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FUEL CELL SYSTEMS FOR VEHICULAR APPLICATIONS*

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I. BACKGROUND

In the consideration of energy-saving high-efficiency transportation alternatives, fuel-cell-powered vehicles appear to hold great promise. Fuel cells are both highly efficient (fuel cells with 50% thermal efficiency have been demonstrated) and nonpolluting (water is the main by-product).

Expenditures on fuel cells for space and utility applications during the past few years have led to dramatic improvements in fuel cell performance.

In August 1977, a fuel-cell-powered vehicle workshop was held at the Los Alamos Scientific Laboratory (LASL). Representatives from the fuel cell industry, automotive industry, national laboratories, and universities met to consider the application of fuel cells to vehicular transportation. The primary vehicle considered was the fuel cell/battery-hybrid vehicle (Fig. 1) in which the fuel cells are paralleled by batteries. The fuel cell is used for cruising power and battery recharge. The batteries supply transient power for acceleration. This configuration obtains performance not unlike that of a modern internal-combustion-engine-(ICE) powered vehicle, while providing large increases in overall efficiency. A reformer provides the hydrogen for the fuel cell from a hydrocarbon fuel; for example, methanol that can be obtained from coal.

Although it was agreed at the workshop that the fuel-cell-powered vehicle does indeed hold great promise, it was also concluded that a more detailed evaluation should be undertaken.

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A recent paper presented at the 14th Energy Conversion Engineering Conference[1] describes the results of a joint program between Brookhaven, US Army MERADCOM, and LASL in which various vehicular applications of fuel cells were evaluated for both technical feasibility and economic potential.

II. ECONOMIC EVALUATIONS SUMMARY

Because it is currently the most developed technologically, the phosphoric acid fuel cell (PAFC) was used as the base line in these evaluations. Data on representative fuel cell systems, utilizing current technology was derived by Energy Research Corporation (ERC).

Two cell sizes (15 and 60 kW) and two fuel options, methanol and propane were included. Figure 2 is a schematic of the 15-kW system. Detailed performance specifications are presented in Sec. III.

Four vehicle types, the city bus, highway bus, delivery van, and general-purpose consumer car were selected for evaluation. Typical drive cycles and economics for these vehicles were gathered, and comparisons were made between the fuel cell vehicle and current internal combustion and diesel engine vehicles. The conclusions of these evaluations are briefly related in the following four subsections.

A. City Bus

In considering possible fuel-cell-powered vehicle applications, the city bus is found to have a number of attractive features as follows:

The procurement cost of a city bus is 80% subsidized by the Federal Government. Therefore, the increased costs in using a high-priced fuel cell (premass production) are less important to the user. In total dollar outlay, the cost of fuel and maintenance tends to dominate the procurement costs. Also, because of particulate pollution and exhaust smells usually associated with city buses, pollution is a serious consideration.

Initial vehicle specifications were based on performance of a current diesel-powered 26,000-lb, 40-ft bus.

Because of the diverse and often inconsistent nature of the drive cycle data available, this report contains a number of "apples and oranges" comparisons, which were "worst cased" whenever possible. In general, the results derived suggest the potential technical and economic feasibility of a fuel-cell-powered city bus.

The battery of choice for the hybrid configuration was the nickel/zinc due to the limited charge rate of a lead-acid cell.

Generally, the city bus is perceived as a good application for fuel cells. This application represents a market of 5000 vehicles per year (in excess of $100,000 each), which would increase the manufacture of fuel cells in a reasonable increment without demanding ultimate mass production costs.

Several fuels were considered. Propane is the most practical in the near term. Diesel fuel was ruled out because of its high sulfur content. It was also pointed out that in the future, as petroleum costs increase (1990), methanol should become an important alternative.

Using the ERC data for a 60-kW phosphoric acid fuel cell, a modest weight decrease was noted and volumetric feasibility was demonstrated.

Fuel cost savings were projected for the 1990s using methanol. Moreover, the costs of fuel, maintenance, and bus procurement were found to be small when compared with the total costs of running a bus line. From this point of view, it was speculated that the future motivations for a fuel-cell-powered bus might well be based on fuel availability.

Furthermore, the visibility of the application is seen as a long-term benefit in demonstrating the value of fuel cells and fuel-cell-powered vehicles.

B. Highway Bus

Technically, the highway bus appears to be an excellent application for fuel cells. The available volume is more than adequate to accommodate a fuel cell/reformer system and the relative weight increase caused by such a system is small.

Vehicle procurement costs would be increased from $120,000 per diesel vehicle today to $145,226 (1978 dollars). At current fuel costs a propane-fueled fuel cell bus would cost a modest 0.47 ¢/mile more to operate. In 1990, the fuel cell bus running on methanol would save 1.56 ¢/mile in fuel costs.

The fuel savings in 1990 over a million mile lifetime could save $15,600 of the procurement differential. These savings, when combined with reduced maintenance costs, could save between $29,000 and $49,000 over the vehicle life.

The primary problem in making projections for the highway bus is lack of experience with the fuel cell in a vehicular environment. For example, the utility application has projected a 40,000-h fuel cell lifetime. If this lifetime were achieved in a highway bus, it would be over twice the lifetime of current buses.

These results, independent of the long lifetime potential, suggest that the fuel-cell-powered bus and large highway truck could be an economically and technically viable option in the 1990 time frame.

C. Consumer Vehicle

A sample fuel-cell-powered consumer car was evaluated. A Volkswagen Rabbit was used as a base line vehicle for comparison purposes between the ICE, diesel engine, and fuel cell. A 15-kW fuel cell version provided performance comparable to that of the diesel Rabbit. Four kilowatt-hours of lead acid battery were used for cold start at 0°F. (Conservatively, it was assumed that the vehicle would be able to cruise at 55 mph on the battery power only for the entire 10 min required for fuel cell start up.)

The entire system, fuel cell, methanol reformer, motor, and batteries were found to fit under the hood of a current Rabbit. The propane system was found to be too large.

The weight of the vehicle was increased by 622 lb; 281 of the extra pounds are accounted for by the batteries. A more detailed description of the effects of weight and batteries and the engineering tradeoffs involved is presented in Sec. III.

Using cost and vehicle mark-up data derived from several sources, including Ford Motor Company, DOT, and Volkswagen, and assuming $200/kW for the fuel cell/reformer system, a fuel-cell-powered Rabbit was projected to have a sticker price of $7239.33.

Fuel consumption was calculated for both 55-mph cruise and the J227 metropolitan drive cycle. Substantial improvements in vehicle system efficiency were found; however, with the projected fuel costs for 1990, no clearcut economic advantage based on fuel savings was found. It was projected that reduced maintenance costs and reliability could be extremely favorable factors in the marketplace.

Throughout this analysis, the question of consumer buying preferences was addressed. It was observed that simple utility appears not to be the dominant factor in consumer preferences. As a result, it was felt that the low noise, low pollution, and reliability of the fuel cell electric car could play important roles in consumer acceptance.

This evaluation produced surprisingly positive results. It did not show that fuel cells were immediate replacements for the internal combustion and diesel engines, but it did demonstrate that a fuel-cell-powered consumer car could be a viable option in the future.

D. Delivery Van

A conventional battery electric vehicle with fuel cell augmentation for on-board recharging was found to be the most promising configuration for a delivery van. Unfortunately, data on delivery van drive cycles are difficult to obtain; therefore, no detailed analysis or preliminary system design was performed. It was concluded, however, that a fuel cell van of the type described should be significantly more efficient than a comparable internal-combustion-engine-powered vehicle. This configuration would also increase the range and number of possible applications for electric delivery vans. Reduced maintenance was suggested as an economic incentive for the development of the vehicle. Maintenance cost reductions (30 to 40%) for battery-powered electric vans have already been demonstrated by the Bell System and the United Parcel Service. Further reductions in maintenance are expected with the addition of the fuel cell, as batteries represent a majority of the maintenance costs in conventional electric vans. The fuel cell not only reduces the number of batteries, but maintains a voltage across the cells, thus prohibiting deep discharge. (This subject will be addressed again in Sec. III.)

It should be noted that the conclusions drawn for the fuel-cell-enhanced delivery van concept might well be extended to a fuel-cell-enhanced urban commuter car.

E. Economic Conclusions

The results of the economic analysis of the four target vehicles strongly suggests the feasibility of the fuel cell vehicle in the

1990s. It should be emphasized that no fuel cell, battery, motor, or vehicle aerodynamic performance improvements were projected in making these assessments.

Technical feasibility was demonstrated in each of the four vehicles studied. Economic viability was more difficult to prove because of the scarcity of uniform vehicular performance, duty cycle, and economic data, and the lack of experience with fuel cells in the vehicular environment. However, since conservative rather than optimistic estimates were used in the analysis, first-order economic viability in the 1990s time frame was predicted.

III. SYSTEMS ANALYSIS

Although the fuel cell/battery-powered electric vehicle has been shown to have the potential for achieving performance similar to that of an ICE-powered automobile, it must be stated at the outset that the ICE automobile has set diffucult standards. Years of evolution and experience have led to the reliable, economic, high-performance vehicle consumers have come to expect. It is evident, therefore, that a fuel cell vehicle, or any other alternative for that matter, will have to be carefully designed with particular emphasis given to understanding the subtleties of various design tradeoffs.

The remaining sections of this report describe initial results of two aspects of the fuel-cell-powered vehicle evaluation program ongoing at LASL. The first section utilizes the results of detailed computer simulations to illustrate a number of the important system design considerations in configuring a fuel cell/battery electric vehicle. The second section describes a fuel-cell-powered golf cart currently being used as an engineering test bed. Although detailed tests are still being run, this section will briefly describe the hardware as it is implemented.

A. A Fuel Cell System for a Passenger Vehicle

This section describes a number of design considerations for a highway passenger vehicle. The design uses today's fuel cell, battery, and electric motor technology. The body and chassis of a General Motors

X car are used because of its five-passenger configuration and low rolling friction (0.0114 lb/lb) and aerodynamic drag ($C_d = 0.417$).*

Data for a 15 kW, methanol-fueled, phosphoric acid fuel cell with a methanol reformer was supplied by Energy Research Corporation. The voltage-current characteristics and fuel consumption are shown in Fig. 3. Table I lists some additional data. The power level of the fuel cell used in the calculations is scaled from 15 kW by changing the number of cells and the cell area. The weight and volume must also be adjusted accordingly.

The motor selected is a dc series-wound 20-hp Prestolite. The motor characteristics were provided by Prestolite and are given in Fig. 4.

The lead-acid battery characteristics shown in Figs. 5 and 6 were obtained from Kordesch.[2] Figure 5 shows the normalized voltage current characteristics for charge and discharge with per cent charge as a parameter. Figure 6 shows the available capacity vs discharge current as well as the function ($\hat{C}_2$) used as an approximation to the experimental data.

Table II is a simplified list of some of the vehicle design considerations. The actual design is an iterative process dependent on detailed component characteristics. To begin with, it is evident that the continuous power rating of the motor must be adequate to maintain highway cruise speed, and that the fuel cell must be able to supply the input power required by the motor under cruise conditions. The battery capacity must be sufficient to supply power during fuel cell start up. The batteries also supply additional power for acceleration and hill climbing.

Figure 7 shows the performance of the Prestolite 20-HP motor when the power is supplied by a 20-kW, 160 cell, 1.39 sq ft/cell fuel cell stack paralleled by a 48-cell, 4.8 kWh (20-h rate) lead-acid battery. The top curve shows motor output power with field weakening (field weakening resistor = field resistance = 0.0098 Ω). The next curve is for the

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*Data from Robert H. Nelson, GM Research Labs, and General Motors Product Information Group.

controller bypassed and the power source connected directly across the motor. The lower curve is the full throttle output power of the source-controller motor combination. The controller has a 500-A current limit and 0.02 Ω, series resistance. Figure 8 shows the full throttle, fourth gear wheel power obtained from the fuel cell, battery, controller, motor combination with a 70.0 rpm/mph drive train. The controller has a 500-A current limit and allows bypass when the motor current drops below the current limit. Figure 8 also shows the vehicle power required to maintain a constant velocity. Note that motor power (either field weakened or a nonfield weakened) crosses the required power at a steep angle, projecting a well-defined top speed. The final drive ratio determines the speed at which the wheel power and required power intersect and therefore determines top speed. Increasing the ratio rpm/mph reduces the top speed but increases motor efficiency at this speed because of the higher rpm.

Another important consideration is the V - I (polarization) characteristic of the fuel cell and the electrical interaction of the fuel cell, battery, and motor. For a given power level, the fuel cell voltage can be increased by increasing the number of cells and decreasing the area. However, this increases the fuel cell current density, which decreases efficiency. A higher system voltage reduces current levels but requires more batteries in series, which can produce a weight penalty. In addition, the role of the fuel cell in maintaining a minimum battery charge during cruise must be considered. Figure 9 shows the power level that can be maintained from a 20-kW fuel cell paralleled by a 48-cell battery with zero battery current, as a function of battery charge. This figure, in effect, specifies the power level that can be maintained without further discharge of the battery. For example, a 160-cell fuel cell, 48-cell battery system can supply 20 kW continuously without discharging the batteries below 58%. If the stack were reduced to 140 cells, the batteries would be discharged to below 10% when the system supplies 10 kW. For a 180-cell stack, the batteries would not be utilized until the system power level went above 26.5 kW. At power levels below 26.5 kW with 100% charge, the fuel cell would supply current to the batteries, thus wasting energy. Figure 9 indicates that a 20-kW, 160-cell stack and a 48-cell lead-acid battery represents a good power source for an electric vehicle with power requirements near 20 kW.

The results of the computer simulation for two vehicles based on the General Motors X car but with different performance characteristics are given in Table III. The first is designed to cruise at 60 mph and has a top speed of 68 mph. The second is designed to cruise at 70 mph and has a top speed of 78 mph. Note that the higher powered vehicle does not have the fastest 0-50 mph time. This is because of the added weight of the larger fuel cell system and emphasizes the importance of weight. Indeed, both vehicles are heavier than one might wish, and both would benefit greatly from possible weight reductions in fuel cells, batteries, and electric motors.

The acceleration times in Table III are obtained by shifting at 4000 rpm. Figure 10 shows the 0-50 mph time as a function of shift point. The rapid rise in 0-50 time at higher shift points results from the sharp decline in motor power at higher rpm shown in Fig. 7. For this example, shifting above 4000 rpm (3000 rpm without bypass) introduces a significant decline in acceleration performance.

The 60-mph cruise vehicle is used as a base line, and more details are given in Table IV. Table V summarizes the results of a number of permutations on the basic 60-mph vehicle. Increasing the number of cells in the stack from 160 to 180 reduces the top speed slightly. However, Fig. 9 shows that this configuration makes little use of the battery except for start up, and would tend to overcharge the batteries. Reducing the stack to 140 cells slows acceleration and slightly increases fuel consumption and top speed. But recall that, from Fig. 9, this configuration can discharge the batteries to less than 10% for sustained cruise.

Removing the transmission reduces the weight but slows the acceleration and increases fuel consumption for the J227 drive cycles because of reduced motor and drive-train efficiency at lower rpm. However, removing the transmission might be very attractive economically.

If the batteries are removed, the reduction in weight nearly compensates for the the reduced power. Only a minor increase in 0-50 mph time is observed (from 13.4 to 13.8 s). The weight reduction and elimination of the power losses in charging and discharging of the batteries also improves fuel economy. However, battery removal requires that the fuel cell be capable of a cold start, something that is not currently available with phosphoric acid cells. A more immediate improvement might result from lighter batteries, for example, nickel zinc.

These preliminary evaluations indicate that a fuel-cell-powered passenger vehicle with acceptable highway performance can be designed using existing fuel cell technology and currently available lead-acid batteries, series dc traction motors, and SCR chopper motor controllers. As advanced batteries, traction motors and controllers become available, and as fuel cell technology advances, substantial improvements in performance should be realized.

B. Golf Cart--Test Bed

In order to gain practical experience and to have at our disposal a test bed for evaluating the performance of a fuel-cell-based propulsion system in a vehicular environment, a fuel-cell-powered golf cart has been designed and constructed. Figure 11 is a photograph of the cart showing the fuel cell mounted behind the seat.

The fuel cell is an 80-cell, 2-kW, air-cooled, phosphoric acid fuel cell built by Energy Research Corporation. The fuel can be either reformed methanol or hydrogen; in this case hydrogen is used and is stored in aluminum scuba tanks on the rear of the vehicle. Figure 12 shows the V - I characteristics of the fuel cell. The batteries are four 12-V SGL 27 deep cycle traction batteries. These batteries, which total 4 kWh (20-h rate), allow separate testing in the all-battery mode. The fuel cell and batteries are coupled together through a diode, which prevents the battery from forcing current through the fuel cell in the reverse direction.

The motor is a 4-hp, General Electric series dc motor; the characteristics are shown in Fig. 13. This particular fuel cell, battery, motor combination is capable of peak outputs over 15 hp. The larger motor was used so that the fuel cell/battery power source can be stressed (through the use of load sleds if necessary). The original resistive controller that came with the golf cart was replaced by a Sevcon chopper controller large enough to supply power to a full sized car.

The design of the cart emphasized simple operation. For example, the cart features semiautomatic timing and sequencing for fuel cell start up and an automatic shutdown sequence. In addition, component protection has received considerable attention. As examples, insufficient fuel shuts down the fuel cell, as does too high an exhaust temperature. Also, a circuit that detects voltage imbalances between internal 11-cell substacks is included. Voltage imbalances indicate potential fuel cell problems such as a fuel starved cell, an abnormal internal temperature, cell reversal, or low fuel.

Figure 14 is a photograph of the fuel control system. The fuel flow is controlled by three solenoid-actuated valves. The fuel cell current is used as a control signal to actuate the solenoids. The fuel control system increases the hydrogen flow for each 10-A increment in fuel cell current. In addition, when the fuel cell current reaches 50 A, a second blower is turned on to increase the flow of cooling air.

The cart has operated smoothly and reliably through the initial check-out tests. The tests performed to date have verified initial performance expectations. Upcoming tests will include detailed evalation of the fuel cell-battery-controller-motor interactions. The system will also be tested under prolonged stress conditions to evaluate the effects of temperature and prolonged high-current operation.

IV. CONCLUSIONS

Based on the results of the economic analysis, system analysis, and actual performance of the golf cart test bed, the conclusions of this report reflect cautious optimism for the potential of fuel-cell-powered vehicles. The systems analyses have shown that the design tradeoffs must be performed carefully, not only in order to achieve vehicle performance, but also ultimately to achieve economic acceptability. The internal combustion engine has set a difficult standard. The message of this paper is that the fuel-cell-powered vehicle has potential but careful and systematic development with consideration of both technical and economic tradeoffs will be required if that potential is to be realized.

REFERENCES

1. J. Byron McCormick, Ronald E. Bobbett, David K. Lynn, Sam Nelson, Supramaniam Srinivasan, James McBreen, and Jim Huff, "Applications of Fuel Cells in Transportation," 14th Intersociety Energy Conversion Engineering Conference, Boston, Massachusetts, August 5-10, 1979.

2. Karl V. Kordesch, Ed., Batteries, (Marcel Dekker, Inc., New York, New York, 1977) Vol. 2.

TABLE I

ENERGY RESEARCH CORPORATION DATA

Name of company	Energy Research Corporation
Fuel cell type	Reformed methanol/air (H_3PO_4)
Size (kW)	15
Status	Conceptual design
Volume (displaced ft^3)	
Cell stack	6.4
Fuel processing	2.4
Thermal mngt. & heat recovery	0.1
Water recovery	None
Weight (lb)	
Cell stack	414.7
Fuel processing	97
Thermal mngt. & heat recovery	11.7
Operating conditions	
Temperature	350°F
Pressure	14.7 psia
Operating characteristics	
Electrode area (ft^2)	1.25
Design voltage	87
Design current	181

TABLE II

VEHICLE DESIGN CONSIDERATIONS

Component Parameter	Determining Factors
Continuous motor power	Cruise speed
Continuous fuel cell power	Cruise speed, motor, and drive train efficiency
Battery capacity	Fuel cell start-up time, additional power for acceleration and hills
System voltage	Power level, safety, battery capacity, desired performance
Battery cells	System voltage
Fuel cell stack cells	Minimum battery charge at cruise, efficiency
Final drive ratio	Cruise speed; combined motor, fuel cell, and battery characteristics

TABLE III

FUEL-CELL-POWERED GM X CAR

Weight (driver plus 1 passenger)	3637	3967
Final drive ratio	5.05	4.36
Rpm/mph (fourth gear)	70.0	61.0
Top speed (with field weakening)	68.3	78.0
Wheel power	25.9	36.7
Cruise wheel power	19.6 hp	28.0 hp
Fuel cell power	19.4 kW	27.4 kW
Miles per gallon of methanol*		
Acceleration to cruise**	21.3	17.5
At cruise	23.1	19.0
At top speed	21.2	16.8
J227 Residential	25.9	22.6
J227 Metropolitan	20.2	19.7
0-30 time	4.8 s	5.4 s
0-50 time	13.4 s	15.6 s
0-60 time	24.6 s	20.9 s
Average fuel cell efficiency	38.5%	38.5%
Average methanol-to-wheel power efficiency*	29.1%	29.5%

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*The high heating value of methanol is 18.9 kWh/gal, about half of the HHV for gasoline.

**Full power acceleration from zero to top speed, 1000 s, then decelerate to cruise speed, total time 5000 s.

TABLE IV

60-MPH CRUISE HIGHWAY FUEL-CELL-POWERED HIGHWAY VEHICLE

Cruise speed	60.8 mph
Maximum speed	68.3 mph
Motor	20 hp
Fuel cell	20 kW, 160 cells, 1.39 ft^2/cell
Battery	48 cells, 4.8 kWh (20-h rate)
Controller	500-A limit, bypass, field weakening
Weight	
Car (GM X car) - engine	2595 - 366 = 2229 lb
DC motor and controller	146
Fuel cell	680
Battery	264
Delta fuel	18
Driver plus 1 passenger	300
	3637 lb

Transmission -- 4 speed manual

Rpm/mph (fourth gear)	70.0

CdA = 0.417, hv = 0.0114 lb/lb

TABLE V

VARIATIONS ON 60-MPH VEHICLE

	Weight (lb)	Wheel Power (Cruise) (hp)	Fuel Cell Power (Cruise) (hp)	Top Speed (mph)	Wheel Power (Top Speed) (hp)	0-50 Mph Time (s)	Miles per Gallon of Methanol		
							Accel. to Cruise (5000 s)	J227 Res.	J227 Metro
60-mph cruise vehicle	3637	19.6	25.9	68.3	25.9	13.4	21.3	25.9	20.2
140-cell stack	3637	19.3	25.4	69.0	26.6	16.8	20.2		
180-cell stack	3637	19.2	25.5	67.2	24.9	13.3	21.4		
Without transmission	3491	19.5	25.8	68.5	25.8	16.8	21.4	20.1	15.7
Without batteries	3373	18.7	24.8	66.9	24.1	13.8	22.7	27.8	22.5
Without transmission and batteries	3227	18.6	24.7	67.1	24.0	16.3	22.8	22.7	19.0
70-mph cruise vehicle	3967	28.0	36.3	78.0	36.7	15.5	17.5	22.6	19.7

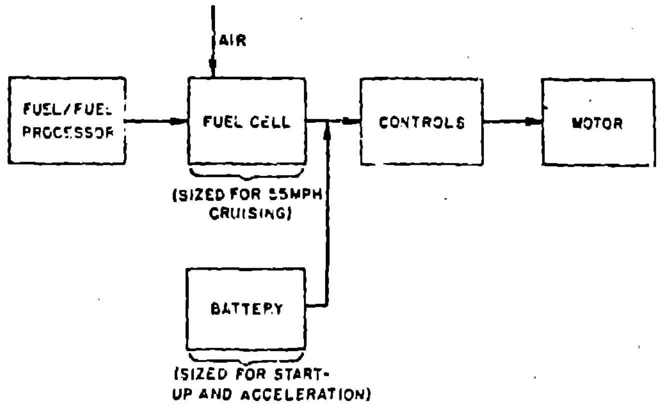

Fig. 1. - Fuel cell/battery-hybrid vehicle

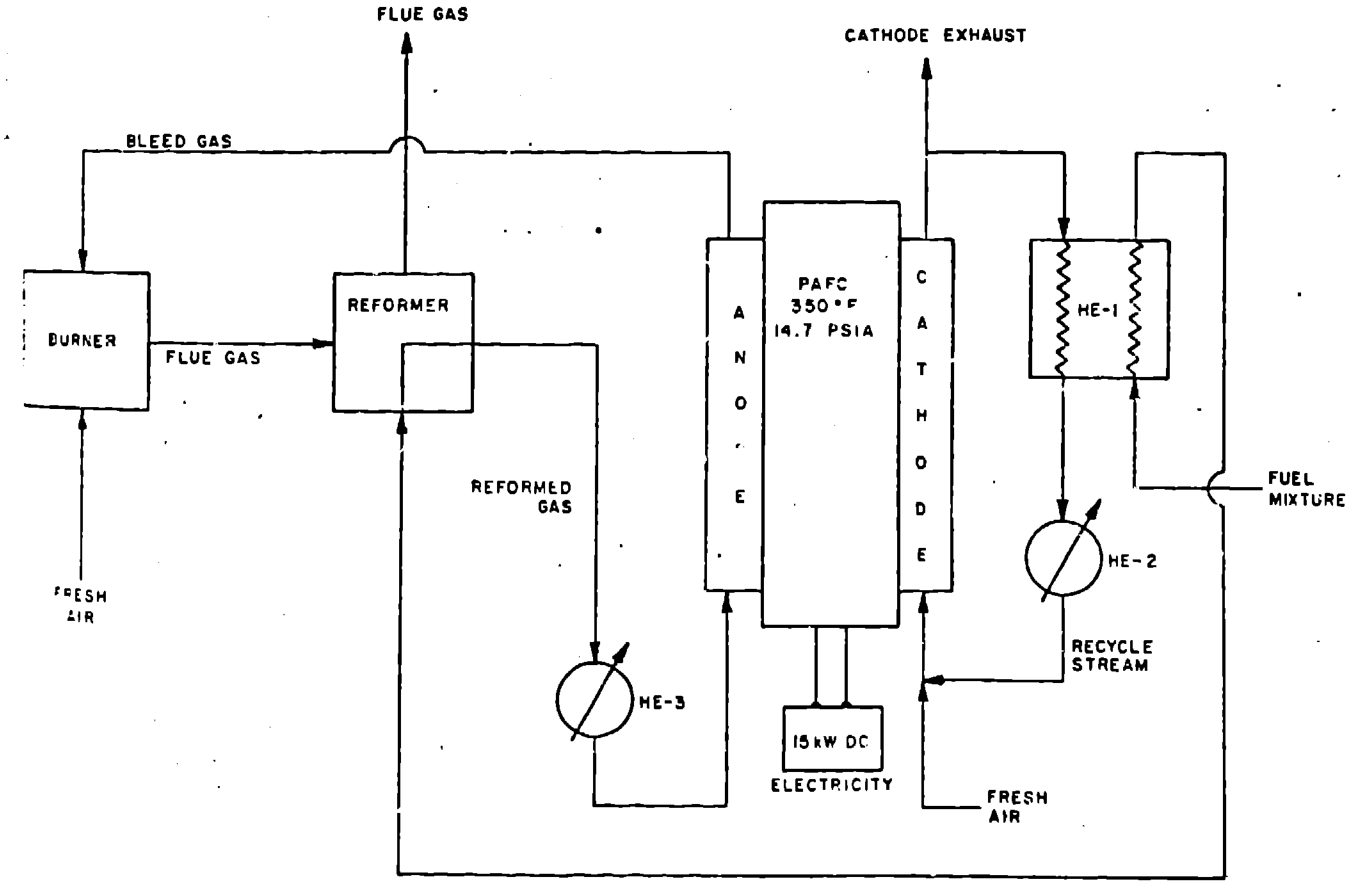

Fig. 2. - Schematic of 15-kW reformed-methanol-air PAFC system

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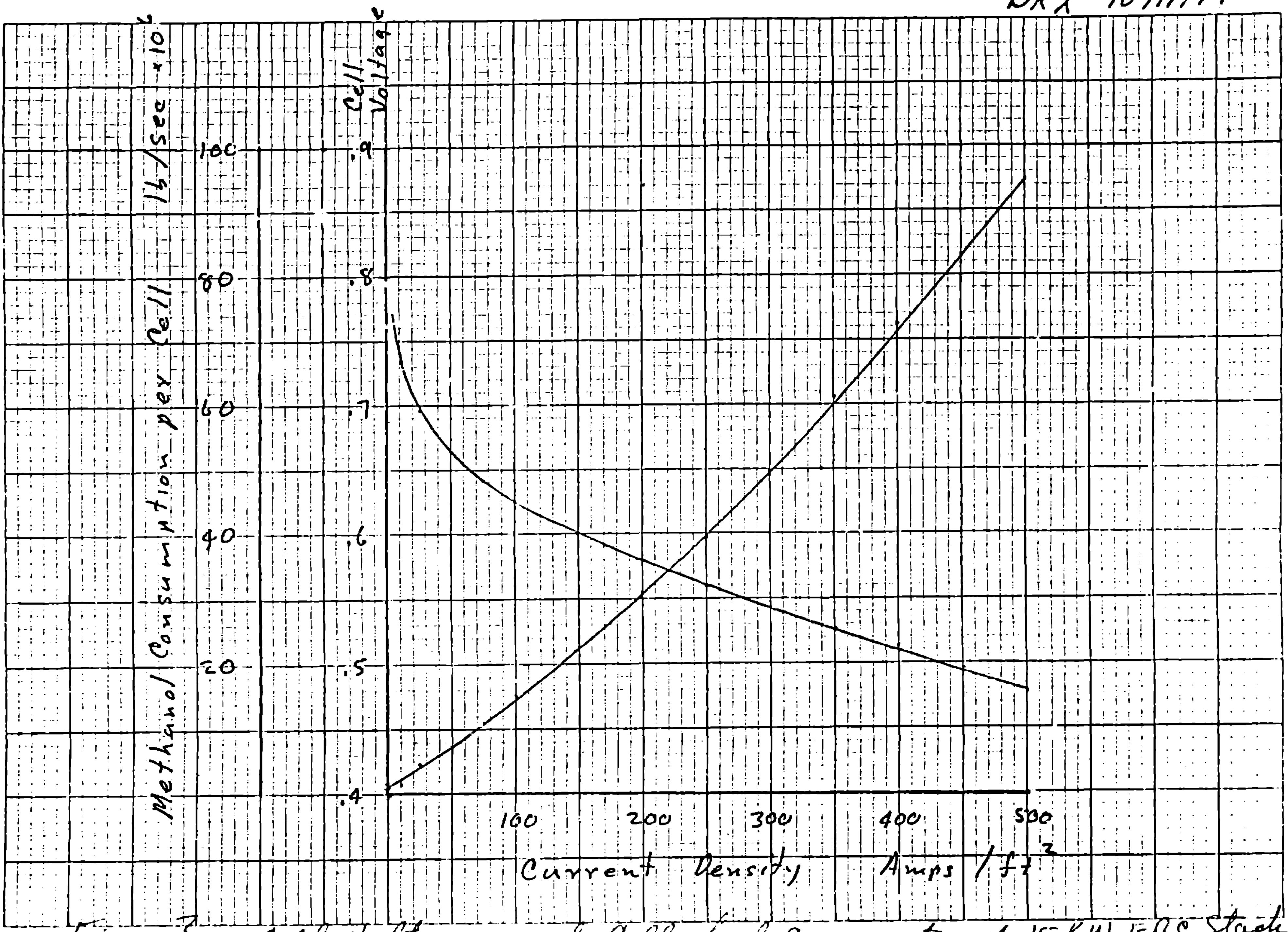

Fig 3 Cell Voltage and Cell fuel Consumption of 15 KW ERC Stack

LCXF-696

Fig ~~2~~4

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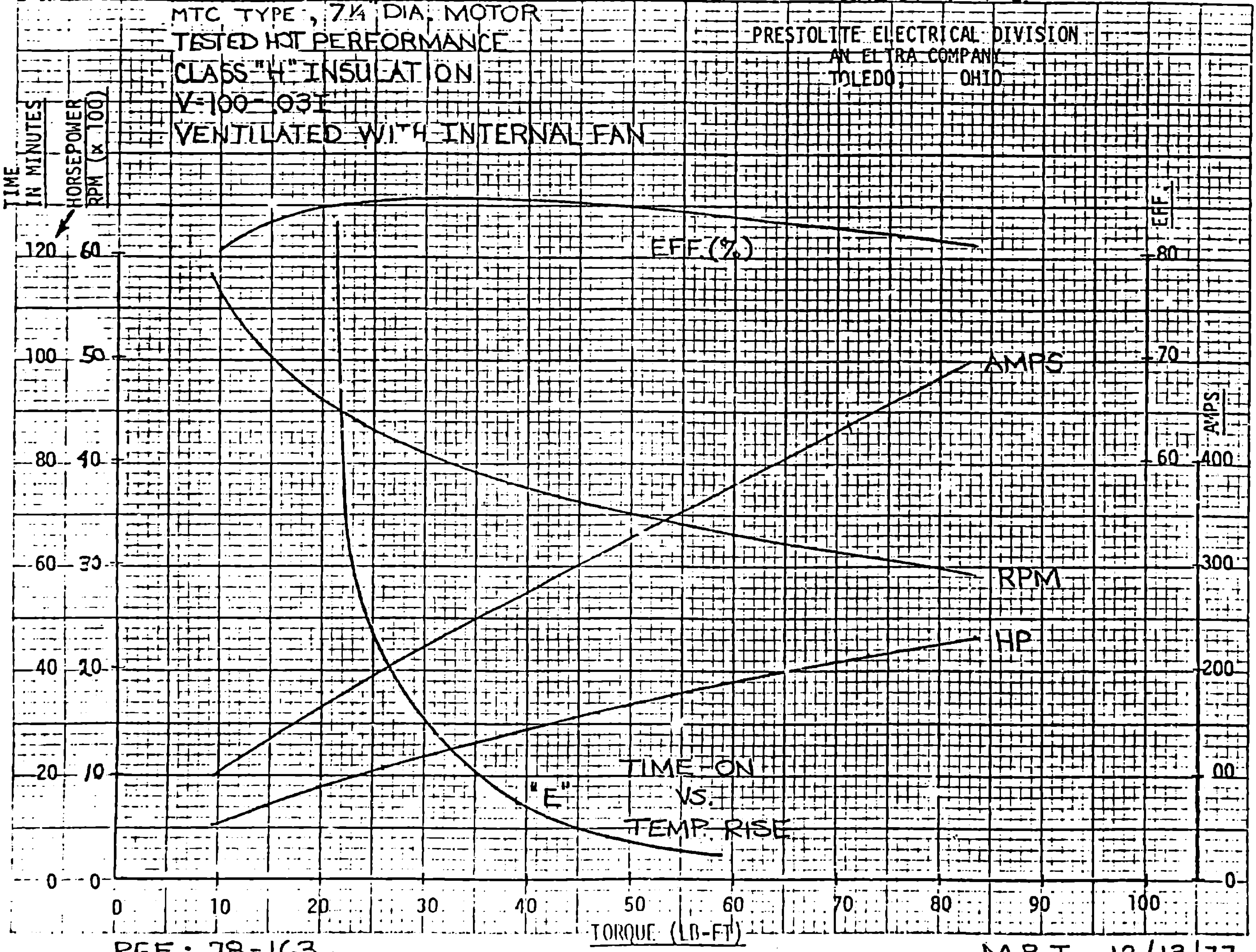

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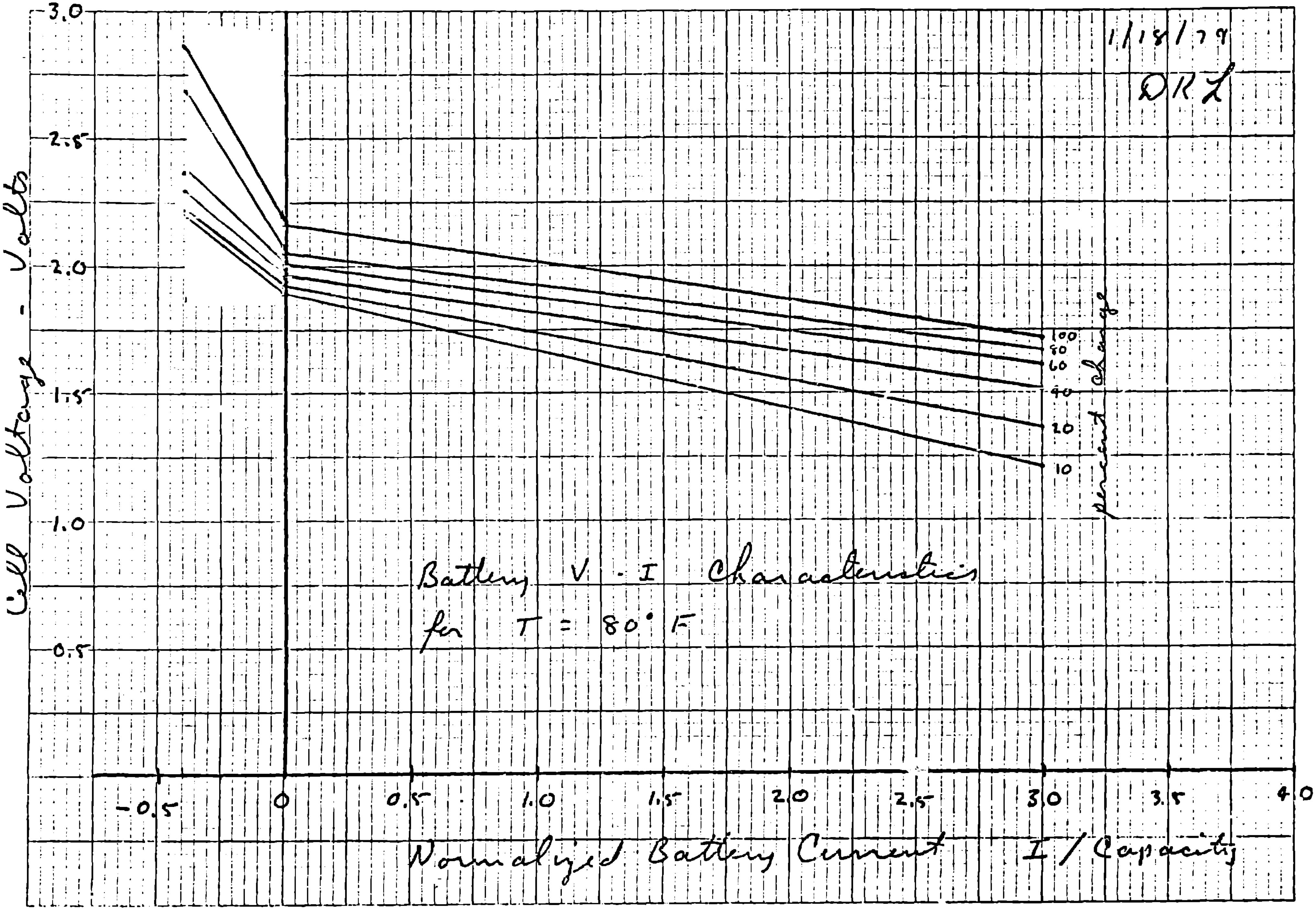
Fig #5



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Battery V-I Characteristics
for T = 80° F

Fig 56

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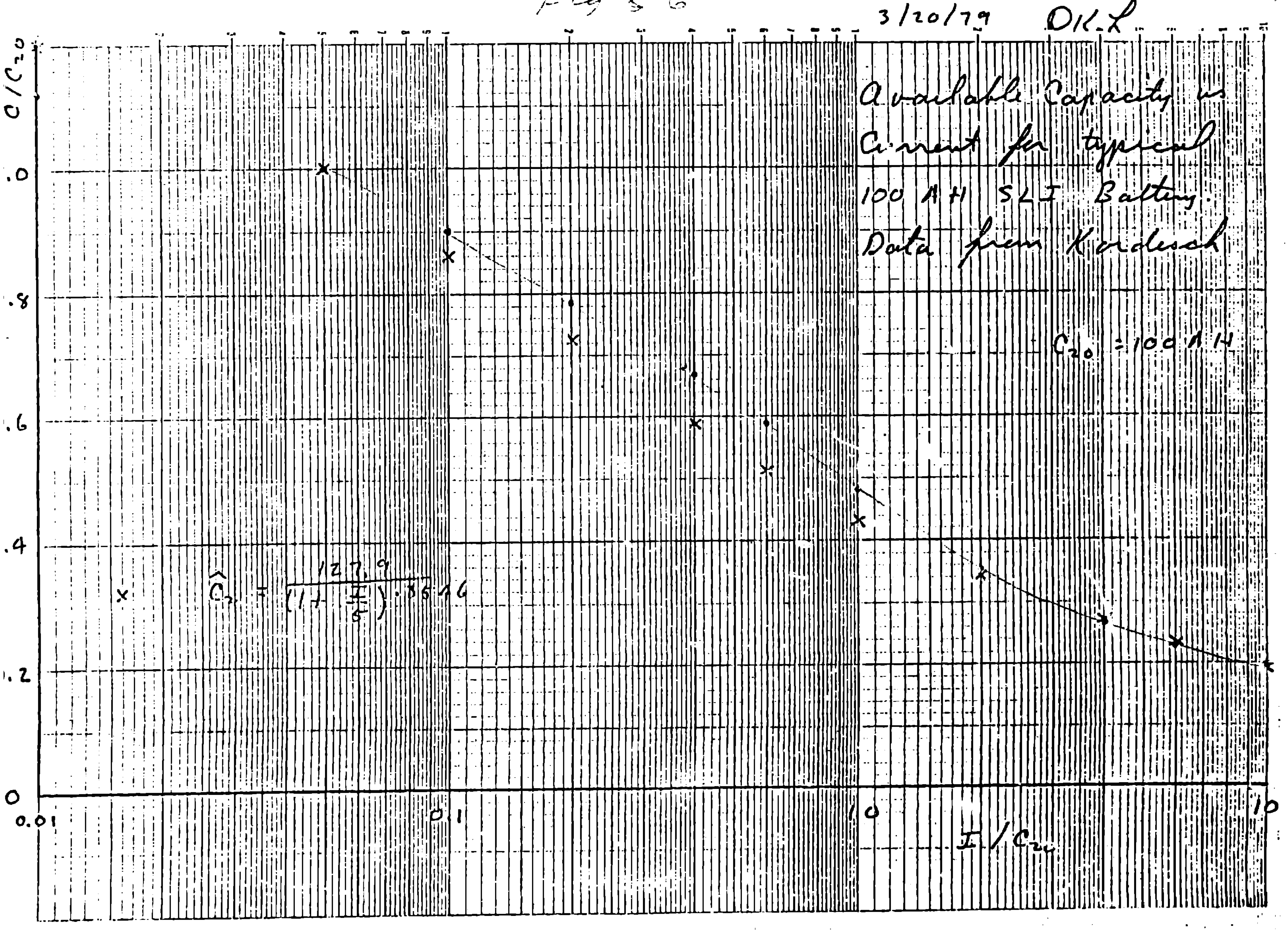
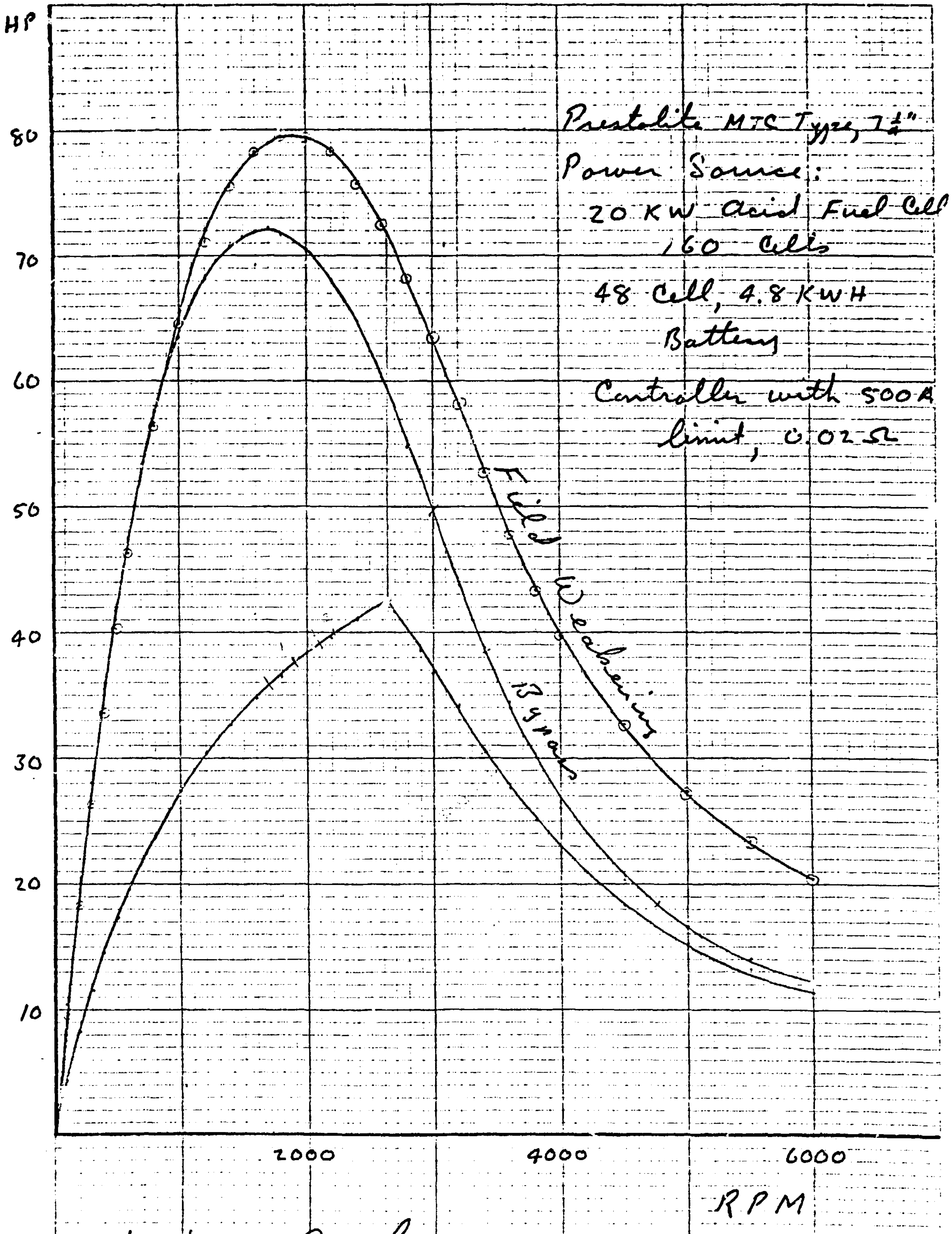


Available Capacity vs Current for typical 100 AH SLI Battery. Data from Kordesch

$C_{20} = 100$ AH

$$\hat{C}_{?} = \frac{127.9}{\left(1+\frac{I}{6}\right)^{.8516}}$$



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(1)

Fig 7

RPM/MPH = 19.96

Fig ~~7~~ 8

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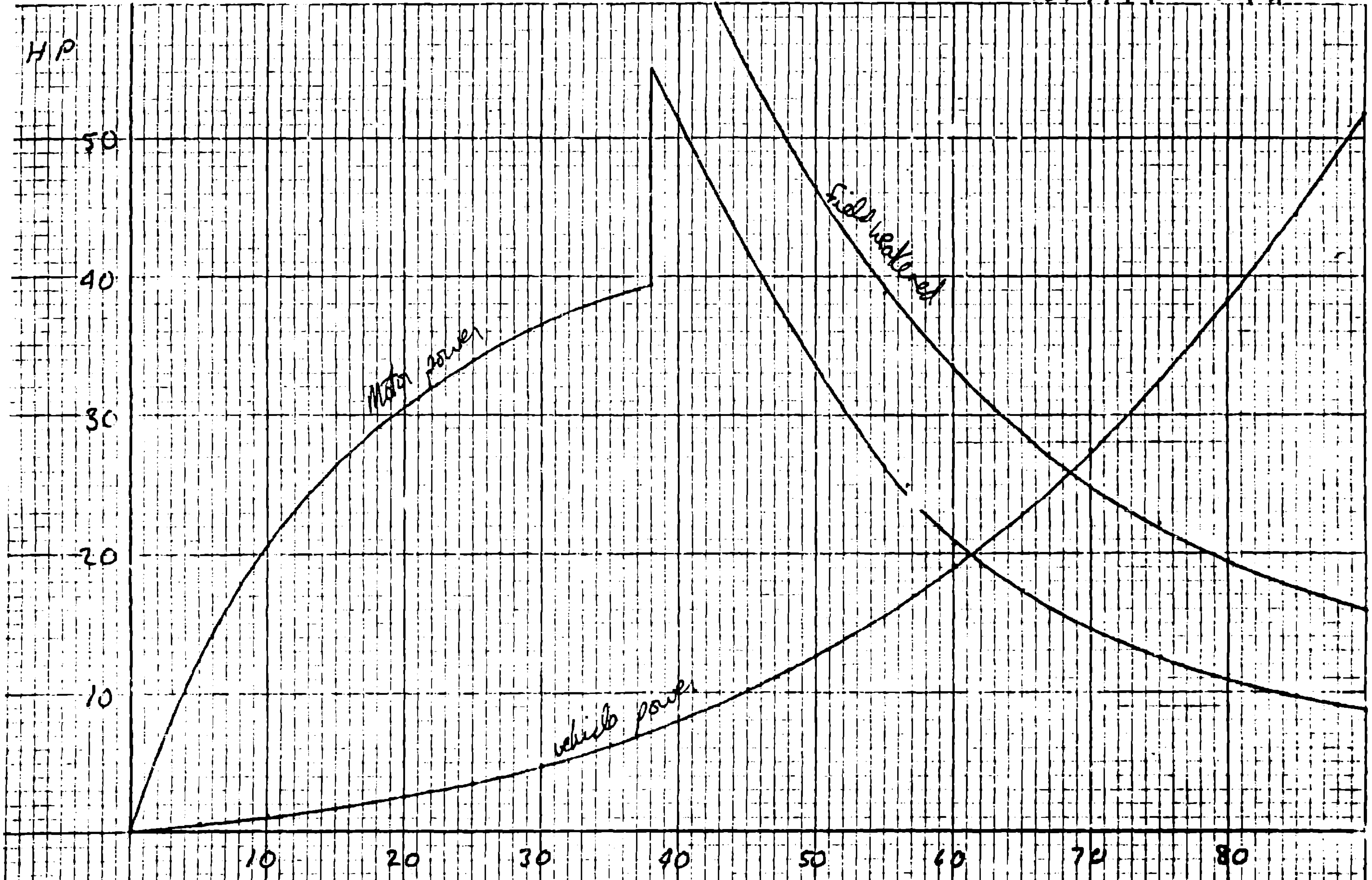

GM X Car Power Requirement

4th Gear Wheel Power, 20KW Acid FC, 4.8 KWH Battery, Prestolite Motor

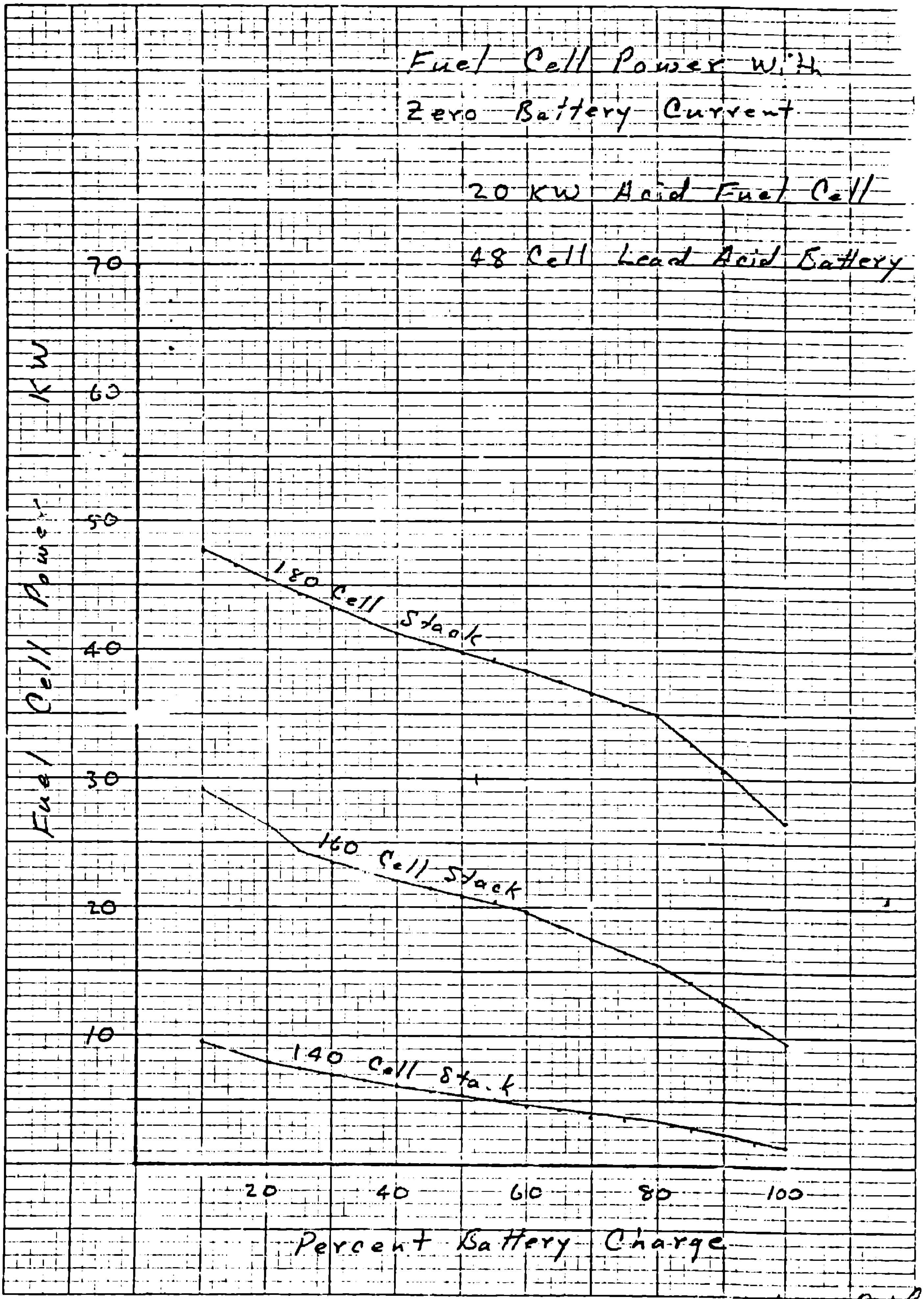

Fig. ([illegible])9

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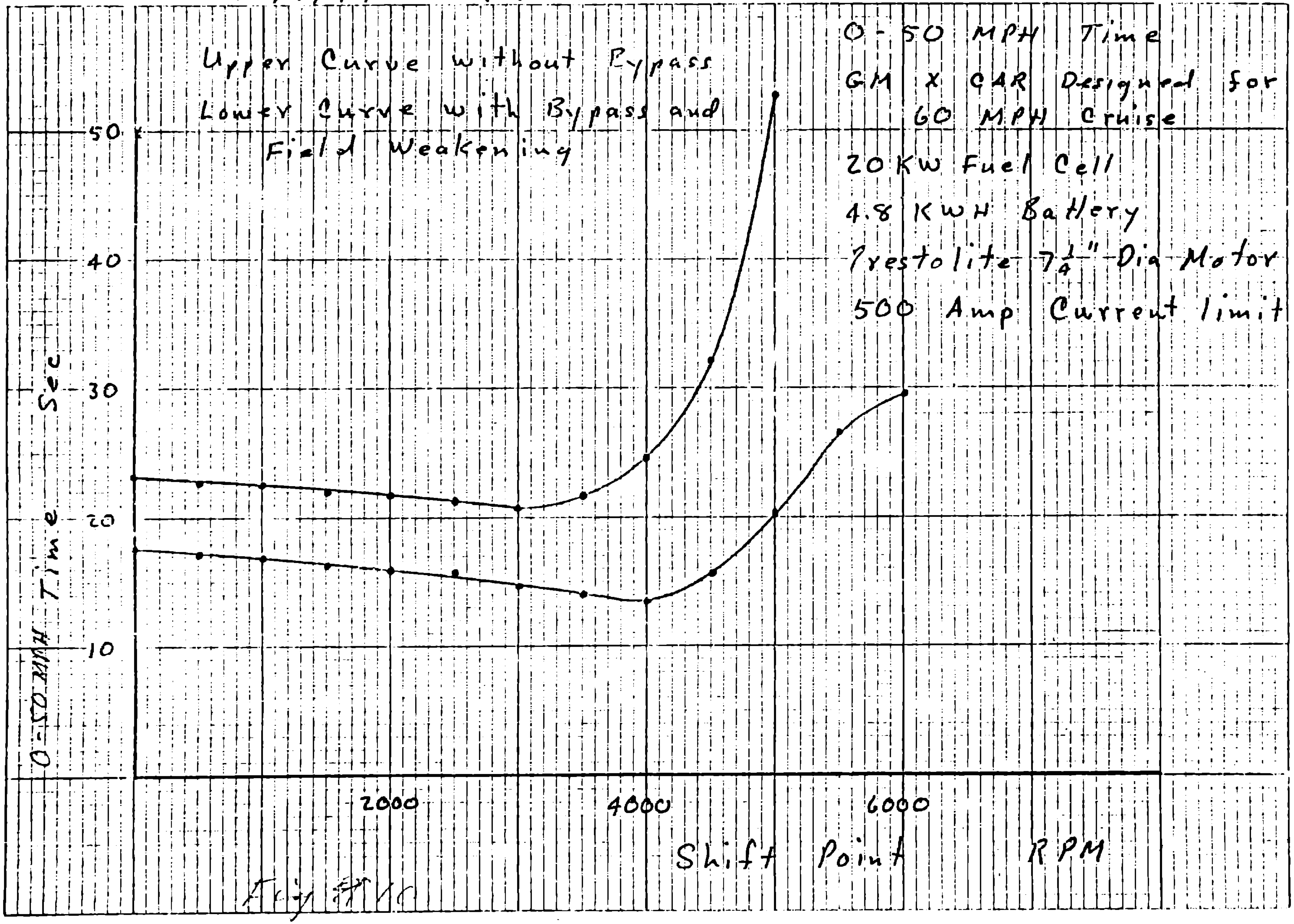

Fig #16

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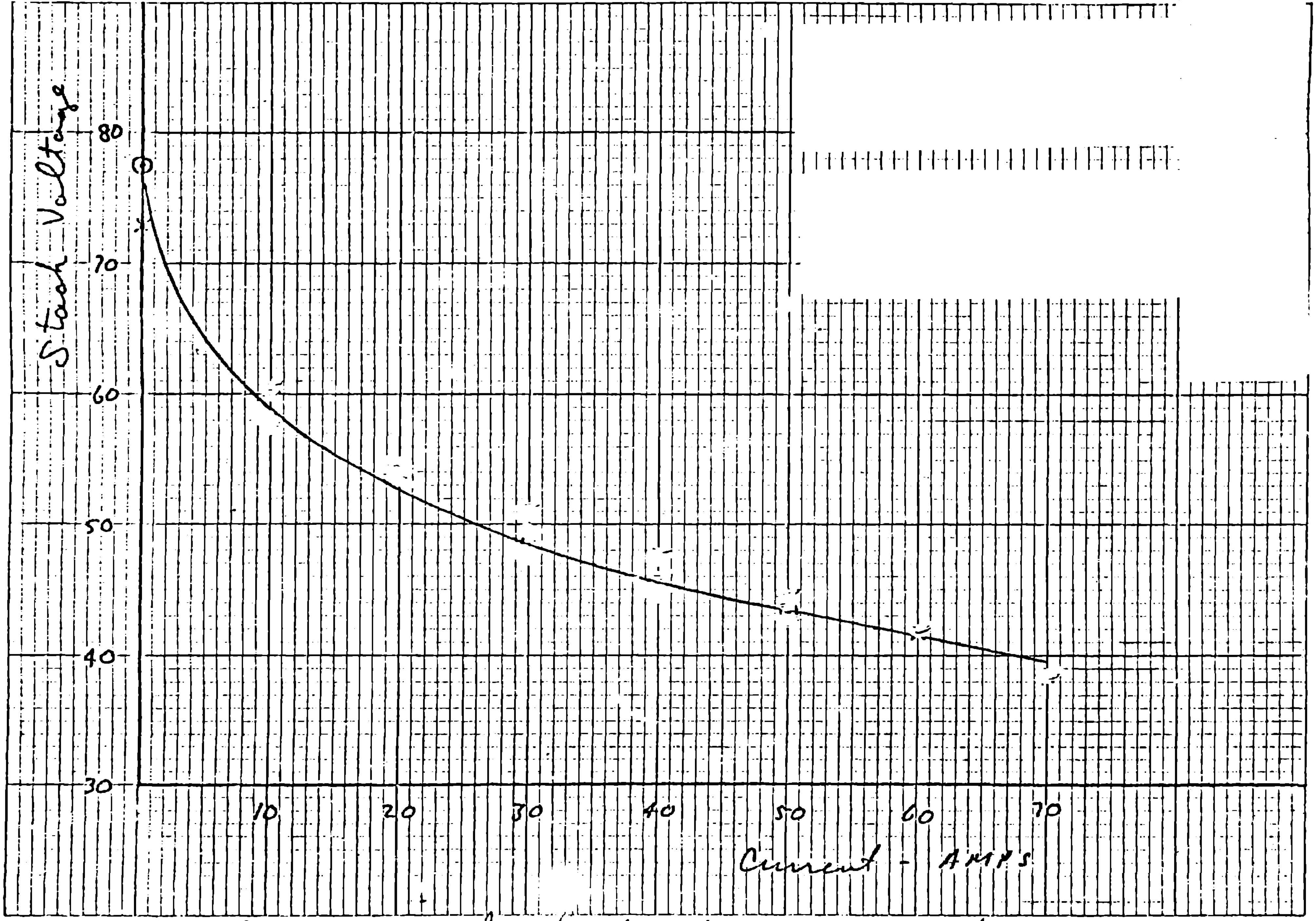

Fig 17 ~~Perf~~ Characteristics of Energy Research Corp 2 KW Fuel Cell

Fig 12. Golf cart motor characteristics

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