/(RPM*FLUX)
      IF(XCUR.GT.AMAX) XCUR= 1.01*AMAX
      BVA = BVX-(RES+BRES)*(XCUR)
      IF(BVA..E.0.) BVA = (.9**N)*BVX
      XFLUX = BVA/RPM
      ER = FLUX-XFLUX
      IF(ABS(ER).LE. 1.E-09) GO TO 240
      FLUX = XFLUX
      GO TO 260
  245 CONTINUE
      IF(PDI.GT.10.*PMMX) GO TO 900
      IF(N.GT.32)CALL EXIT
  240 CONTINUE
      IF(FCR.LT.FCRX) GO TO 280
      NX = NX -1
      IF(NX.LE.0) GO TO 290
      RPM = VA*GRA(NX)
      BVX =BV - CBM1
      IF ( RPM..T.SPEEDI) BVX = 1.1*BVX*RPM/SPEEDI
      WRITE(16,920) NX
  920 FORMAT(20H SHIFT DOWN TO NG =      ,I3)
      GO TO 270
  290 BVX = BVX*.90
      NX = 1
      IF(BVX.LT..01) GO TO 280
      GO TO 270
  280 CONTINUE
      IF(ABS(XCUR).GT.AMAX) XCUR = XCUR*AMAX/ABS(XCUR)
      ACUR = XCUR
      IF(ABS(FCR).GT.FCRX)FCR=FCRX
      BCUR = XCUR + FCR
      X= BVX/BV
      XI2R = (XCUR**2)*RES+(FCR*BV)
      IF((X.LT. .25).AND.(PDX.LT.0.)) BCUR =0.
      GO TO 500
C    FIND VALUES FOR REGENERATION
  200 CONTINUE
      FLUX = FLX*(FLUF(1.6*6.))
      RPMM = VA*GRA(1)
      CEMFM = RPMM*FLUX
      XV = BV/2.
      IF(CEMFM..E.XV) GO TO 292
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      XC = ((ABS(PDI))/CEMFM)/1.04
      XV = XV + ((RES+BRES)*XC) +CBM1
      IF(CEMFM.LE.XV) GO TO 292
      GO TO 270
  292 WRITE(16,904) VA,PDI
  904 FORMAT(48H INADEQUATE COUNTER EMF TO PROVIDE REGENERATIVE ,
     123HBRAKING AT VELOCITY =    ,F7.3, 12H FT/SEC AND   ,F15.2,6H WATTS)
      BCUR = 0.
  500 CONTINUE
      IF((BCUR.GT.0.).AND.(PD.LT.1.5)) BCUR = 0.
      IF(RES..E.0.) BCUR=-BCUR
      PB = PDIM + XI2R + EDDY + HYST + WNDXM + BFXM
      PBA = PB
C   SET POWER LOSS FOR CONTROLLER
C     PBX=JUNCTION LOSS,PBASE=BASE JUNCTION LOSS,PSWT=SWITCHING LOSS
      PBX=CBM0+ABS(CBM1*BCUR)+(((BM2*BCUR**2)/4)
      PBASE=(.8+.02*(BCUR/40))*BCUR/5
      PSWT=BCUR*BV*1.6/1000.
      PBX=(PBX+PBASE+PSWT)*1.2
      PB = PB + PBX
      BCUR = PB/BV
      PBAR = PB / WB
      IF(RES..E.0.) PBAR = -PBAR
      IF(PB.EQ.0.) PB =1.E-08
      IF(PD.EQ.0.) PD =1.E-08
      IF(ACUR.GT.AMAX) WRITE(16,901)
          SUMD=SUMD+VA*DT/5280.
      IF(PDIM.EQ.0.) PDIM = 1.E-08
      IF(PBA.EQ.0.) PBA = 1.E-08
      XMEFF = 100.*PDIM/PBA
      XOEFF = 100.*PD/PB
      IF  (PD.LT.0.) XOEFF = 100.*PB/PD
      IF(PDIM.LT.0.) XMEFF=100.*PBA/PDIM
      ACCUM = ACCUM + PB*DT/3600.
      IF(MOD(NNP,36).NE.0) GO TO 248
      WRITE(16,134) IX1
      WRITE(16,126) IX2
      WRITE(16,140)TESTW,WB,RATIO,TXMR1,TXMR2,TXMR3,RPR
      WRITE (16,132)
  248 CONTINUE
      NNP = NNP + 1
      WRITE (16,138) SUMD,VA,NX,PD,PDIM,RPM,BVX,ACUR,XI2R,EDDY,HYST,
     1WNDXM,BFXM,PBX,PB,BCUR,XMEFF,XOEFF,ACCUM
  138 FORMAT(1X,1F6.4,1F8.3,I3,1X,3F8.0,1X,2F6.1,3X,6F6.0,1F8.0,1F7.1
     1,1X ,2F6.2,1F9.2 )
      FQ = ACX
  960 RETURN
 1000 BCUR=0.
      RPM = 0.
      ACUR =0.
      PDIM = 0.
      BVX = 0.
      XI2R = 0.
      EDDY = 0.
      HYST = 0.
      WNDXM = 0.
      BFXM = 0.
      GO TO 500
  900 WRITE(16,901)  PDI,PMMX,RPM
  901 FORMAT(1X,25HEXCESSIVE POWER REQUIRED   ,16H PDI AND PMMX =   ,4E15.
     15)
      A = .98 * A
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      VN = VT + A*DT
      VA = (VT+VN) / 2.
      JFLAG = 1 + JFLAG
      GO TO 9..
      END
      FUNCTION FCUR(FLUX,FIR,FLX)
C     THIS FUNTION GIVES THE FIELD CURRENT
C     THIS FUNCTION GIVES THE FIELD CURRENT REQUIRED FOR
C   A GIVEN FLUX
      FLXX(X) = 5.7*TANH(.13226*X) +.1033*X + .5
      AX1(X,Y) = (X-.5)*Y/((5.7*.13226+.1033)*6.)
      AX2(X,Y) = (X-6.2)*Y/(.1033*6.)
      FL = FLUX/FLX
      IF(FL.LT. 6.9) GO TO 100
      FCUR = AX2(FL,FIR)
      GO TO 120
  100 FCUR = AX1(FL,FIR)
  120  FX    = FCUR*6./FIR
  160 FLT = FLXX(FX)
      ER = FL-FLT
      IF(FL.LT.5.) GO TO 130
      FX = FX+((ER*FX/(FLT-3.)))
      GO TO 140
  130 FX = FX +((ER*FX/(FLT-.5)))
  140 IF(ABS(ER).LT.1.E-09) GO TO 150
      GO TO 160
  150 FCUR = FX*FIR/6.
      RETURN
      END
  ADVANCED EV PROPULSION SYSTEM CONCEPT A6 SINGLE MOTOR /DR.AXLE W/TRANS. WF AC1
  718.67    600.00    300.      1.299      6.0       .00238     1.04
   11.5     .008      1.0970E-05 9.630E-08 19.      31.        76.
  7.2565     59.       250.      1.50      .1248    .2495E-04  .0066
  25.00E+03 7200.     9000.     375.       96.      194.       .0050      96.
  67.       5.        10.       9.        9.        240.      .02        .84
  45.00E+03 240.      233.      388.      240.      .001024
  10.       .24       .0058     210.
  40.00E+03 241.      238.      388.      240.      .001031
  123.      3.75      .006      250.
   96.      15.       20.       900.      2.5       55.
   29.18    35.26     46316.    4.        500.
  30.00E+03 23158.    46316.    200.      241.      196.       .0062      93.
  45.       5.        5.        5.        40.       666.6      5.5
   1.000    1.74      3.86      .4158-01  .083E-05  .222E-01   50.        275.
  ADVANCED EV PROP. SYST. CONCEPT D2 ONE MOTOR/BUFFER W/CVT ONE AXLE DRIVE  DC1
  718.67    600.00    300.      1.299      6.0       .00238     1.04
   11.5     .008      1.0970E-05 9.630E-08 19.      34.        76.
  5.4444     59.       250.      1.50      .1666    .3333E-04  .006666
  26.00E+03 5400.     7300.     200.       96.      207.       .0055      90.4
  57.       5.        8.        13.       7.        180.      4.5
  29.00E+03 240.      238.      414.      180.      .0012
  10.       .24       .0258     210.
  45.00E+03 241.      238.      425.      180.      .0015
  150.      3.75      .006      250.
   96.      15.       20.       1175.     2.5       55.
   29.18    35.26     46316.    4.        500.
  34.00E+03 23158.    46316.    200.      241.      196.       .0208      92.
   60.      7.        6.        5.        3.         90.       4.5
   1.000    1.74      3.86      .555E-01  .111E-05  .222E-01   50.        275.
    SAE J227 DRIVING CYCLE  45 MPH CRUISE CONDITION APPROX. CONST. POWER ACCEL.
   122.
   3.54    7.08    10.62    14.16    17.70    21.24    24.78    28.32    31.86    35.4
```

37.756	39.973	42.075	44.076	45.990	47.827	49.597	51.305	52.958	54.562
56.119	57.634	59.111	60.551	61.959	63.334	64.681	66.00	66.00	66.00
66.	66.	66.	66.	66.	66.	66.	66.	66.	66.
66.	66.	66.	66.	66.	66.	66.	66.	66.	66.
66.	66.	66.	66.	66.	66.	66.	66.	66.	66.
66.	66.	66.	66.	66.	66.	66.	66.	66.	66.
66.00	66.00	66.00	66.00	66.00	66.00	66.00	66.00	65.109	64.230
63.362	62.505	61.658	60.822	59.995	59.178	58.371	57.573	51.176	44.779
38.382	31.985	25.588	19.191	12.794	6.397				
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
0.	0.								

2.

ACCELERATION FROM 0 TO 55 MPH IN 15 SECONDS.

30.	.5								
3.766	7.533	11.3	15.067	18.833	22.6	26.367	30.133	33.9	37.567
40.905	43.905	46.712	49.360	51.874	54.271	56.566	58.772	60.898	62.952
64.942	66.872	68.748	70.573	72.354	74.091	75.789	77.449	79.074	80.667

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16. Abstract

A study for evaluation of advanced electric propulsion system concepts with flywheels for electric vehicles predicts that advanced systems can provide considerable performance improvement over existing electric propulsion systems with little or no cost penalty. Using components specifically designed for an integrated electric propulsion system avoids the compromises that frequently leads to a loss of efficiency and to inefficient utilization of space and weight. A propulsion system using a flywheel power energy storage device can provide excellent acceleration under adverse conditions of battery degradation due either to very low temperatures or high degrees of discharge. Both electrical and mechanical means of transfer of energy to and from the flywheel appear attractive; however, development work is required to establish the safe limits of speed and energy storage for advanced flywheel designs and to achieve the optimum efficiency of energy transfer. Brushless traction motor designs using either electronic commutation schemes or dc-to-ac inverters appear to provide a practical approach to a mass producible motor, with excellent efficiency and light weight. No comparisons were made with advanced system concepts which do not incorporate a flywheel.

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