Batteries and Fuel Cells

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Alternative Traction Power for Locomotives and Self-Powered Railcars

U.S. Department of Transportation
Research and Special Programs Administration
Transportation Systems Center
Cambridge MA 02142

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16. Abstract

A preliminary study on the application of batteries and fuel cells as alternative motive power to diesel engines has been conducted. Three motive power consists are analyzed using the Boston to New York portion of the Northeast Corridor as a typical scenario for establishing the requirements. Various types of batteries and fuel-cell configurations have been analyzed to meet the established requirements.

The preliminary study has shown that both batteries and fuel cells can be used today for certain motive-power applications, but a more detailed study should be conducted to establish more firmly their technical and economic feasibility. A comprehensive evaluation of the future development of batteries and fuel cells for railroad traction application is necessary. An R&D plan should be developed and designed to achieve equivalent performance to the diesel engine from these alternative powerplants.

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PREFACE

This study has been prepared by the Electrical Power and Propulsion Branch at the Transportation Systems Center (TSC) for the Office of Passenger Systems, Associate Administrator for Research and Development, Federal Railroad Administration (FRA). Its purpose is to provide a preliminary analysis and assessment of the application of batteries and fuel cells as alternative power to the conventional diesel engine.

The assistance of Richard A. Novotny and Neubar Kamalian of the Office of Passenger Systems, FRA, is acknowledged. The assistance of the Power Systems Division, United Technologies Corporation, and the Electric Power Research Institute in providing data on fuel cells is also acknowledged.

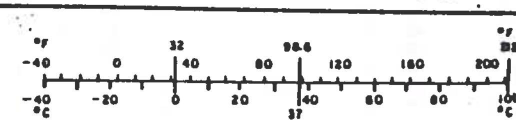
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Executive Summary

Reduction of domestic oil consumption and imports is an important national objective. A target for such reduction is the transportation industry, with the automobile as the prime candidate, and other modes such as the railroads as secondary candidates. One obvious method for reducing oil consumption in railroads would be with electrification. Alternative methods which do not require the capital investment for electrification are those systems whose on-board power plants would not require liquid petroleum as fuels. These alternatives would include, among others, batteries and fuel cells. Batteries would utilize the energy of the electric utility system, a system which is a low consumer of liquid petroleum. Fuel cells would be capable of operating on such fuels as methanol, hydrogen, and derivatives of coal. The rapid technological improvement of batteries and fuel cells prompts a serious study of these alternatives.

Since the extensive work on fuel cells as power sources for U.S. space programs, both the U.S. Army and the U.S. electric utility industry have pursued programs for development of ground-based units. The Army program is directed at developing a family of silent light-weight power sources up to 5.0 kW. The electric utilities, through the joint program with Electric Power Research Institute (EPRI), Department of Energy (DOE), Consolidated Edison Co., and United Technologies, Inc., are installing a 4.5 MW fuel cell in Manhattan, for connection to the existing electric power system. The alternative of batteries receives its impetus from the 20-year experience of the German Federal Railroad in operating a 230-car fleet powered entirely with current technology lead-acid batteries. Again, the electric utility industry is supporting a test program on a large lead-acid battery bank interconnected with a solid-state converter to the electric power network to act as a load leveler. Work on the advanced sodium-sulfur battery includes the DOE-funded development work by Ford and Dow Chemical Co. for electric-vehicle propulsion, and the British Rail tests on a 10 kWh 176-cell battery for motive power application. Technological improvements of both fuel cells and batteries are taking place directly in the size, power and energy ranges that are making them suitable for railroad applications.

Scope of Study and Results

Prior to conducting an in-depth study of the alternatives, a preliminary study on the application of fuel cells and batteries to a specific set of applications was carried out and is the subject of this report. Three motive power consists were analyzed. They were: (1) SDP40F diesel-electric locomotive with five Amfleet trailing cars; (2) AEM7 electric locomotive with five Amfleet trailing cars; (3) five Metroliner self-powered cars. The 232-mi Boston-to-NYC route was selected for study purposes, with selected cruising speeds of 90 mi/h, 120 mi/h, and 150 mi/h. The total energy for the trip, the peak power, and the average energy consumption in kWh/gross-ton-mile were found for each consist and for each maximum cruising speed, to establish the requirements for the batteries and fuel cells. In addition, the volume and weight made available by removing the existing propulsion plant (exclusive of traction motors) for the batteries and fuel cells were calculated for the two locomotives and Metroliner cars, from which the energy density requirements for batteries and the power density requirements for batteries and cells were determined. Various types of batteries and fuel cell configurations were analyzed to meet the established requirements.

For the evaluation, three promising types of batteries were analyzed, namely, (1) advanced lead-acid, (2) nickel-zinc, and (3) sodium-sulfur, for their specific energy (Wh/kg) and specific power (W/kg). For the consists and route studied, only the sodium-sulfur battery could meet the requirements of the SDP40F consist with a maximum cruising speed of 90 mi/h and be compatible with the weight and volume constraints. The initial requirements for the other combinations of batteries and consists could not be satisfied for both the energy density and power density. However, the other consists could be operated over the selected route by either reducing the acceleration performance below that obtained with the existing propulsion systems or reducing the vehicle weight. Current self-powered U.S. cars, such as the Metroliner, are significantly heavier and powered to achieve somewhat higher performance than the battery powered cars used in Germany. Weight reductions and/or acceleration performance reductions of U.S. self-powered cars would significantly improve their performance in the battery-powered mode.

Both the AEM7 and Metroliner consists have insufficient volume for a fuel cell power plant to meet the selected route requirements. United Technologies, Inc. prepared four configurations of 2000 kW fuel cells for the SDP40F locomotive in this study. The configurations proceeded in increasing state of new technology, from a 1947 ft^3 state-of-the-art plant using methanol and water as fuel, to a 1155 ft^3 advanced type using cryogenic hydrogen as fuel. The projected lifetime of the fuel cells is 150,000 h with major cell refurbishing at 40,000 h intervals. Efficiency of the fuel cell is projected as 40 percent, compared to the diesel engine-generator efficiency of about 30 percent, including the idling time.

Conclusions and Recommendations

This preliminary study has shown that both batteries and fuel cells can be used in certain motive power propulsion applications today, but that a more detailed study is warranted. The detailed study should include a comprehensive evaluation of the future development of batteries and fuel cells for the railroad application. The study should also work out the system design concept, performance characteristics and life-cycle costs of the locomotives and self-powered cars selected for the study. With this information, an R&D plan for future work should be designed to achieve the battery and fuel-cell propulsion systems that will reduce oil consumption by the railroad industry, yet provide equivalent performance.

1. INTRODUCTION

This report is a study of application of batteries and fuel cells to locomotives and self-powered cars for intercity passenger trains. Requirements of train consists are developed and compared with battery and fuel cell capabilities. Effective applications are identified and analyzed.

This study is motivated by the current development of batteries and fuel cells. The Electric Power Research Institute (EPRI) and the Department of Energy (DOE) are funding various advanced battery and fuel cell projects which have a high potential for successful development and commercialization in the 1980's. Applications include electric utility energy storage and power sources, power sources to meet the energy needs of buildings and industrial processes, and electric or hybrid vehicles.

Potential advantages of battery and fuel cell application to railroad traction include the following:

1) economy of electric propulsion;
2) reduced capital costs compared to conventional electrification;
3) reduced maintenance costs;
4) reduced petroleum consumption, noise and pollution;
5) more flexible operation; and
6) electric utility load levelling.

In Section 2 energy and power requirements are assessed for intercity passenger trains. Battery characteristics and capabilities are discussed in Section 3. Fuel cell characteristics and capabilities are discussed in Section 4. Energy and power requirements are compared with battery capabilities in Section 5 in order to identify effective applications of batteries to railroad traction. In Section 6 effective applications of fuel cells to railroad traction are identified. Conclusions and recommendations are given in Section 7.

2. ENERGY AND POWER REQUIREMENTS FOR LOCOMOTIVES AND SELF-POWERED CARS

In this section, energy and power requirements are assessed for intercity passenger trains. Train consists and route characteristics are selected and data are presented. Average train energy consumption and power are calculated for the selected consists and route, at specified maximum cruising speeds. Also, available weight and space for alternative power sources are estimated for the consists. Energy and power requirements are then summarized in terms of densities for the selected consists.

2.1 Train Characteristics

The following consists are considered for reference and comparison with battery or fuel cell-powered trains.

1) The SDP40F diesel electric locomotive and five Amfleet trailing cars.
2) The AEM7 electric locomotive and five Amfleet trailing cars.
3) Five Metroliner self-powered cars.

1) The SDP40F is an Amtrak intercity passenger train locomotive - a 3000 hp diesel electric, 6 axle, 6 motor, 198 ton unit built by Electro-Motive Division of General Motors (EMD). It is designed and geared for intermediate-speed passenger service, up to 90 mi/h, and features a single cab with full-width nose and body.

The SDP40F has a fuel capacity of 3200 gal. Although fuel consumption depends on speed profile and track grade, a typical value based on recent studies (Ref. 1) of existing diesel electrics is 220 gross ton mi/ gal. Using this value, a consist of an SDP40F and five Amfleet trailing cars, with a total gross weight of 528 tons including passengers, has about a 1300 mi range.

The SDP40F also has two 2500 lb steam generators for passenger car heating/ air conditioning, with a 3500 gal water capacity.

Speed-tractive effort curve, dimensions and weight list are shown in Figs. A. 1, A. 2 and Table A. 1.

2) The AEM7 is an electric locomotive, being built by EMD for use in the Northeast Corridor. It is a 4-axle, 4 motor, 101 ton, 7000 hp unit with 4500 kW of continuous power available at the wheels. 6200 kW is available for short periods. Speed-tractive effort curve, dimensions and weight list are shown in Figs. A. 3 and A. 4 and Table A. 2.

3) The Metroliner is an Amtrak high-speed self-powered car geared for 130 mi/h maximum speed, built by Budd. This 4-axle, 4 motor, 88 ton self-powered car operates between NYC and Washington, DC, and has an average initial acceleration of 1. 0 to 1. 2 mi/h/s. The Metroliner coach seats 76 passengers. Speed-tractive effort curve, dimensions and weight list are shown in Figs. A. 5 and A. 6.

The locomotive-hauled trailing cars in this study are assumed to be Amfleet coaches, which are 60 ton, 85 ft passengers cars in general use throughout the USA.

2.2 Route Characteristics

Route characteristics including permitted speeds are major factors in determining train energy requirements. The Boston-NYC route is selected for study purposes.

Typical schedules of some of the Boston-NYC trains are shown in Table A.3. The 232 mi (373 km) distance has seven to thirteen stops. Trip time varies from 4 h 45 min to 5 h 25 min. There is a 10 to 15 min stop in New Haven, CT, to change from diesel-electric to electric locomotive. Average speed is 48-55 mi/h. The Boston-NYC track grade is relatively flat.

2.3 Average Energy Requirements

Average train energy consumption, specified in kWh/gross ton mi, depends on the train speed profile, its pattern of acceleration, cruise and deceleration maneuvers, as well as track grade.

Fig. A.7 shows energy consumption at the traction motors, based on a Jet Propulsion Laboratory study (Ref. 2) of locomotive-hauled trains and self-powered trains for passenger service between NYC and Washington, DC. As shown, energy consumption varies from 0.047 to 0.080 kWh/gross ton-mi, as the maximum speed varies from 105 to 150 mi/h.

A 1975 MITRE Corp. study (Ref. 3) reports average energy consumption at traction motors of 0.056 kWh/ gross ton mi, which includes both passenger and freight service in the USA. The MITRE report also states that energy efficiency of a diesel-electric is about equal to that of an electric locomotive.

Average energy consumption for battery operated trains of the German Federal Railroad (Ref. 4) is 0.043 kWh/ gross ton mi. These 82 ton trains, including a 49 ton battery powered car, a 22 ton trailing car and an 11 ton passenger load, operate at a maximum speed of 60 mi/ h.

Energy consumption is calculated for the three selected consists (Section 2.1) between Boston and NYC.* Energy consumption is summarized in Tables 2.1, 2.2, and 2.3 for runs with seven intermediate stops. Three values of maximum cruising speeds are shown:

Table 2.1:	90 mi/ h	- All three consists
Table 2.2:	120 mi/ h	- AEM7 and Metroliner consists
Table 2.3:	150 mi/ h	- Metroliner consist only

The calculations are made by applying the Davis equation (Ref. 5) for the leading car and trailing cars for each consist, using car weights and selected maximum cruising speeds, to obtain energy consumed during cruising. Additionally the speed-tractive effort curves, Figs. A.1, A.3 and A.5 are used to calculate energy

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*It is assumed here that the entire route is electrified since this is required for consists 2 and 3.

TABLE 2-1. ENERGY CONSUMPTION BOSTON TO NEW YORK CITY
90 mi/h MAXIMUM SPEED

Route	Distance	No. Stops	Energy Consumed at Input to Traction Motors		
			SDP40F& 5 Cars	AEM7 & 5 Cars	5 MU Cars
Boston - Providence	mi 44	2	kWh 757	kWh 740	kWh 831
Providence - New London	62	2	1034	1001	1079
New London - New Haven	54	1	872	769	856
New Haven - NYC	72	3	1228	1197	1329
Total - kWh	232	8	3891	3707	4095 (819/car)
Gross tons for consist			528	442	470
Average Energy Consumption kWh/gross ton-mile			0.032	0.036	0.038

TABLE 2-2. ENERGY CONSUMPTION--BOSTON TO NEW YORK CITY 120 mi/h MAXIMUM SPEED

Route	Distance	No. Stops	Energy Consumed at Input to Traction Motors	
			AEM7 & 5 Cars	5 MU Cars
Boston - Providence	mi 44	2	kWh 1074	kWh 1110
Providence - New London	62	2	1476	1459
New London - New Haven	54	1	1253	1176
New Haven - NYC	72	3	1745	1777
Total - kWh	232	8	5548	5522 (1105/car)
Gross tons for consist			442	470
Average Energy Consumption kWh/gross ton - mi			0.054	0.051

TABLE 2-3. ENERGY CONSUMPTION--BOSTON TO NEW YORK CITY 150 mi/h MAXIMUM SPEED

Metroliner Consist			Energy Consumed at Input to Traction Motors
Route	Distance	No. Stops	5 MU Cars
Boston - Providence	mi 44	2	kWh 1489
Providence - New London	62	2	2007
New London - New Haven	54	1	1665
New Haven - NYC	72	3	2406
Total - kWh	232	8	7567 (1513/car)
Gross tons for consist			470
Average Energy Consumption kWh/gross ton-mi			0.069

consumed while accelerating after each of the seven intermediate stops. The speed-tractive effort curves are approximated by intervals of constant force (or constant acceleration). Total energy consumption is then obtained by adding the energy consumed during accelerating to the energy consumed during cruising.

As shown in Table 2.1, the 528 ton SDP40F - 5 car consist requires 3891 kWh into the traction motors over the 232 mi route for a 90 mi/h maximum speed. The 442 ton AEM7 - 5 car consist requires 3707 kWh, and the 470 ton 5 car Metroliner requires 4095 kWh (819 kWh/self-powered car).

As shown in Table 2.2, the AEM7 - 5 car consist requires 5548 kWh into the traction motors for a 120 mi/h maximum speed. The 5 car Metroliner requires 5524 kWh (1105 kWh/self-powered car).

As shown in Table 2.3, the 5 car Metroliner consist requires 7567 kWh (1513 kWh/self-powered car) into the traction motors for a 150 mi/h maximum speed.

Comparison of the calculations in Tables 2.1-2.3 with the data published in Refs. 2, 3 and 4 show a good correlation, indicating that the calculations are reasonable estimates of energy consumption.

2.4 Power Requirements

Peak power input to the traction motors is calculated for the three selected consists. The calculations are made by multiplying the peak tractive effort and the maximum velocity at which peak tractive effort occurs, using the speed-tractive effort curve for each consist, Figs. A.1, A.3, and A.5. (Note that the maximum velocity at which peak tractive effort occurs is reduced by 25% for the AEM7 locomotive and Metroliner at 90 mi/h maximum cruising speeds, corresponding to a gear ratio change for limiting the maximum speed).

As shown in Table 2.4, the SDP40F diesel electric locomotive requires 2000 kW peak power input to the traction motors. The AEM7 electric locomotive requires 5100 kW at 90 mi/h maximum cruising speed, and 6800 kW at 120 mi/h. The Metroliner requires 1463 kW/car at 90 mi/h, and 1950 kW/car at 120 and 150 mi/h.

TABLE 2-4. PEAK POWER REQUIREMENTS - LOCOMOTIVES AND SELF-POWERED CARS

	Peak Power at Input to Traction Motors		
Maximum Cruising Speed	90 mi/h	120 mi/h	150 mi/h
Units	kW	kW	kW
SDP40F locomotive	2000	---	---
AEM7 locomotive	5100	6800	---
Metroliner MU car	1463/car	1950/car	1950/car

2.5 Available Weight and Space for Batteries and Fuel Cells

Certain equipment can be removed from existing locomotives and self-powered cars for total battery or fuel cell operation, making weight and space available for batteries or fuel cell power sources. Weight and space availability are summarized in Table 2.5 for the three selected consists.

Removable equipment for the SDP40F locomotive includes (1) fuel tank and fuel, (2) diesel engine and auxiliaries, (3) generator and auxiliaries and (4) ballast. Available weight and space totals are 60 tons and 1700 ft^3, respectively.

Removable equipment for the AEM7 locomotive includes (1) pantograph, (2) transformer, plus circuit breaker, surge arrester and smoothing reactor, and (3) thyristor converter plus harmonic filters and controls. AEM7 available weight and space totals are 24 tons and 1300 ft^3, respectively.

The pantograph, transformer and thyristor equipment can also be removed from the Metroliner car, leaving 10 tons and 800 ft^3 available for installing batteries or fuel cells.

TABLE 2.5. WEIGHT AND SPACE AVAILABLE FOR BATTERIES OR FUEL CELLS (IF PRESENT DIESEL OR POWER CONDITIONING EQUIPMENT WERE REMOVED).

Removable Equipment	Available Weight	Available Volume
	tons	ft^3
SDP40F Locomotive		
Fuel tank and fuel	15.3	430.
Diesel engine (plus auxiliary equipment)	17.3	750
Generator (plus auxiliary equipment)	8.5	150
Ballast	15	70
Other	4	300
Total	60	1700
AEM7 Locomotive		
Pantograph	0.9	150
Transformer (plus reactor, auxilliaries)	14.	400
Thyristor converter (plus auxiliaries)	7.6	300
Other	1.5	450
Total	24.	1300
Metroliner MU Car		
Pantograph	0.3	--
Transformer	6.0	200
Smoothing reactor	1.4	50
Thyristor converter (plus auxiliaries)	1.1	150
Other	1.2	400
Total	10.	800

2.6 Summary of Energy, Power, Weight and Space Requirements

Energy and power density requirements for passenger service between Boston and New York City are summarized in Tables 2.6, 2.7 and 2.8. Energy and power requirements (Tables 2.1-2.4) are combined with available weight and volume (Table 2.5) to determine the requirements for energy per unit weight (specific energy), energy per unit volume, power per unit weight (specific power), and power per unit volume.

The battery specific energy and energy per unit volume requirements shown in Tables 2.6 - 2.8 are based on a 232 mi trip, without battery recharging or battery exchange, and without increasing the total weight or volume of the consist.

As shown in Table 2.6 batteries with 71 Wh/kg are required for the SDP40F - 5 car consist at 90 mi/h maximum speed. Battery specific energy required for the AEM7 - 5 car consist and the Metroliner self-powered cars are 172 and 90 Wh/kg, respectively. Battery specific energy for the AEM7 is considerably higher, primarily because less weight can be made available for batteries by removal of existing equipment.

Corresponding battery requirements of specific energy and energy per unit volume are shown in Tables 2.7 and 2.8 for 120 and 150 mi/h maximum speeds, respectively.

TABLE 2-6. SUMMARY OF ENERGY, POWER, WEIGHT AND SPACE REQUIREMENTS FOR BATTERIES OR FUEL CELLS PASSENGER SERVICE, BOSTON - NEW YORK CITY 90 mi/h MAXIMUM SPEED

Consist	Energy (1) Required at Traction Motor Input	Peak Power Required at Traction Motor Input	Available (2) Weight	Available (2) Volume	Batteries		Batteries or Fuel Cells	
					Required Specific Energy (3)	Required Energy per Unit Volume (3)	Required Peaks Specific Power	Required Peaks Power per Unit Volume
	kWh	kW	kg	m^3	Wh/kg	Wh/cm^3	W/kg	kW/m^3
SDP40F-5 cars	3891	2000	54,500	48.2	71	0.08	37	42
AEM7 - 5 cars	3707	5100	21,800	36.8	170	0.10	234	139
5 Metroliner	4095 (819 kWh/car)	1463/car	45,400 (9,080)	113 (22.7 m^3/car)	90	0.036	161	65

NOTE:

1) Boston-NYC, 232 mi, 90 mi/h maximum speed, 8 stops, Table 2.1
2) Without increasing total weight or volume of consist, Table 2.5
3) Without battery recharging or battery exchange

TABLE 2-7. SUMMARY OF ENERGY, POWER, WEIGHT AND SPACE REQUIREMENTS FOR BATTERIES OR FUEL CELLS PASSENGER SERVICE, BOSTON - NEW YORK CITY 120 mi/h MAXIMUM SPEED

Consist	Energy (1) Required at Traction Motor Input	Peak Power Required at Traction Motor Input	Available (2) Weight	Available (2) Volume	Batteries		Batteries or Fuel Cells	
					Required Specific Energy (3)	Required Energy per Unit Volume (3)	Required Peaks Specific Power	Required Peaks Power per Unit Volume
	kWh	kW	kg	m^3	Wh/kg	Wh/cm^3	W/kg	kW/m^3
AEM7-5 cars	5548	6800	21,800	36.8	254	0.15	312	185
5 Metroliner	5524 (1105 kWh/car)	1950/car	45,400 (9,080)	113. (22.7 m^3/car)	122	0.049	215	86

NOTE:

1) Boston-NYC, 232 mi, 120 mi/h maximum speed, 8 stops, Table 2.2
2) Without increasing total weight or volume of consist, Table 2.5
3) Without battery recharging or battery exchange

TABLE 2-8. SUMMARY OF ENERGY, POWER, WEIGHT AND SPACE REQUIREMENTS FOR BATTERIES OR FUEL CELLS PASSENGER SERVICE, BOSTON - NEW YORK CITY 150 mi/h MAXIMUM SPEED

Consist	Energy (1) Required at Traction Motor Input	Peak Power Required at Traction Motor Input	Available (2) Weight	Available (2) Volume	Batteries		Batteries or Fuel Cells	
					Required Specific Energy (3)	Required Energy Per Unit Volume (3)	Required Peaks Specific Power	Required Peaks Power per Unit Volume
	kWh	kW	kg	m^3	Wh/kg	Wh/cm^3	W/kg	kW/m^3
5 Metroliner Self-propelled Cars	7567 (1513 kWh/car	1950/car	45,400 (9,080)	113. (22.7 m^3/car)	167	0.067	215	86

NOTE:

1) Boston-NYC, 232 mi, 150 mi/h maximum speed, 8 stops, Table 2.3.
2) Without increasing total weight or volume of consist, Table 2.5.
3) Without battery recharging or battery exchange.

As shown in Table 2.6, peak power requirements of 37 W/kg and 42 kW/m^3 are specified for the SDP40F power source (batteries or fuel cells) for a 90 mi/h maximum cruising speed. Requirements for the AEM7 power source are 234 W/kg and 139 kW/m^3. Requirements for the Metroliner power source are 161 W/kg and 65 kW/m^3. Also, Tables 2.7 and 2.8 show power density requirements at 120 and 150 mi/h maximum cruising speeds, respectively.

3. BATTERIES

In this section, batteries are discussed with respect to application to railroad traction. After a brief review of battery operation in Section 3.1, battery characteristics which are of interest to railroad traction are given in Section 3.2. Section 3.3 summarizes the status of existing commercial batteries, and Section 3.4 discusses experience with battery-operated trains in Germany. Current development work on advanced batteries is discussed in Section 3.5, and technical as well as economic prospects for advanced batteries are given in Section 3.6.

3.1 Battery Operation

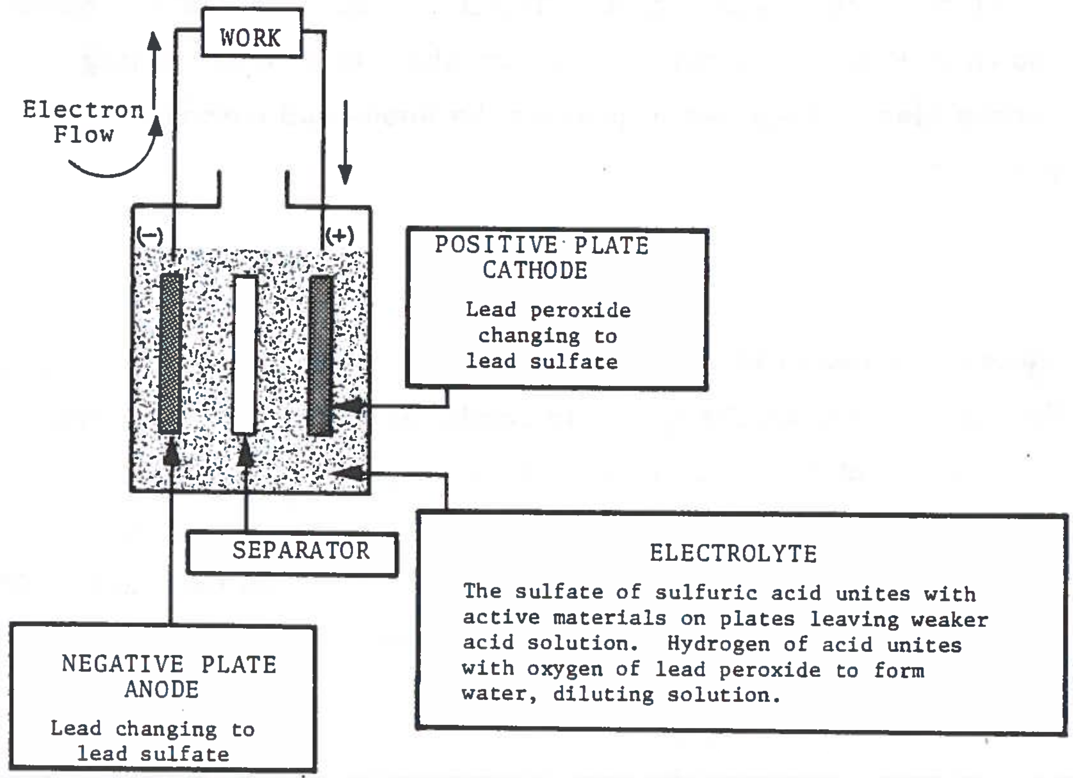
A battery is a device for storing energy in chemical form which can be released in electrical form. It is comprised of units called cells which are connected in series or in series-parallel combinations.

The basic components of all battery cells are two electrodes, denoted anode and cathode, and an electrolyte. When a battery is discharging, ions in the electrolyte chemically react with the anode to produce electrons (an "oxidation") which are transferred through the electrical circuit to the cathode. The electrons combine with the cathode (a "reduction"). Thus the basic idea is that a combination oxidation-reduction occurs, called a redox couple, which causes electrons to flow in the electrical circuit.

An example is the lead-acid battery, shown in Fig. 3.1, where the anode is lead (Pb), the cathode is lead peroxide (PbO_2) and the electrolyte is sulfuric acid (H_2SO_4) (Ref. 6). The separator shown in Fig. 3.1 is normally a thin sheet of non-conducting porous plastic required to prevent the anode and cathode from touching.

Battery operation is based on the so-called double sulfate theory. During discharge, lead combines with hydrogen sulfate ions (HSO_4^-) at the anode to produce electrons (e^-) which flow in the electrical circuit, hydrogen ions (H^+) which flow in the electrolyte, and lead sulfate ($PbSO_4$) which deposits on the anode. At the cathode, lead peroxide (PbO_2) combines with hydrogen sulfate ions (HSO_4^-), hydrogen ions (H^+), and electrons (e^-) to produce lead sulfate (which deposits on the cathode) and water. The electrolyte, sulfuric acid, disassociates into hydrogen ions and hydrogen sulfate ions, which react with the electrodes. The electrolyte acts as both a reactant and an ion-transport medium. As the battery discharges, the concentration of sulfuric acid decreases and both anode and cathode electrodes absorb lead sulfate. During recharge, the reverse actions occur.

It is noted that "secondary" batteries, such as the lead-acid battery are rechargeable batteries whereas "primary" batteries are not rechargeable.



A. Schematic Representation of a Cell

Anode: $Pb + HSO_4^- \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} PbSO_4 + H^+ + 2e^-$

Cathode: $PbO_2 + 3H^+ + HSO_4^- + 2e^- \rightleftharpoons PbSO_4 + 2H_2O$

Overall: $Pb + PbO_2 + 2H^+ + 2HSO_4^- \rightleftharpoons 2PbSO_4 + 2H_2O$

B. Reactions

FIGURE 3-1. LEAD ACID BATTERY

3.2 Battery Characteristics

The following battery characteristics are discussed with respect to application to railroad traction:

1) Rated specific energy - Wh/kg
2) Rated specific power - W/kg
3) Cycle life - no. of charge/discharge cycles
4) Depth of discharge - %
5) Overall efficiency - %
6) Capital cost - $/kWh
7) Others - charge time, safety, reliability, environmental effects.

These characteristics are defined below:

1) Rated specific energy is the rated energy which the battery can deliver per unit battery weight. High specific energy is desirable in order to obtain adequate vehicle range with a reasonable battery weight.

2) Rated specific power is the rated power which the battery can deliver per unit battery weight. High specific power is desirable in order to obtain adequate vehicle acceleration capability.

Specific energy and specific power of lead-acid batteries are interrelated. The relation is shown in Fig. 3.2 for an existing lead-acid battery. The physical phenomenon underlying the relation is explained as follows: operation at higher specific power corresponds to higher reaction rates at the electrodes, giving lower concentrations of electrolyte and electrode reactants, which in turn inhibits further reactions, and thus decreases specific energy.

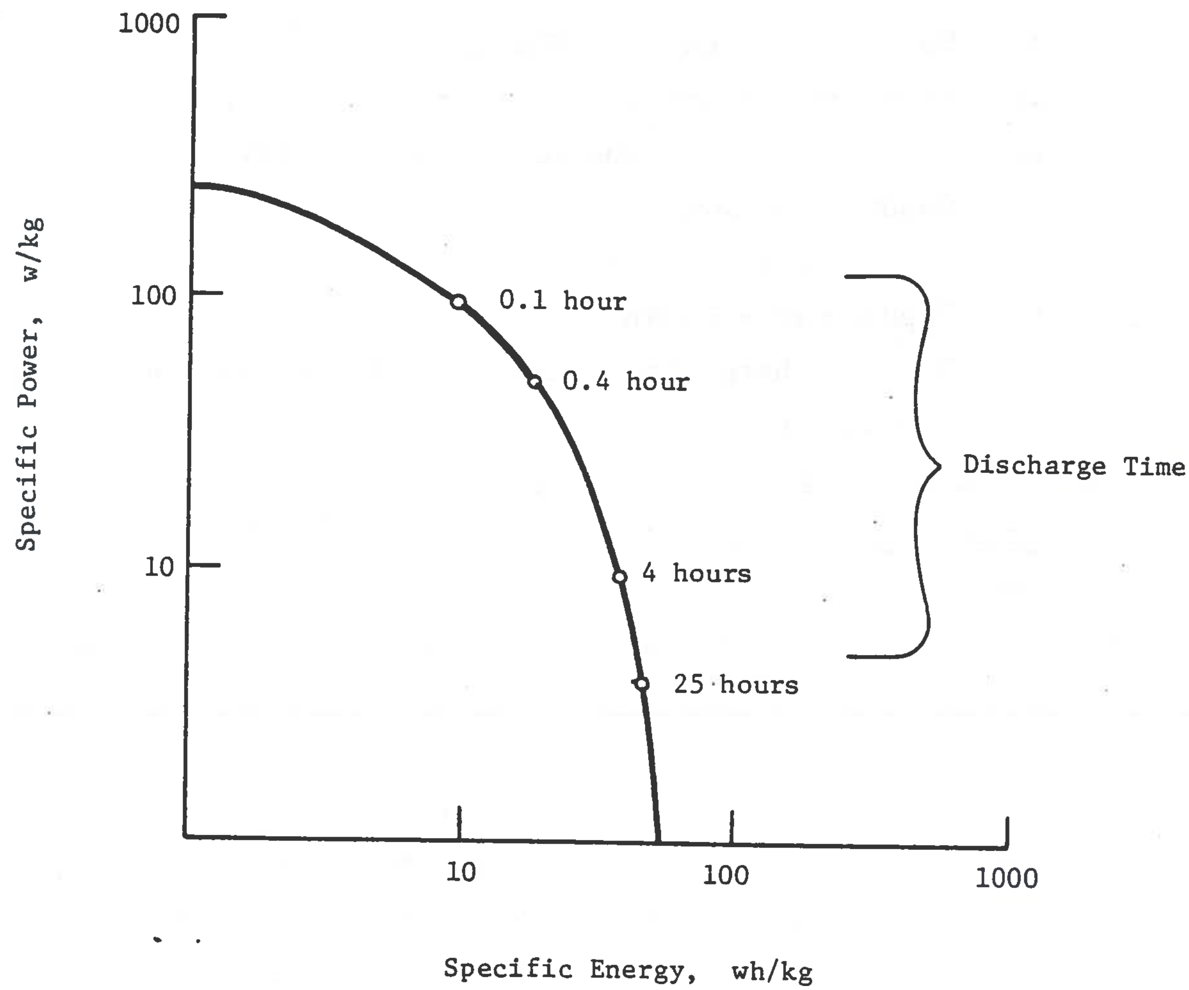


FIGURE 3.2. SPECIFIC ENERGY -- SPECIFIC POWER CURVE DELCO 512® LEAD-ACID BATTERY*

*Based on Reference 7.

With respect to railroad transport application, the tradeoff between specific energy and specific power translates into a tradeoff between vehicle range and acceleration capability. Good range is provided by batteries with high specific energy, and good acceleration capability is provided by batteries with high specific power. Conversely, for a given battery, reduced acceleration maneuvers will result in increased range. Lead-acid battery performance is thus dependent on a vehicle's speed-time profile (its pattern of acceleration, cruise and deceleration maneuvers).

In addition to energy and power per unit weight, energy and power per unit volume should also be considered due to space limitations on many vehicles. However, weight density is normally the limiting factor for vehicle applications rather than volume density.

3) Cycle life is the number of charge-discharge cycles that a battery is capable of delivering before wear-out or failure occurs. It is a measure of its useful life. Cycle life is a complicated phenomenon depending on depth of discharge, ambient temperature, idle time between uses, rate of charge and discharge, and other factors. Years of testing are required to assess cycle life in the environment in which the battery is operated.

4) Depth of discharge specifies the percentage of rated energy which is useable. A battery is not normally completely discharged, otherwise its cycle life would be adversely affected. Accordingly, the rated specific energy of a battery is higher than its useable specific energy.

5) Overall efficiency is the ratio of energy that can be drawn from the battery to the corresponding energy that must be supplied to the battery. Losses in the form of heat are incurred during the charge and discharge cycles. Overall (or round trip) battery efficiency is the product of the charge and discharge efficiencies. Energy losses (or less than 100% efficiency) contribute to vehicle operating costs, as well as limiting vehicle range.

6) Capital cost of batteries is specified in terms of cost per unit of stored energy which the battery can deliver, $/kWh. For a known cycle life, capital cost can be combined with operating cost to determine an overall measure for comparison with other technologies. For example, the present worth of capital and operating costs can be amortized over the distance the vehicle is driven during its useful life, to determine a life-cycle cost in cents/km.

7) Other factors include charge time, safety, reliability and environmental effects. For battery-operated trains, passenger stops of 10 minutes or longer could be used for partial battery recharging. Also, another option is battery exchange, especially where long charge times preclude recharging at passenger stops.

3.3 Status of Existing Commercial Batteries

The lead-acid battery is the only technology now commercially available in a form suitable for vehicle use. An example is the Varta type H585V1 lead-acid battery, whose characteristics are shown in Table 3.1. This battery is used in the M.A.N. Elektrobus, operating in West Germany.

TABLE 3-1. CHARACTERISTICS OF LEAD-ACID BATTERY FOR M.A.N ELEKTROBUS VARTA - TYPE H585VI

Characteristic	Units	Value
Rated specific energy (at 5 h discharge rate)	Wh/kg	27
Rated specific power (at 5 h discharge rate)	W/kg	5.4
Peak specific power	W/kg	35
Cycle life (at 60% depth of discharge, 55°C maximum temperature)	No. of Cycles	1500
Overall efficiency	%	60
Charge time (from 60% depth of discharge)	h	3.3
Rated volume energy density	Wh/cm^3	0.07
Rated power per unit volume	kW/m^3	14
Peak power per unit volume	kW/m^3	94.

The experimental Delco 512 battery developed by General Motors has a specific energy in excess of 55 Wh/kg, and peak specific power in excess of 110 W/kg, previously shown in Fig. 3.2. However, the battery at present does not provide satisfactory cycle life at deep discharges associated with vehicle use.

Original equipment manufacturer's 1979 price of lead-acid batteries is estimated to be $50/kWh. (Ref. 7).

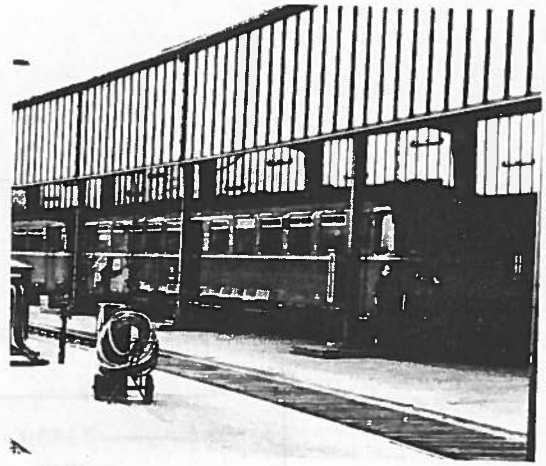
3.4 Experience with Battery-Operated Trains

The German Federal Railroad is currently operating a fleet of some 230 railcars powered entirely by lead-acid batteries. These trains provide intercity passenger service on over 3000 mi of track routes in the north, central and south of West Germany (Ref. 4). Many of the cars were placed in service more than 20 years ago. The cars average 56,000 mi per year with speeds up to 60 mi/h and ranges of 150-250 mi (depending on schedule) per battery charge.

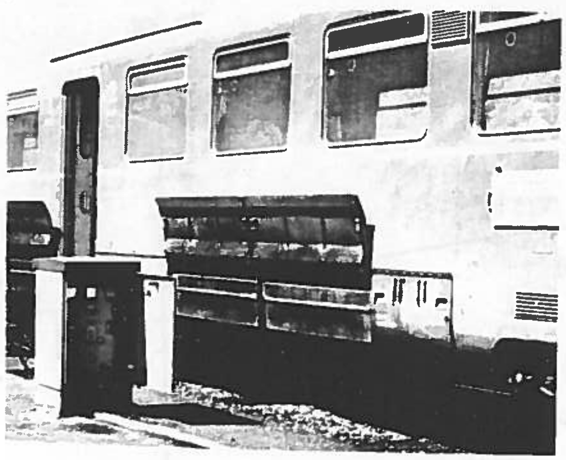
The ETA 515 4-axle car, shown in Figs. 3.3 and 3.4, was designed to pull one trailer car (ESA 515). In 1956, test runs obtained distances of 324 mi with 14 stops and a mean speed of 40 mi/h. However, battery exchanges were required to obtain this range.

Characteristics of these battery-operated trains are shown in Tables 3.2 and 3.3. In comparison with the Metroliner self-powered car, Fig. 2.6, the German car is lighter - 49 vs. 80 tons - and is designed to operate at lower maximum speeds - 60 vs. 130 mi/h.

Model 515 rail car



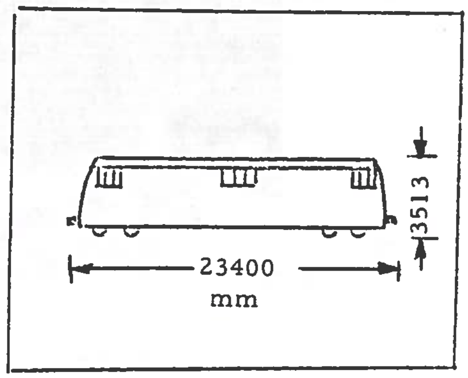
Model 517 rail car



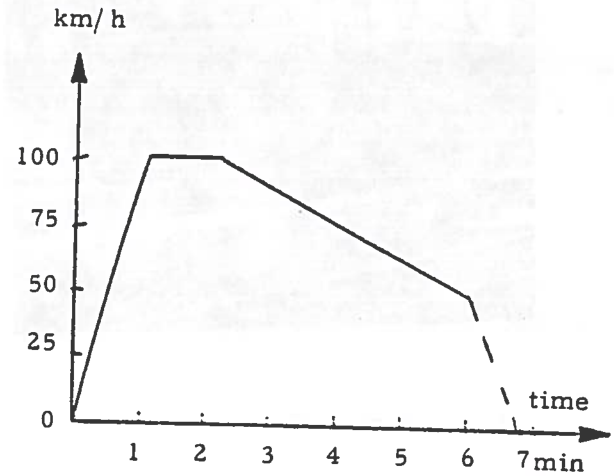
Complete battery for electric trains

FIGURE 3-3. BATTERY-OPERATED RAILCARS
GERMAN FEDERAL RAILROAD

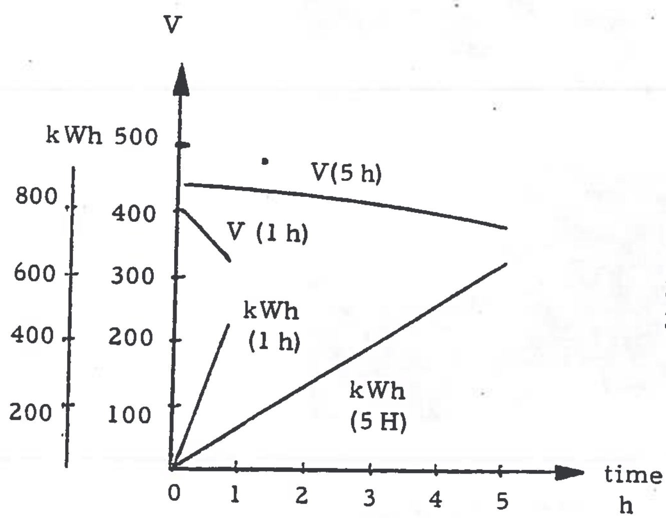
*Courtesy: Progressive Railroading



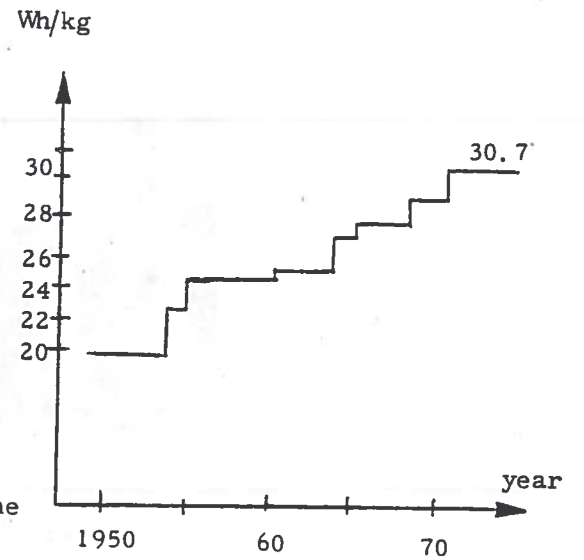
Model 515



Speed Diagram of Battery Railcar



Discharge Curves of the Railcar Traction Battery (VARTA 8 TR 5 Cells)



Development of the 3-h Energy Density

FIGURE 3-4. CHARACTERISTICS OF BATTERY-OPERATED RAILCARS GERMAN FEDERAL RAILROAD - (REF. 4)

TABLE 3-2. CHARACTERISTICS OF BATTERY-OPERATED RAILCARS, GERMAN FEDERAL RAILROAD (REF. 4)

Car Characteristics (ETA/ ESA 515)	Units	Battery Car	Trailer Car	Total
Length	ft	76.7	76.7	153.4
Gross Weight (with batteries, without passengers)	tons	49	22	71
No. axles	No.	4	4	8
No. motors	No.	2	0	2
Rated motor power	kW	100	—	200
Rated motor voltage	V	440	—	
No. passenger seats	No.	68	82	150

Operating Characteristics	Units	Value
Range (without battery exchange/ recharge)	mi	155
Average speed	mi/ h	40
Maximum speed	mi/ h	60
Acceleration capability	mi/ h/ s	1.1
Battery exchange time	min	30
Average electrical energy consumption (2.2 kWh/ km, 82 t gross weight)	kWh/ton-mi	0.043

TABLE 3-3. CHARACTERISTICS OF LEAD-ACID BATTERY FOR ETA 515 RAILCAR, GERMAN FEDERAL RAILROAD, VARTA-TYPE (REF. 4)

Battery Characteristics	Units	Value
Type		lead-acid
Rated specific energy (3 h discharge rate)	Wh/kg	30.7
Rated specific power	W/kg	10.2
Peak specific power	W/kg	30
Cycle life	No.	1500
Overall efficiency (estimated)	%	60
Depth of discharge	%	70
Weight	tons	16
Footprint area	ft^2	110
Height	ft	2.67
Rated energy	kWh	440
Average voltage	V	400
Charge time - 40% charge	min	30
- 90% charge	min	90
- 100% charge	min	360

3.5 Current Development Work

More than 25 types of advanced batteries have been proposed for electric highway vehicle applications. The following three, selected by EPRI as a basis for technology projections (Ref. 8) are discussed:

1) Zinc-chlorine
2) Sodium-sulfur
3) Lithium-metal sulfide

1) The zinc-chlorine battery uses zinc as the anode, chlorine gas as the cathode, and aqueous zinc chloride as the electrolyte.

Two problems associated with the zinc-chlorine battery are: (a) the corrosive and toxic nature of chlorine gas; (b) dendrite formations on the anodes. Dendrites are uneven zinc deposits which cover the anode during charging. Their sharp edges tend to penetrate the cell separator, causing a battery failure.

A zinc-chlorine battery was demonstrated in a Chevrolet Vega in 1972. The demonstration used a safe method for storing chlorine gas, without pressure, in which the chlorine is absorbed in water to form a non-corrosive chlorine hydrate. In addition, the battery uses a slightly acidic electrolyte in which the zinc anode can be reformed without rapid dendrite formation.

EPRI and DOE are currently funding a zinc-chlorine project, with Energy Development Associates (EDA), Madison Heights, Michigan, as major developer. EDA, a subsidiary of Gulf plus Western, has opened a pilot manufacturing plant in Greensboro, North Carolina with the capability of producing up to one hundred 50 kWh zinc-chlorine batteries per day beginning January 1981.

2) The sodium-sulfur battery uses molten sodium as the anode, molten sulfur as the cathode, and beta alumina as the electrolyte and separator. Beta alumina is a solid ceramic material capable of conducting sodium ions. The overall reaction creates sodium polysulfide (Na_2S_3). The sodium and sulfur electrodes are maintained in a molten state by control of the operating temperature between 300 and 350° C.

The sodium sulfur battery was invented by Ford Motor Company in the 1960's. Major technical problems are: (a) inability of a cell to accept full charge; (b) corrosion of the sulfur container; (c) difficulty of component fabrication; (d) degradation of seals; and (e) low cycle life. Particularly important is the high operating temperature, which intensifies safety problems during recharging or collision. Major improvements have been reported by developers. In particular, chrome-coated steel serves as an improved sulfur container. Also, new seals and a high quality electrolyte have been developed.

The DOE is currently funding sodium-sulfur projects, with Ford and Dow Chemical Co. as major developers. Also, General Electric has a sodium sulfur project, sponsored by EPRI.

British Rail is working on a sodium-sulfur battery for use in railroad traction (Ref. 10, 17). A 10 kWh sodium-sulfur battery comprising 176 cells has been tested by British Rail (Ref. 18). Applications include multiple unit cars and battery/electric hybrid locomotives.

EVA-Chloride is currently developing a 150 kWh sodium-sulfur battery for a 7.5 ton electric delivery vehicle (Ref. 16).

3) The lithium-metal sulfide battery uses lithium as the anode, iron sulfide as the cathode, and a lithium chloride, potassium chloride mixture as the electrolyte. Lithium is the earth's lightest solid element, with a weight density equal to one-thirtieth that of lead. Lithium also has one of the highest electrochemical potentials of any feasible anode material.

One technical problem associated with the lithium-metal sulfide battery is the difficulty in maintaining seals in a battery that operates up to 650°C.

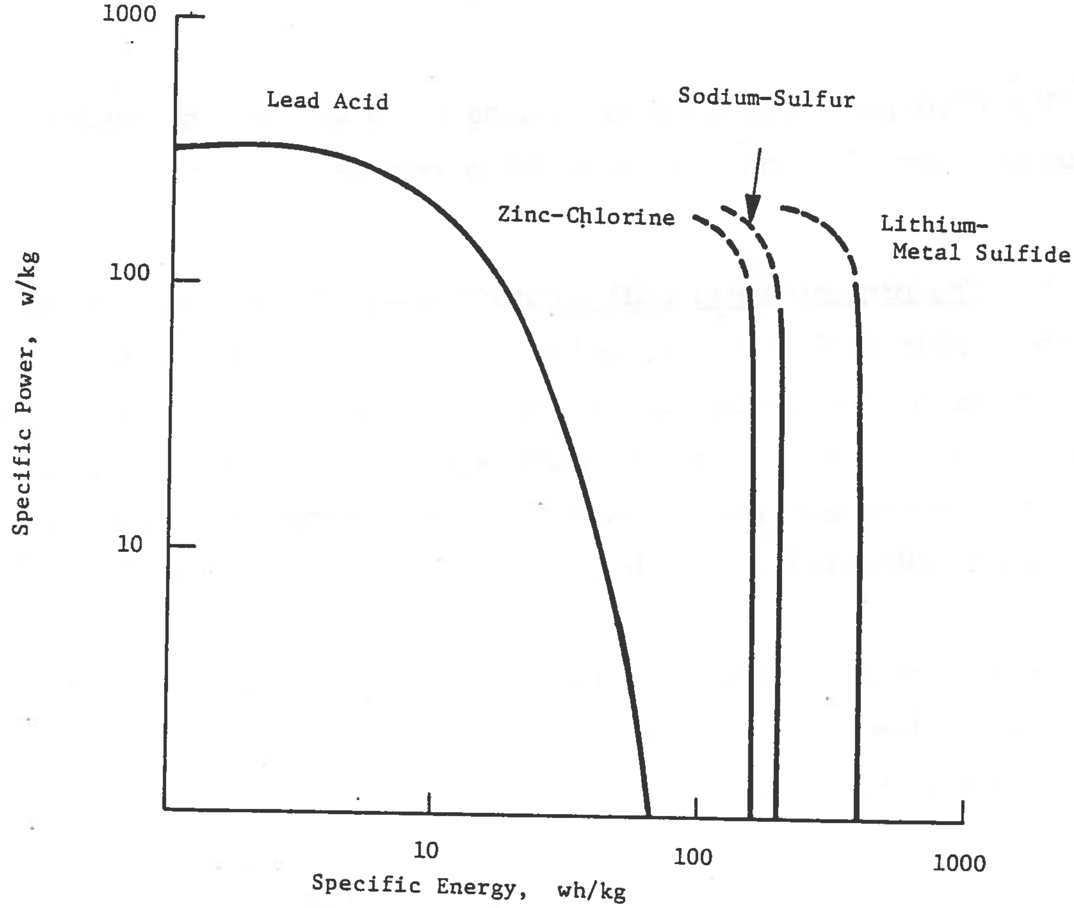
General Motors is currently developing a lithium-metal sulfide battery, and has recently reported a reduced operating temperature of 425°C.

3.6 Prospects - Technical and Economic

Table 3.4 shows a summary of projected battery characteristics given by EPRI (Ref. 8) for an advanced lead-acid battery as well as the three battery technologies discussed in Section 3.5.

The EPRI projections are intended to represent a range of possible future technology developments, and are based on estimates from published reports. As shown, specific energy projections range from 62 to 440 Wh/kg, compared to 35 Wh/kg for commercially available lead-acid batteries. Date of commercial availability ranges from 1982 for the advanced lead-acid battery to beyond 1995 for the lithium-metal sulfide battery.

TABLE 3-4. EPRI SUMMARY OF PROJECTED BATTERY CHARACTERISTICS*



A. Specific Energy-Specific Power Curves

Battery Type	Advanced Lead-Acid	Zinc-Chlorine	Sodium-Sulfur	Lithium Metal Sulfide
Rated Specific Energy (Wh/kg)	62	170	220	440
Cycle Life (cycles)	300	1000	1000	1000
Overall Electrochemical Efficiency (percent)	60	70	80	90
OEM Price (1975$/kWh)	$35	$41.20	$27.60	$36.50
Date of Commercial Availability	1980	1982-1985	1987-1995	1995->2000

B. Technical - Cost Assumptions

*EPRI EA-623, July 1978 (Ref.8)

A more recent EPRI projection is shown in Table 3.5 (Ref.. 9). It is noted that the more recent EPRI specific energy projections (Table 3.5) are lower than their earlier projections (Table 3.4). Table 3.5 also includes two additional batteries, where the nickel-zinc battery is most notable.

The nickel-zinc battery uses zinc as the anode, nickel oxide as the cathode, and an aqueous electrolyte of about a 40% solution of potassium hydroxide. It is widely publicized by General Motors, which prefers to call it a zinc-nickel oxide battery, as a very likely near-term candidate for electric cars. Specific energy is about three times that of existing lead-acid batteries.

In contrast to the EPRI summaries, Table 3.6 shows another summary of advanced batteries based on interviews (Ref. 10) of battery experts over a 3-year period. In addition to the battery technologies presented by EPRI, others are given in Table 3.6, where the lithium-air battery is the most notable.

The lithium-air battery uses lithium as the anode, consumes air at the cathode, and uses a potassium hydoxide solution as the electrolyte. The battery operates at ambient temperature, and the lithium anode is replaceable. During discharge, lithium carbonate in the form of a dry powder is collected by pumping carbon dioxide through the battery. Specific energy is estimated at up to 100 times that of existing lead-acid batteries.

TABLE 3-5. EPRI BATTERY PROJECTION (REF. 9)

	BATTERY PROSPECTS—EV APPLICATION								
Battery Type	Temperature (°C; °F)		Energy Density (Wh/kg; Wh/lb)		Power Density (W/kg; W/lb)		Estimated Cycle Life (charges)	Estimated Cost ($/kWh)	Estimated Availability (year)
Lead-acid	Ambient		40	18	70	32	>1000	70	1982
Nickel-iron	Ambient		55	25	100	45	>2000	100	1983
Nickel-zinc	Ambient		75	34	120	55	>500	100	1982
Zinc-chlorine	30–50	85–120	90	41	90	41	>1000	75	1985
Sodium-sulfur	300–350	570–660	90	41	100	45	>1000	75	1985
Lithium-iron sulfide	400–450	750–840	100	45	100	45	>1000	80	1985

TABLE 3-6. ADVANCED BATTERY SUMMARY (REF. 10) (BASED ON INTERVIEWS OF BATTERY EXPERTS)

Developer, maker or researchers	Couple materials	Electrolyte	Circulating pump	Operating temperature	Specific power	Watt-hours/lb advanced type	Special features
Many	Lead/lead dioxide	Sulfuric adid	No	Ambient	Good	18	Low cycle life; low specific power
Eagle-Picher, Gould, Toyota	Nickel/ iron	Potassium hydroxide	No	Ambient	Good	30	Early availability; high cycle life
GM, ESB, Yardney ERC, Atomics Int. Fiat, Gould	Nickel/ zinc	Potassium hydroxide	No	Ambient	Good	41	Zinc shape changes; zinc dendrites reduce cycle life
Japanese and French companies	Zinc/ air (fixed type)	Potassium hydroxide	No	Ambient	Low	56	Hard to recharge
	Zinc/ air (circulating electrolyte)	Zinc powder in pot-hyd	Yes	Ambient	Low	45	Empty and refill tank to recharge
Eagle-Picher, GM Rockwell, Gould	Lithium/metal sulfide	Lithium chloride potassium chloride	No	750° F	High	72	Offers waste heat for car heat or A/C
Dow, GE, Brown-Boveri, Ford, EVA-Chloride	Sodium/sulfur	Beta alumina Boron glass	Yes	570° F	High	90	Couple materials may be dangerous on road
EDA (Gulf & Western)	Zinc/ chlorine	Aqueous zinc chloride	Yes	Ambient	High	68	Chlorine stored as refrigerated hydrate
Exxon Research Univ. of British Columbia	Lithium/titanium disulfide- Lithium molydenum disulfide	Propylene carbonate/ methyl acetate	No	Ambient	High	72	Uses intercalation effect; molydisulfide a natural low cost mineral
Lockheed	Lithium/ air Aluminum/air	Water Potassium hydroxide	Yes	Ambient	High	3045	Mechanically recharged fuel cell long range full performance potential in future

It is noted from Table 3.4A that specific power is independent of specific energy for all advanced batteries except the lead-acid. Thus, operation at high specific power does not decrease specific energy for these advanced batteries. This is an important consideration for applications where high accelerations demand high power drains for short intervals.

It is difficult to make any accurate projections of performance and cost for advanced technology batteries. In the past, initial announcements of new and promising battery technologies were followed by technical difficulties in the laboratory. In particular, all batteries are subject to both internal and external corrosion. Accordingly, the projections of Tables 3.4-3.6 could have large error margins.

The following advanced batteries are selected for reference and comparison of battery-powered trains:

1) Advanced lead-acid
2) Nickel-zinc (or zinc-nickel oxide)
3) Sodium-sulfur

These advanced batteries are likely candidates for vehicle application, and provide a range of technology developments in the 1980's.

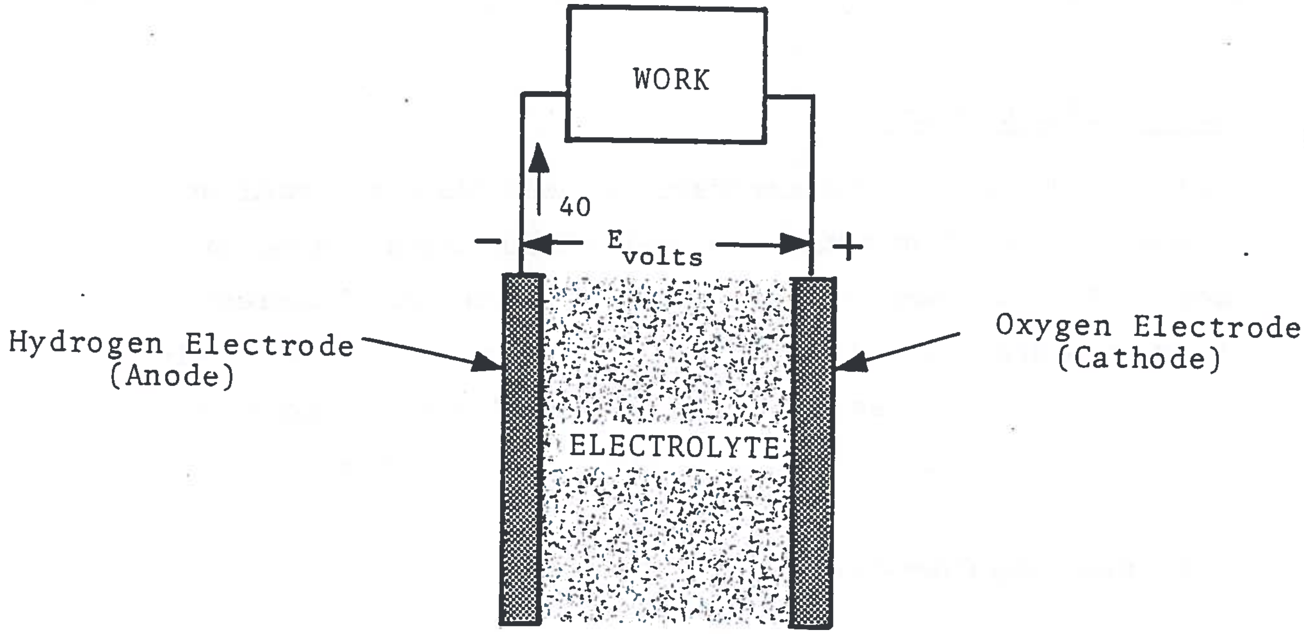
4. FUEL CELLS

In this section, fuel cells are discussed with respect to railroad traction. A brief introduction to fuel cell operation is given in Section 4.1, and fuel cell characteristics which are of interest to railroad traction are presented in Section 4.2. Current development work is discussed in Section 4.3, and technical and economic prospects for fuel cells are given in Section 4.4.

4.1 Fuel Cell Operation

A fuel cell converts the chemical energy of a fuel directly to electrical energy without intermediate combustion or thermal cycles. An example is the hydrogen fuel-cell shown in Fig. 4.1 (Ref. 15). It combines hydrogen and oxygen to produce electric energy and water.

The fuel cell is similar to a battery in that it contains two electrodes and an electrolyte. The first generation utility fuel cell (Ref. 15) uses hydrogen-rich fuel as the anode reactant, oxygen or air as the cathode reactant, and phosphoric acid as the electrolyte. At the anode, hydrogen splits into electrons, which are transferred through the electrical circuit to the cathode, and hydrogen ions, which are transferred through the electrolyte to the cathode. At the cathode, oxygen combines with the electrons and hydrogen ions to produce water.



A. Schematic Representation of a Cell

Anode: $H_2 + 2OH \longrightarrow 2H_2O + 2e^-$

Cathode: $1/2\ O_2 + H_2O + 2e^- \longrightarrow 2OH^-$

Overall: $2H_2 + O_2 \longrightarrow 2H_2O$

B. Reactions

FIGURE 4-1. THE HYDROGEN FUEL CELL

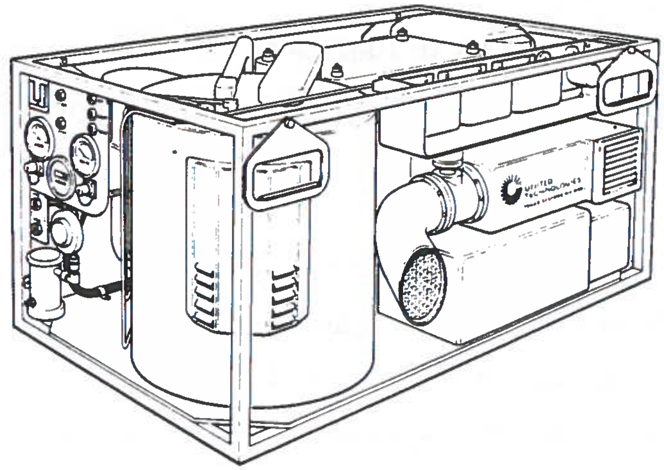
4.3 Current Development Work

Research and development of fuel cells for aerospace and electric utility applications have led to several recent improvements in fuel cell performance.

The U.S. Army fuel cell program is directed primarily at developing a family of silent, lightweight fuel cell power sources with output ratings of 0.4 to 5.0 kW (Ref. 12). One example is a 1.5 kW methanol fuel cell, where reformed methanol is used in the anode, air at the cathode, and phosphoric acid as the electrolyte. A fuel processor called a low-temperature steam reformer is used to process premixed methanol and water. Characteristics of this power source are shown in Fig. 4.2.

EPRI, DOE and Consolidated Edison Company of New York currently have a joint utility/government program to install a 4.5 MW fuel cell power source on the Con. Ed. power system in Manhattan (Ref. 13). United Technologies, Inc., South Windsor, Connecticut, is building and delivering the fuel cells to the Con. Ed. site.

The first-generation utility fuel cell has a fuel processor which converts naphtha or natural gas to a hydrogen-rich gas, which is then supplied to the anode. At the anode, hydrogen is disassociated into electrons and hydrogen ions. At the cathode, oxygen from air combines with the electrons and hydrogen ions to produce water in the form of steam. Hydrogen ions flow in the phosphoric acid electrolyte. Operating temperature for this fuel cell is 350° F.



A. Layout*

Characteristic	Units	Value
Specific power	W/kg	19
Power per unit volume	kW/m^3	7.6
Lifetime	h	6000
Rated output	kW	1.5
Weight	lb	175
Volume	ft^3	7
Fuel consumption	lb/kWh	1.22
Start time	min	15
MTBF	h	1500
Temperature range	°F	-65- + 125
No. of starts	No.	2000

B. Characteristics

FIGURE 4-2. 1.5 KW U.S. ARMY METHANOL FUEL CELL POWER SOURCE

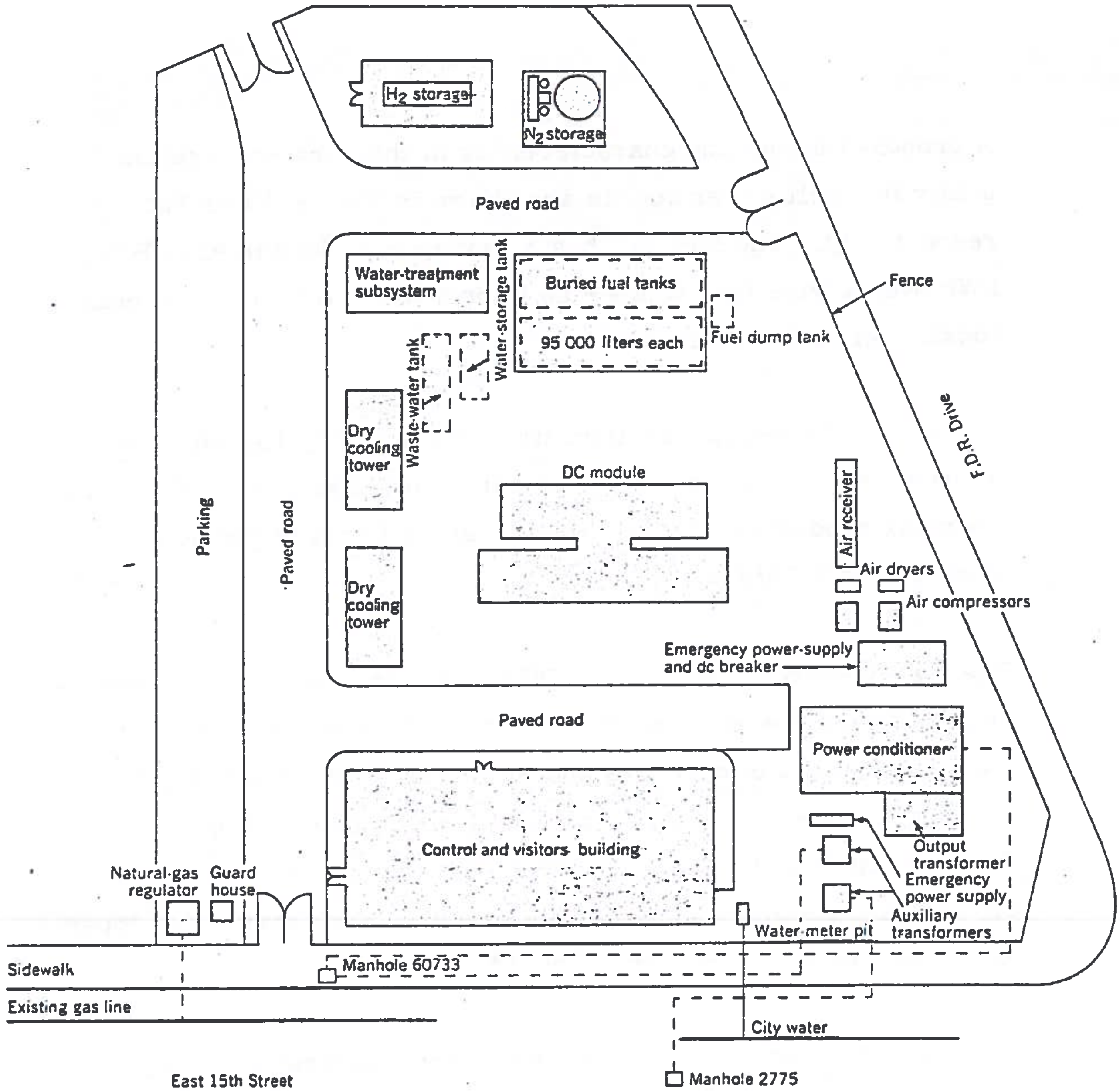
*Reprinted by permission of the Electrochemical Society, Inc.

A proposed layout and characteristics of this first-generation, utility fuel cell power source are shown in Fig. 4.3 and Table 4.1, respectively. The fuel cell has a heat rate of 9000 to 9300 BTU/kWh over a wide load range - an improvement over conventional fossil-fuel power sources.

Projected commercial availability of these utility fuel cell power sources is 1985, at an estimated initial installed cost of $1000/kW. As mass production is introduced, installed cost is projected to decrease to $350/kW (Ref. 13).

The Gas Research Institute and DOE are also supporting the development of a 40 kW phosphoric acid fuel-cell power source to supply the energy needs of buildings and industrial processes. A pilot version of the 40 kW unit has accumulated 17,000 h of operation. The unit, shown in Fig. 4.4, incorporates provision for heat recovery, and recovers water for its own use. The major developer is United Technologies, Inc. (Ref. 14).

EPRI and DOE are also developing a second-generation utility fuel-cell with characteristics shown in Table 4.2. This 5 to 10 MW fuel cell uses molten carbonate as the electrolyte, and can consume either processed low-sulfur distillate or gasified coal at the anode. To achieve an improved heat rate of 7500 BTU/kWh (2.2 J/Ws), the cell operating temperature is raised to 1200° F, as opposed to 350° F for a phosphoric acid fuel cell (Ref. 15).

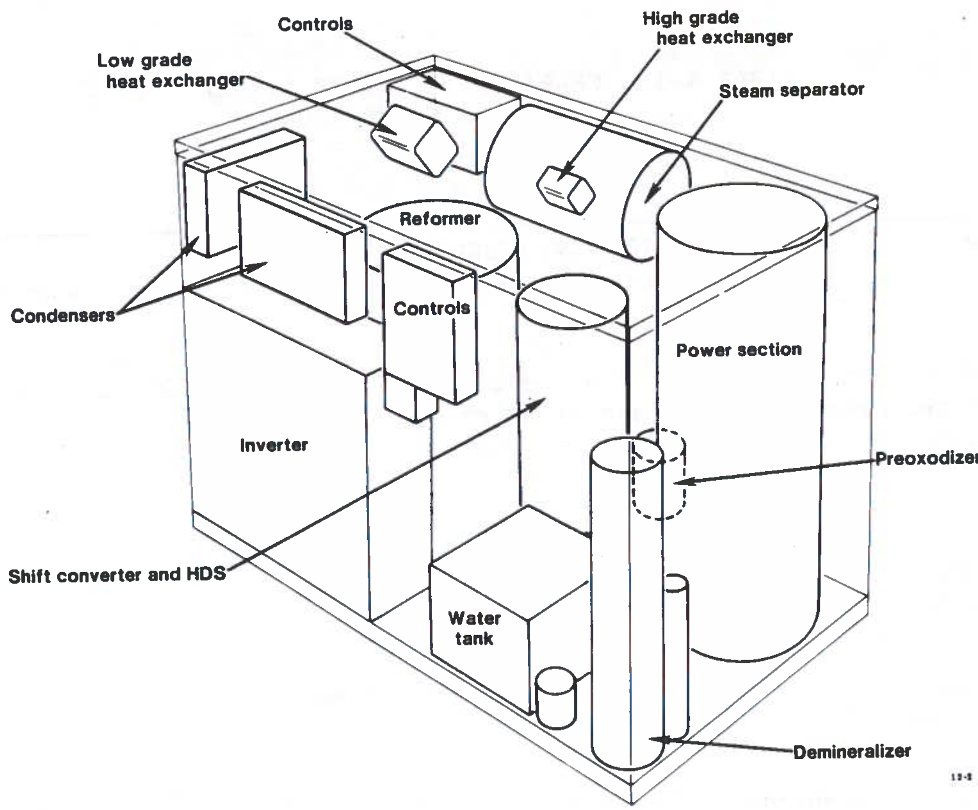


(Area = 35,000 ft^2)

FIGURE 4-3. PROPOSED LAYOUT OF 4.8 MW UTILITY FUEL CELL POWER SOURCE

TABLE 4-1. CHARACTERISTICS OF 4.8 MW UTILITY FUEL CELL POWER SOURCE

Heat rate	2.72 J/Ws (9300 Btu/kWh) at rated power 2.64 J/Ws (9000 Btu/kWh) at 30 percent of rated power
Power	
Power rating	4.5 MW (net ac) at sea level and 350°F at unity power factor
Minimum power	25 percent of rated power
Standby	Zero output power
Life	
Design life (with scheduled overhaul maintenance)	20 years
Fuels	
Liquid	Naptha or selected kerosene
Gaseous	Natural gas
Emissions	
Approximate emissions during normal operation	Microgram per joule input: NO_x = 0.009, SO_2 = 0.00001; particulates = 0.000001; smoke = none
Load-response time	
Minimum power to rated output	15 seconds
35-percent power to rated output	0.5 second
Electrical output	
Power form	3 phase; 60 ± 0.1 Hz
Voltage	13.8 kV ac
Fault currents	Under line-fault conditions, output current will not exceed 1.1 per unit on an rms basis over one cycle
Operation	
Control	Automatic, from remote or on-site controller
Modes	Load, spinning reserve, standby off, and no-load power-factor correction
Start	Four hours from 21°C (70°F)
Miscellaneous	
Ambient temperature	-34°C to + 43°C (-30°F to +110°F)
Acoustic noise	55 dB(A) 30 meters from power plant perimeter
Heat-rejection method	Air-cooled (dry cooling tower)
Commercial Availability	1986



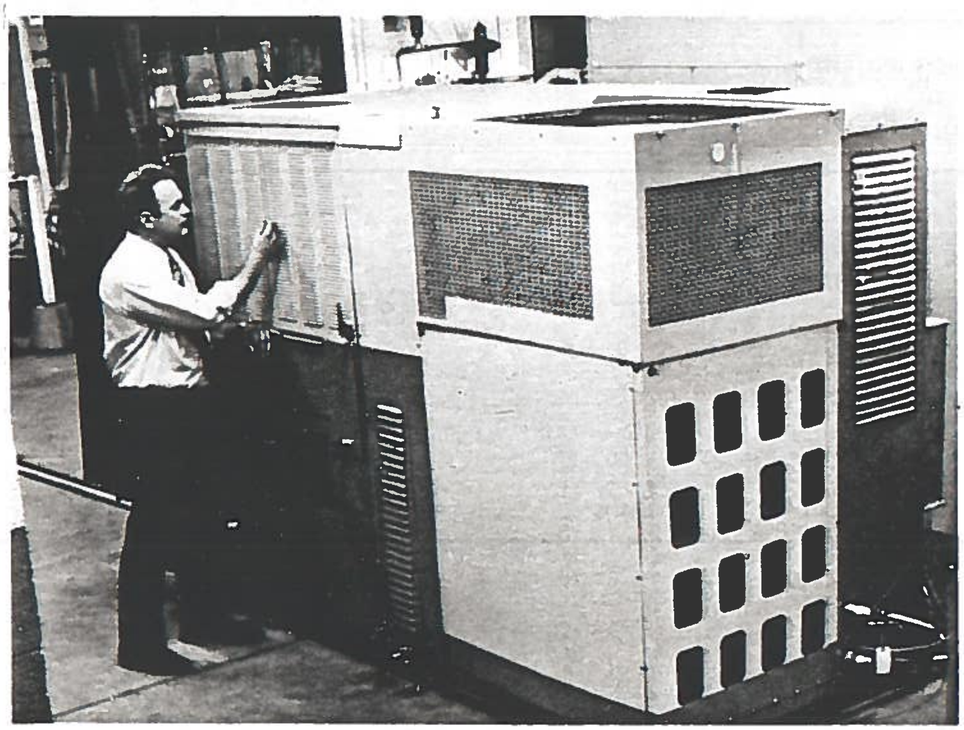


FIGURE 4-4. 40 KW FUEL CELL POWER SOURCE

*Figures reprinted by courtesy of United Technology Corporation

TABLE 4-2. CHARACTERISTICS OF SECOND-GENERATION UTILITY FUEL CELL POWER SOURCE (5 to 10 MW)

Heat rate	7500 BTU/kWh
Fuel	Coal gas
Electrolyte	Molten carbonate
Cell voltage	0.78 V dc
Cell temperature	650°C
Design lifetime	160 000 h
Time between cell stack refurbishings	40 000 h
Design cell current density	160 mA/cm^2
Commercial availability	1990

Two additional projects associated with the second-generation utility fuel cell are described here. One is an EPRI R&D project concerned with achieving molten carbonate cells which yield a 40,000 h life and high electrochemical cell performance. United Technologies, Inc. is the developer.

The second project, supported by DOE, involves a team of contractors managed by Argonne National Laboratory. This activity is aimed at integration of a molten carbonate fuel cell and a coal gasifier. Contractors include GE, Energy Research Corp., Institute of Gas Technology, and Oak Ridge National Laboratory.

4.4 Prospects - Technical and Economic

Table 4.3 shows a summary of projected fuel cell power source characteristics for the two fuel cell types currently under development, the phosphoric acid and molten carbonate fuel cells. These projections are based on a recent EPRI status report (Ref. 11).

Both the phosphoric acid and molten carbonate fuel cells have a design lifetime goal of 40,000 operating hours before requiring major cell replacement (Ref. 11). The molten carbonate fuel cell has an

TABLE 4-3. SUMMARY OF PROJECTED FUEL CELL POWER SOURCE CHARACTERISTICS (REF. 11)

Fuel Cell Type (Electrolyte)		Phosphoric Acid	Molten Carbonate
Characteristic	Units		
Lifetime-Operating Hours	h	40,000	40,000
Heat Rate	BTU/kWh	9300 - 8300	7500
Date of Commercial Availability		1985	1990
Capital Cost	1979 $/kW	350-1000	---

improved heat rate (7500 BTU/kWh) compared to the phosphoric acid fuel cell (9300-8300 BTU/kWh). Commercial availability of molten carbonate (1990) is estimated to be five years behind availability of phosphoric acid (1985). Projected capital cost of the phosphoric acid fuel cell power source, $350/kW to $1000/kW, will depend on the quantities of these power sources that are produced.

Fuel cells have primarily been designed for (1) aerospace applications, where power ratings are low and cost is not a major factor, and (2) utility applications, where weight and volume are not major factors. Accordingly, fuel cell application to railroad traction requires a special design.

Table 4.4 shows a comparison of fuel cell design constraints for railroad traction with fuel cell design constraints for aerospace and electric utility applications.

TABLE 4-4. COMPARISON OF DESIGN CONSTRAINTS FOR THREE FUEL CELL APPLICATIONS

Design Constraint	Area of Application for Fuel Cells		
	Aerospace	Electric Utilities	Railroad Traction
Required Weight	important	not important	somewhat important
Required Volume	important	not important	important
Power Rating	low	very high	high
Initial Cost	not important	important	somewhat important

5. APPLICATION OF ADVANCED BATTERIES TO RAILROAD TRACTION

In this section the energy and power requirements determined in Section 2 for the three selected consists operating on the Boston to NYC run are compared with the characteristics of the three advanced batteries selected in Section 3, in order to determine effective applications of advanced batteries to railroad traction. Section 5.1 considers the SDP40F - 5 car consist. Section 5.2 considers the AEM7 - 5 car consist. Section 5.3 considers the Metroliner 5 car consist. The impact of altered operations on the energy and power requirements are analyzed in Section 5.4. Economics of battery operations are discussed in Section 5.5.

5.1 SDP40F-5 Car Consist

The SDP40F-5 car consist requires a specific energy of 71 Wh/kg at the input to the traction motors, based on the following assumptions given in Section 2: (1) 232 mi distance, 8 stops; (2) 90 mi/h maximum cruising speed; (3) no increase in the total weight of the locomotive when replacing the conventional energy source with batteries; (4) no battery exchange or recharging during the 232 mi trip. In order to satisfy the 71 Wh/kg requirement, the rated specific energy of a battery must be greater, since only part of the battery rated energy is useable. Based on a 70% depth of discharge, a useable specific energy of 71 Wh/kg corresponds to a rated specific energy of 101 Wh/kg. Thus the rated specific energy requirement for the SDP40F-5 car consist is 101 Wh/kg.

Table 5.1 summarizes the consist requirements given in Section 2 and the capabilities of the advanced batteries selected in Section 3. As shown in Table 5.1, the advanced lead-acid and nickel-zinc batteries have projected rated specific energies less than 101 Wh/kg; whereas the sodium-sulfur battery has a projected rated speciific energy greater than 101 Wh/kg.

As shown in Table 5.1, the SDP40F-5 car consist also requires a peak specific power of 37 W/kg at the input to the traction motors. The projected peak specific power of all of the advanced batteries is greater than the 37 W/kg requirement.

It is also noted that specific power is independent of specific energy for all except the lead-acid battery. Thus operation at high specific power does not decrease the specific energy for these advanced batteries. When operating a lead-acid battery at high specific power, more energy is required due to a decrease in specific energy. Lead-acid battery energy requirements should therefore consider the consist speed-time profile.

It is concluded that only the sodium-sulfur battery satisfies both the specific energy and specific power requirements of the SDP40F-5 car consist, based on the selected assumptions of Section 2. Successful development of the sodium-sulfur battery would provide a potentially effective application to the SDP40F-5 car consist.

TABLE 5-1. CONSIST REQUIREMENTS VERSUS BATTERY CAPABILITIES

		CONSIST REQUIREMENTS[1]						BATTERY CAPABILITIES[2]		
	Consist	SDP40F	AEM7		Metroliner			Battery		
	Maximum Cruising Speed	90 mi/h	90 mi/h	120 mi/h	90 mi/h	120 mi/h	150 mi/h	Advanced Lead-Acid	Nickel-Zinc	Sodium-Sulfur
Rated[3] Specific Energy	Wh/kg	101	243	363	129	173	237	40-62	90	200-220
Peak Specific Power	W/kg	37	234	310	161	215	215	100	100	100

1) Refer to Section 2

2) Refer to Section 3

3) Rated specific energy requirements for the consists are based on 70% depth of discharge and the selected assumptions given in Section 2.

5.2 AEM7-5 Car Consist

AEM7-5 car consist requires a specific energy of 170 Wh/ kg at the input to the traction motors for a 90 mi/ h maximum cruising speed, based on the assumptions given in Section 2. Corresponding battery rated specific energy must be 243 Wh/ kg or greater, based on 70% depth of discharge. Also, required specific energy is 254 Wh/ kg for a 120 mi/ h maximum cruising speed, which corresponds to a battery rated specific energy of 363 Wh/ kg. Rated requirements are listed in Table 5.1

As shown in Table 5.1, none of the three advanced batteries selected have a specific energy capability sufficient for the AEM7 requirement.

As shown in Table 5.1, the AEM7-5 car consist also requires a peak specific power of 234 W/ kg at the input to the traction motors for a 90 mi/ h maximum cruising speed. None of the advanced batteries under development have this specific power capability.

The AEM7 locomotive is designed for high peak power to obtain high acceleration. Also the available weight for batteries, 24 tons, as shown in Table 2.5, is relatively low. As a result, the peak specific power requirement for batteries is high.

It is concluded that application of batteries to the AEM7-5 car consist would not be feasible, based on the selected assumptions.

5.3 Metroliner

The Metroliner self-powered car requires a specific energy of 90 Wh/kg at the input to the traction motors for a 90 mi/h maximum cruising speed, based on the assumptions given in Section 2. Battery rated specific energy must be 129 Wh/kg or greater, based on a 70% depth of discharge. Corresponding rated specific energy required is 173 Wh/kg at 120 mi/h maximum cruising speed and 237 Wh/kg at 150 mi/h maximum cruising speed. Rated requirements are listed in Table 5.1.

As shown in Table 5.1, the sodium-sulfur battery has a projected rated specific energy which satisfies the Metroliner requirement for 90 and 120 mi/h maximum cruising speeds, but not for the 150 mi/h speed.

As shown in Table 5.1, the Metroliner also requires a peak specific power of 161 Wh/kg at the input to the traction motors for a 90 mi/h maximum cruising speed. None of the advanced batteries under development have this specific power capability.

The Metroliner is also designed for high peak power to obtain high acceleration. It is also a relatively heavy self-powered car, 88 tons, with little weight available for batteries, 10 tons, as shown in Table 2.5. As a result, the peak specific power requirement for batteries is high. It is concluded that application of batteries to the Metroliner would not be feasible, based on the selected assumptions.

5.4 Impacts on Energy and Power Requirements

The following three options are discussed with respect to their impact on specific energy requirements for the New York to Boston run: (1) battery exchange; (2) weight reduction; (3) speed reduction. The results are summarized in Table 5.2.

As shown in Table 5.2A, the advanced lead-acid battery satisfies the SDP40F specific energy requirements with battery exchanges at one or two stops. The nickel-zinc battery satisfies the SDP40F specific energy requirements with a battery exchange at one stop. The sodium-sulfur battery satisfies the SDP40F specific energy requirements without battery exchange. The necessary numbers of battery exchanges are also shown for the AEM7 and Metroliner consists.

As shown in Table 5.2B, the nickel-zinc battery satisfies the SDP40F specific energy requirements with a 30% consist weight reduction (from 528 to 370 t). The sodium-sulfur battery satisfies the SDP40F requirements without consist weight reduction. Necessary consist weight reductions are also shown for the AEM7 and Metroliner consists.

As shown in Table 5.2C, the advanced lead-acid battery satisfies the SDP40F specific energy requirements with a 30-55% speed reduction (from 90 to 40-63 mi/h). The nickel-zinc battery satisfies the SDP40F requirements with a 7% speed reduction (to 83 mi/h). The sodium-sulfur battery satisfies the SDP40F specific energy requirements without speed reduction. Necessary speed reductions are also shown for the AEM7 and Metroliner consists.

TABLE 5-2. ENERGY IMPACTS OF ALTERING OPERATIONS FOR THE NEW YORK-BOSTON RUN

		Number of Battery Exchanges Necessary to Satisfy Specific Energy Requirements		
		BATTERY		
Consist	Maximum Cruising Speed	Advanced Lead Acid	Nickel Zinc	Sodium Sulfur
SDP40F - 5 Cars	90 mi/h	1-2	1	0
AEM7 - 5 Cars	90 mi/h 120 mi/h	3-6 5-9	2 4	1 1
Metroliner	90 mi/h 120 mi/h 150 mi/h	2-3 2-4 3-5	1 1 2	0 0 1

Table 5.2 A

		% Consist Weight Reduction Necessary to Meet Specific Energy Requirements		
		BATTERY		
Consist	Maximum Cruising Speed	Advanced Lead Acid	Nickel Zinc	Sodium Sulfur
SDP40F - 5 Cars	90 mi/h	*	30	0
AEM7 - 5 Cars	90 mi/h 120 mi/h	*	*	40-60 *
Metroliner	90 mi/h 120 mi/h 150 mi/h	*	*	0 0 30-35

*Necessary weight reduction > 75%

Table 5.2B

	% Reduction of 90 Mi/h Maximum Cruising Speed to Satisfy Specific Energy Requirements		
	BATTERY		
Consist	Advanced Lead Acid	Nickel Zinc	Sodium Sulfur
SDP40F - 5 Cars	30-55	7	0
AEM7 - 5 Cars	**	60	8-15
Metroliner	50-65	27	0

**Speed reduction> 75%

Table 5.2C

Table 5. 3 shows the % reduction in consist peak power necessary for application of advanced batteries. The consist peak specific power requirements shown in Table 5.1 must be reduced to 100 W/ kg, which is the capability of the advanced batteries selected.

As shown in Table 5. 3, no reduction in SDP40F peak power is necessary for application of advanced batteries. A 57 to 68% reduction in AEM7 peak power is necessary, and 38-53% reduction in Metroliner peak power in necessary.

A reduction in consist peak power results in reduced acceleration for a specified consist weight, and a corresponding increase in accelerating time. As shown in Table 5. 3, no increase in SDP40F accelerating time is necessary for application of advanced batteries. A 77 to 99% increase in AEM7 accelerating time is necessary, and a 61 to 102% increase in Metroliner accelerating time is necessary.

TABLE 5-3. POWER IMPACTS OF ALTERING OPERATIONS FOR THE NEW YORK-BOSTON RUN

Consist	Maximum Cruising Speed	% Reduction in Peak Power Necessary for Application of Advanced Batteries	Corresponding % increase in accelerating time
SDP40F - 5 Car	90 mi/h	0	0
AEM7 - 5 Car	90 mi/h 120 mi/h	57 68	99 77
Metroliner	90 mi/h 120 mi/h 150 mi/h	38 53 53	61 102 62

5.5 Economics

It is expected that battery-powered railroad traction would have the economic features of conventional all-electric traction.

Capital costs for battery-powered traction are estimated to be lower than for conventional all-electric traction, due to the elimination of the catenary or third rail and a network of feeder substations.

Energy costs for battery-powered traction are estimated to be about the same as for conventional all-electric traction. Although energy losses for batteries are 20-30% higher than for catenaries, batteries can be charged during off-peak utility hours at lower rates. Maintenance costs for battery-powered traction are also estimated to be about the same as for conventional all-electric traction.

Battery-powered trains have been operating in West Germany for more than 20 years, featuring the economy of electric propulsion and the flexibility of self-powered units (Ref. 4).

A detailed economic study of battery-powered traction is left as an item for further study.

6. APPLICATION OF FUEL CELLS TO RAILROAD TRACTION

This section considers the application of fuel cells to railroad traction. Section 6.1 compares the requirements for the SDP40F-5 car consist determined in Section 2 with the preliminary design characteristics of a fuel cell power source designed for the SDP40F locomotive. Section 6.2 discusses economics.

Preliminary analysis of volume availability of the AEM 7 and Metroliner consists shows insufficient volume for a fuel cell power plant. Therefore, application of fuel cells to these consists is not investigated further in this study.

It is noted that utilization of waste heat and water recovery from fuel cell power sources, which could replace the SDP40F steam generators, would increase the removable equipment shown in Table 2.5, making additional weight and space available for fuel cells. However, this factor is not considered here.

6.1 SDP40F-5 Car Consist

Conceptual designs of a fuel cell power source for the SDP40F locomotive were considered based on discussions with various fuel cell organizations. A block diagram of the power source is shown in Fig. 6.1. The fuel cells would be of the type being considered for utility applications. Hydrogen-rich fuel is used in the anode, air in the cathode, and phosphoric acid as the electrolyte. A fuel processor converts the fuel, a mixture of methanol and water, to the hydrogen-rich gas. A turbo compressor supplies air to the cathode,

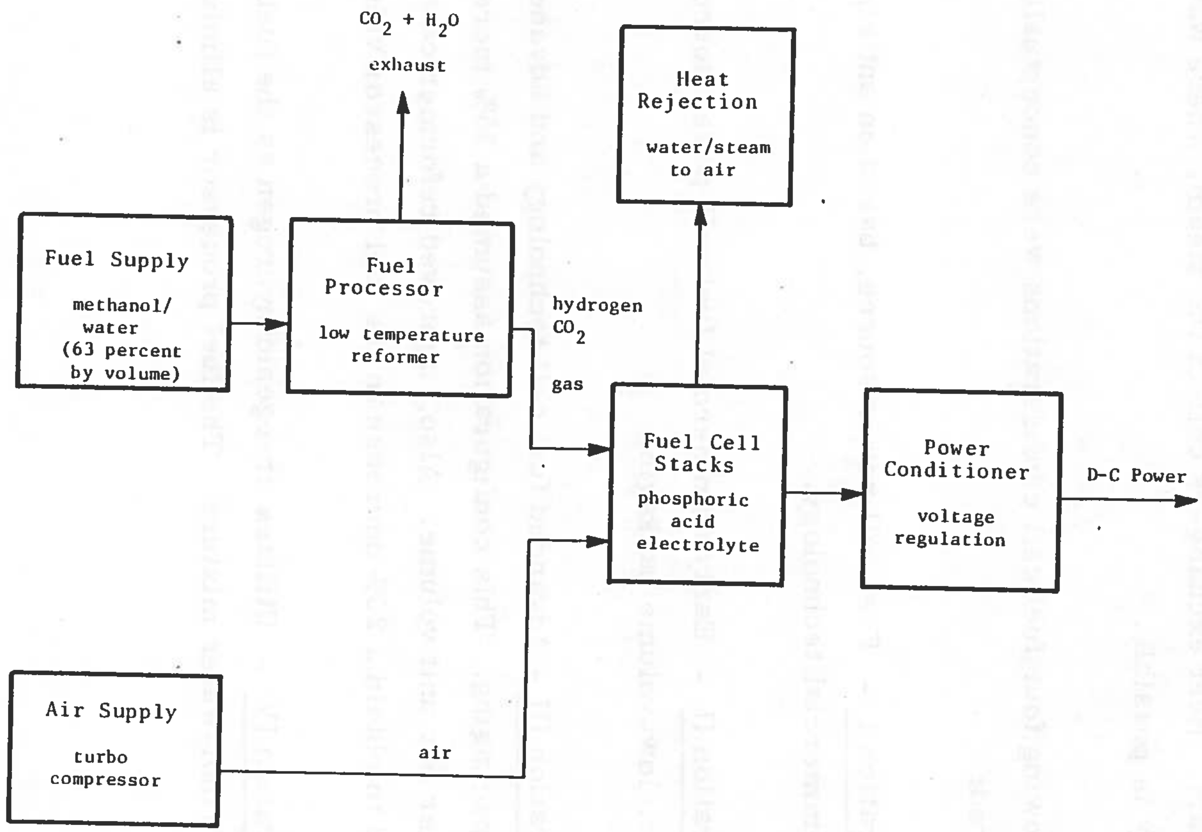


FIGURE 6-1. BLOCK DIAGRAM FUEL CELL POWER SOURCE FOR SDP40F LOCOMOTIVE

where oxygen combines with hydrogen ions and electrons to produce steam. Heat exchangers collect the steam, where water recovery is possible.

The following four fuel cell configurations were conceptually considered:

Configuration I - Fuel cell power source, based on anticipated early commercial technology.

Configuration II - Early commercial fuel cell power source with advanced, low-volume packaging.

Configuration III - Advanced fuel cell technology and advanced, low-volume packaging. This configuration assumed a 25% increase in cell power per unit volume. Also, improved reformer catalysts were assumed to obtain a 20% decrease in the fuel processor volume.

Configuration IV - Utilizes cryogenic hydrogen as the fuel, instead of a methanol-water mixture. The fuel processor is eliminated.

Table 6.1 shows the required characteristics of a fuel cell power source for the SDP40F locomotive, developed in Section 2, together with the preliminary estimates for the four fuel cell configurations.

As shown in Table 6.1 the volume of Configuration I is 10% larger than the required maximum for the SDP40F power source, resulting in 10% reduction in power per unit volume. The other conceptual configurations, however, potentially could satisfy the SDP40F volume requirements. Also, the other estimated characteristics of Configurations II, III and IV appear to satisfy the SDP40F requirements.

Table 6.1 also shows that pollutants from emissions of all the fuel cell configurations are significantly lower than the 1979 Environmental Protection Agency requirements for heavy duty diesel engines. Fuel cells are a clean source of power.

The projected operating lifetime of the fuel cell power sources, also shown in Table 6.1, is 150,000 hours, with major cell refurbishing anticipated at 40,000 hour intervals. Thus a fuel cell powered locomotive would have an operating life equal to or greater than the SDP40F diesel-electric locomotive.

It is concluded that advanced commercial technology is required to develop a fuel cell power source which is suitable for the SDP40F locomotive. Fuel cells are a potentially effective application to the SDP40F - 5 car consist.

TABLE 6-1. PRELIMINARY CONCEPTUAL CHARACTERISTICS FOR FOUR CONFIGURATIONS OF FUEL CELL POWER SOURCES FOR THE SDP40F LOCOMOTIVE

Characteristic	Units	SDP40F Requirement	Estimated Fuel Cell Configuration			
			I	II	III	IV
Peak power	kW	2000	2000	2000	2000	2000
Fuel capacity equivalent	kWh	3900	3900	3900	3900	3900
Voltage	V	600	600	600	600	600
Max. Dimensions (L x W x H)	ft x ft x ft	24 x 9 x 8	26 x 9 x 8	15 x 9 x 8	13 x 9 x 8	15 x 9 x 8
Approximate volume	ft^3	1700	2000	1200	1100	1200
Max. Weight	tons	60	45	60	56	51
Peak specific power	W/kg	37	49	37	39	43
Peak power per unit volume	kW/m^3	42	37	61	69	61
Rated efficiency	%	—	40	40	40	40
Rated heat rate	J/Ws	—	2.5	2.5	2.5	2.5
Start time (from cold)	min	—	120	120	60-120	60-120
Time - no load to full load	s	10	3	3	3	3
Economic life	h	50,000	150,000	150,000	150,000	150,000
Time between major overhauls	h	25,000	40,000	40,000	—	—
Pollutants	G/BHP-hr					
H-C		1.5*	0.0001	0.0001	0.0001	0.0001
CO		125*	None	None	None	None
NO_x + HC		10*	0.07	0.07	0.07	0.07
Opacity	%	15-50*	None	None	None	None

*1979 EPA Requirements for Heavy Duty Diesel Engines

6.2 Economics

A preliminary estimate of capital costs and operating costs of a fuel cell-powered locomotive is presented in this section. All costs are given in terms of 1980 dollars. A detailed economic analysis of fuel cell-powered locomotives is left as an item for further study.

The capital cost of a SDP40F diesel electric locomotive is estimated to be \$950,000. Estimated cost of the SDP40F diesel equipment, including diesel engine, generator, fuel tanks, cooling and auxiliary equipment, is \$400,000.

The capital cost of a fully-developed 2000 kW fuel cell power source suitable for the SDP40F locomotive is estimated to be \$750,000 based on the following component costs: \$100/kW for the fuel cell stack, \$100/kW for the power conditioning, \$75/kW for the fuel processor using water/methanol as the fuel source, and \$100/kW for heat rejection, air supply and fuel tanks.

Present cost of diesel fuel is \$6/MBTU (based on \$.80/gal). Present cost of methanol fuel (for a fuel cell-powered locomotive) is estimated to vary from \$7.80 to \$14.15/MBTU. This estimate is based on methanol derived from coal (Ref. 19).

Efficiency of a diesel engine-generator is about 36%. However, diesel-electric locomotives are generally kept running at idle when they are not in load service, for maintenance reasons, which reduces the efficiency to about 33%. In comparison, estimated efficiency of a fuel cell power source is 40%. The efficiency improvement for a fuel cell power source reduces fuel operating costs and on-board fuel requirements.

Projected operating lifetime of the fuel cell power source is 150,000 h, with 40,000 h between major overhauls, which exceeds the SDP40F requirements.

Maintenance costs of fuel cell-powered locomotives are estimated to be approximately the same as for diesel-electric locomotives.

Based on the above estimates, the fuel cell-powered locomotive is presently more expensive than the SDP40F diesel electric locomotive. However, as the cost of diesel fuel increases, the fuel cell-powered locomotive becomes more competitive. It is concluded that the cost of a fuel cell-powered locomotive is sufficiently attractive to warrant a detailed design and economic study.

7. CONCLUSIONS AND RECOMMENDATIONS

This report has considered the application of batteries and fuel cells to locomotives and self-powered cars for intercity passenger service.

Conditions for Study

Three conventionally-powered consists have been selected for reference and comparison with battery or fuel cell-powered trains, using as a scenario for the the analysis an 8-stop 232-mi Boston-NYC route:

- The SDP40F locomotive and five Amfleet-trailing cars
- The AEM7 locomotive and five Amfleet trailing cars
- Five Metroliner self-powered cars.

Three maximum cruising speeds have been used for these comparisons:

- 90 mi/h for all three consists
- 120 mi/h for the AEM7 and Metroliner consists
- 150 mi/h for the Metroliner consist.

Three advanced batteries have been selected for comparison of battery-powered trains:

- Advanced lead-acid
- Nickel-zinc
- Sodium-sulfur.

Four fuel-cell configurations using a phosphoric acid electrolyte were considered for the consists:

- Configuration I - State-of-the-art technology
- Configuration II - State-of-the-art technology with advanced packaging.

Configuration III - Advanced technology with advanced packaging

Configuration IV - Utilization of cryogenic hydrogen fuel

Conclusions on Batteries

As a result of studying the use of batteries on the three consists we conclude the following:

1) Based on the requirements for specific energy and specific power, and the selected assumptions, the sodium-sulfur battery satisfies the requirements of the SDP40F-5 car consist. Application of batteries to the AEM7 or Metroliner consists would not be feasible, on the same basis.

2) Batteries can be used in all cases for the Boston-NYC run if operations are altered by one or more of the following means:

- Battery exchanges enroute to add more available energy.
- Maximum cruising speed reduction to reduce the energy requirements.
- Reduction of acceleration to reduce the peak power requirements.

3) Sodium-sulfur batteries can also be used for the AEM7 and Metroliner consists if the consist weight is reduced to lessen the energy and peak power requirements.

Emphasis on weight reduction is illustrated by existing battery-powered multiple unit cars operating in West Germany. These cars weigh 49 tons with batteries, compared to the 88 ton Metroliner self-powered car.

4) The cost of battery-powered railroad traction in comparison with conventional all-electric traction looks attractive enough to warrant a detailed economic study. The economic feature of battery-powered traction is illustrated by the West German experience with battery-powered self-powered cars.

5) Future battery development could increase the energy and power densities of batteries for application to railroad traction, and further improve their attractiveness.

Battery powered consists have the following potential applications to railroad traction:

1) Self- Powered Battery Car, suitable for intercity passenger trains now serviced by multiple units powered by conventional all-electric or diesel.

2) Multiple Unit Electric/ Battery Hybrid Vehicle, which would operate as an electric multiple unit on electrified portions of a track, and as a battery powered unit on non-electrified portions. Batteries could be charged while operating on the electrified track.

3) Electric Locomotive with Auxiliary Battery, which would operate primarily in the electric mode, with short time "off-wire" capability in the battery mode. Batteries could be charged while operating in the electric mode.

4) Diesel Electric Locomotive with Auxiliary Battery, which would operate primarily in the diesel mode, with short time battery operation.

5) Battery Locomotive, which would operate fully battery powered. Batteries could be exchanged or charged during intermediate stops or at ends of runs.

Conclusions on Fuel Cells

As a result of studying the use of fuel cells on the three consists we conclude the following:

1) Fuel cells are a potentially effective application to the SDP40F-5 car consist, based on the selected assumptions. Fuel cells do not appear effective for the other two consists, based on current technology.

2) The cost of a fuel cell-powered locomotive, although presently higher than a diesel electric locomotive, looks attractive enough to warrant a detailed economic study. As the cost of diesel fuel increases, the fuel cell-powered locomotive becomes more competitive.

3) Future fuel cell developments could provide potentially effective applications to other consists.

Recommendations

As a result of this study, we recommend the following actions:

1) Develop more battery data - the battery projections reported here require updating because of a rapidly changing state of the art.

2) Obtain additional data on the West German technical and economic experience with battery-operated trains. Obtain additional data from British Rail on the status of their technical development activities on the sodium-sulfur battery.

3) Investigate the environmental, institutional and safety-related factors for battery and fuel cell-powered trains.

4) Prepare a detailed study of battery and fuel cell-powered trains which includes the following steps:

   Perform an industry survey
   Develop system requirements
   Determine state of the art of batteries and fuel cells
   Develop system design concept
   Determine performance characteristics of concept
   Determine life cycle costs.

Develop an R&D plan for future work
Prepare detailed research, development and demonstration plans for (1) a battery-operated multiple unit car; (2) a fuel cell-powered locomotive whose characteristics are similar to those of the SDP40F diesel electric locomotive.

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APPENDIX A

FIGURES AND TABLES

The following figures and tables are contained in this Appendix.

The report of new technology appears in Appendix B.

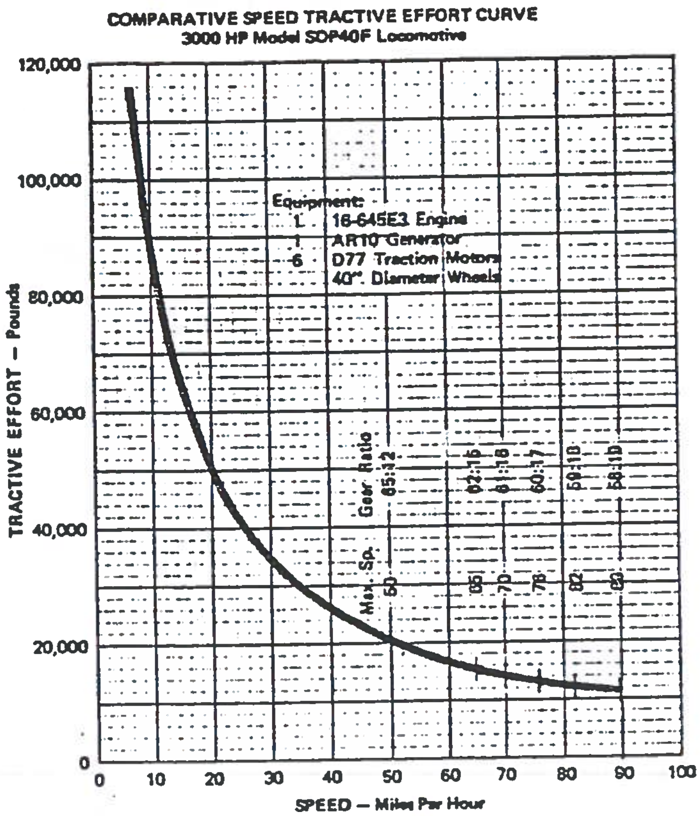
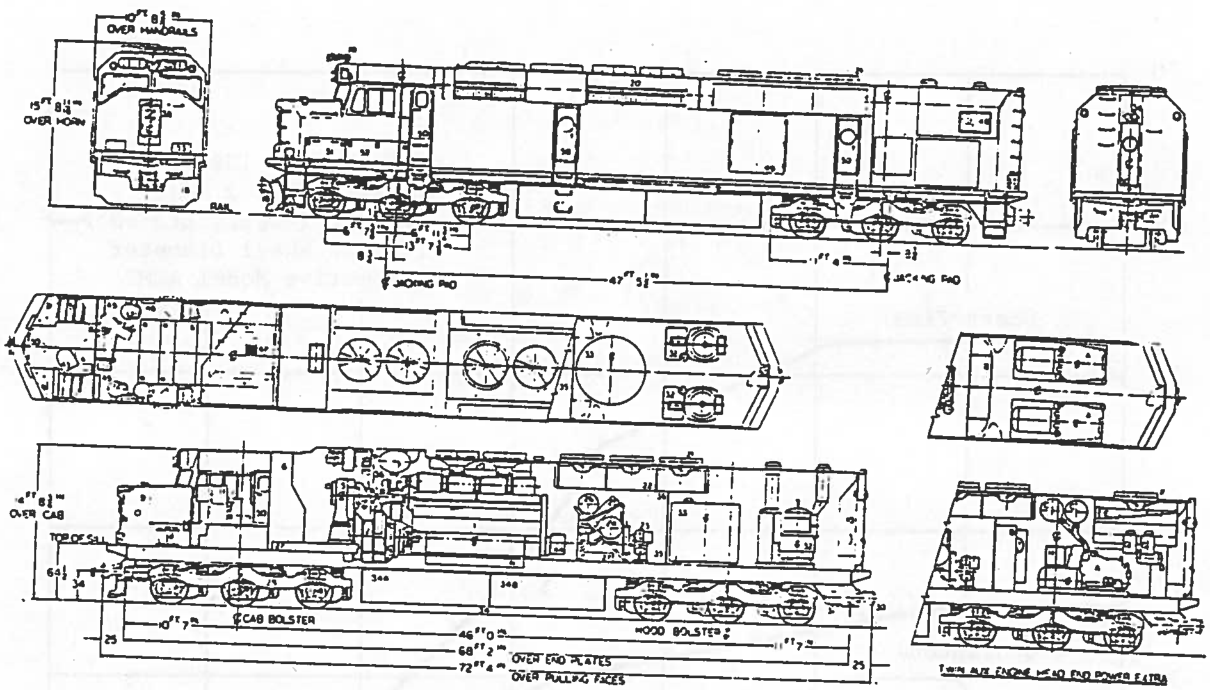


FIGURE A-1. SPEED TRACTIVE EFFORT CURVE - SDP40F



General Motors Model SDP40F

1. ENGINE — 16-645E3
2. GENERATOR-ALTERNATOR AR10
* 3. AUXILIARY GENERATOR 18 KW
4. GENERATOR-ALTERNATOR BLOWER
5. TRACTION MOTOR BLOWER
6. ELECTRICAL CONTROL CABINET
* 7. EXHAUST SILENCER
8. BATTERIES — MS420
9. SAND BOX—CAB END 28 CU. FT.
10. SAND BOX—HOOD END 28 CU. FT.
11. ENGINEERS CONTROL STAND-A.A.R.
12. CAB SEAT
13. ELECTRICAL CABINET AIR FILTER
14. INERTIAL CARBODY FILTERS
15. ENGINE AIR FILTERS-PAPER
16. FIRE EXTINGUISHER
*17. WATER COOLER
*18. SNOW PLOW PILOT
*19. HORN — 5 CHIME
*20. DYNAMIC BRAKES
21. COOLING FANS
22. RADIATORS
23. AIR COMPRESSOR - WBO
24. LUBE OIL FILTER
25. LUBE OIL COOLER
26. ENGINE WATER TANK
27. TRACTION MOTOR AIR DUCT
28. TRUCK — HTC
29. TRACTION MOTOR — D77
*30. COUPLER — TYPE F
*31. DRAFT GEAR — MS 390
*32. STEAM GENERATOR-2500# — VAPOR OK 4625
*33. DECK WATER TANK-1500 GAL. BOILER WATER
*34. COMB. FUEL WATER TANK (34A-2500 GAL FUEL-34B — 2000 GAL. BOILER WATER)
35. ENGINE ROOM CROSSOVER
36. ENGINE ROOM PARTITION
37. NUMBER BOX
38. HEADLIGHT
39. JACKING PADS
*40. OSCILLATING LIGHT
*41. LARGE OIL PAN
42. BELL
*43. TOILET
44. LUBE OIL STRAINER
45. CAB HEATER — HOT WATER
*46. CAB HEATER — ELECTRIC STRIP
47. INERTIAL FILTER BLEED AIR DISCHARGE
*48. STEAM GENERATOR COMPARTMENT VENTILATING AIR
49. MAINTENANCE DOOR-BOTH SIDES
50. PERSONNEL DOOR
51. BATTERY ACCESS
52. AIR BRAKE EQUIPMENT ACCESS
53. SAND TRAP ACCESS

*MODIFICATION

Model .... SDP40F 3000 HP Six Motor Diesel-Electric Locomotive
Type:
AAR DESIGNATION .... C-C
Common Designation 1660
Arrangement .... The Locomotive consists of one unit complete with engine, generator, trucks and all necessary accessories for single or multiple unit operation, with a control cab at the front.
Nominal Dimensions:
Distance, pulling face of coupler to centerline of truck .... Front 12' 8"
Rear 14' 8"
Distance between bolster centers .... 46' 0"
Truck—rigid wheel base .... 13' 7"
Distance, pulling face front coupler to rear coupler .... 72' 4"
Width over cab sheeting .... 10' 0"
Width over handrail supports .... 10' 3 ½"
Height, top of rail to top of cooling fan guard .... 15' 7 3/16"
Width over basic arm rests .... 10' 4"
Drive:
Driving motors .... Six
Driving wheels .... 6 Pair
Diameter wheels .... 40"
Weights and Supplies:
Total loaded weight on rails (including calculated weight of optional dual steam generators and optional 6000 gallon total fuel and water capacity) .... 396,000# ± 4,000
Fuel (basic) .... 3,200 gal.
Combination fuel/water maximum .... 6,000 gal. total
Total capacity option .... 2,500 gal. fuel
3,500 gal. water
Sand .... 56 cu. ft.
Cooling water .... 254 gal.
Lubricating oil .... 243 gal.

FIGURE A-2. GENERAL MOTORS MODEL SDP40F GENERAL CHARACTERISTICS, WEIGHTS AND DIMENSIONS*

*Courtesy of Car & Locomotive Cyclopedia, 1974 and 1980.

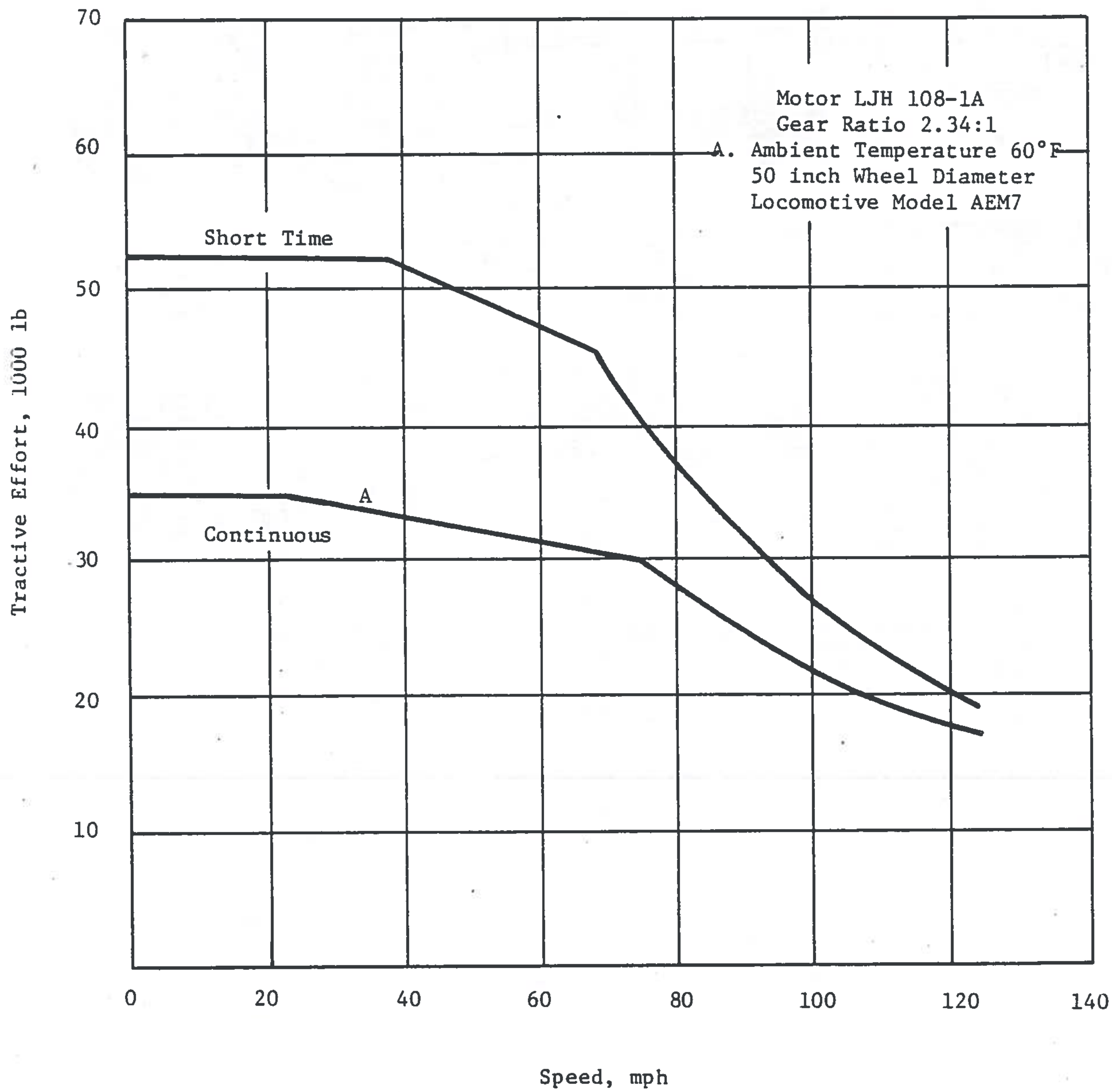


FIGURE A-3. SPEED-TRACTIVE EFFORT CURVE - AEM7

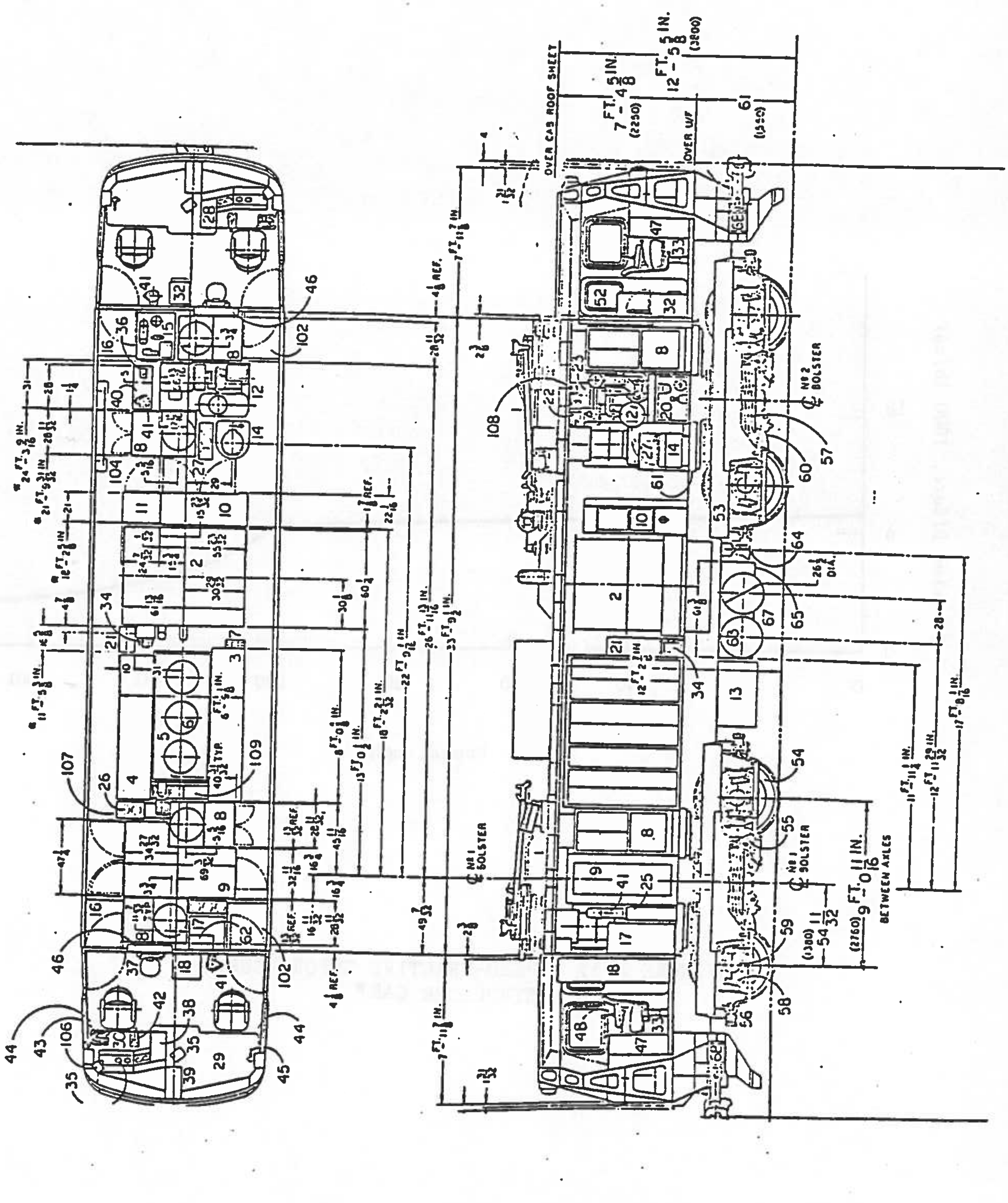


FIGURE A-4. AEM7 DIMENSIONS

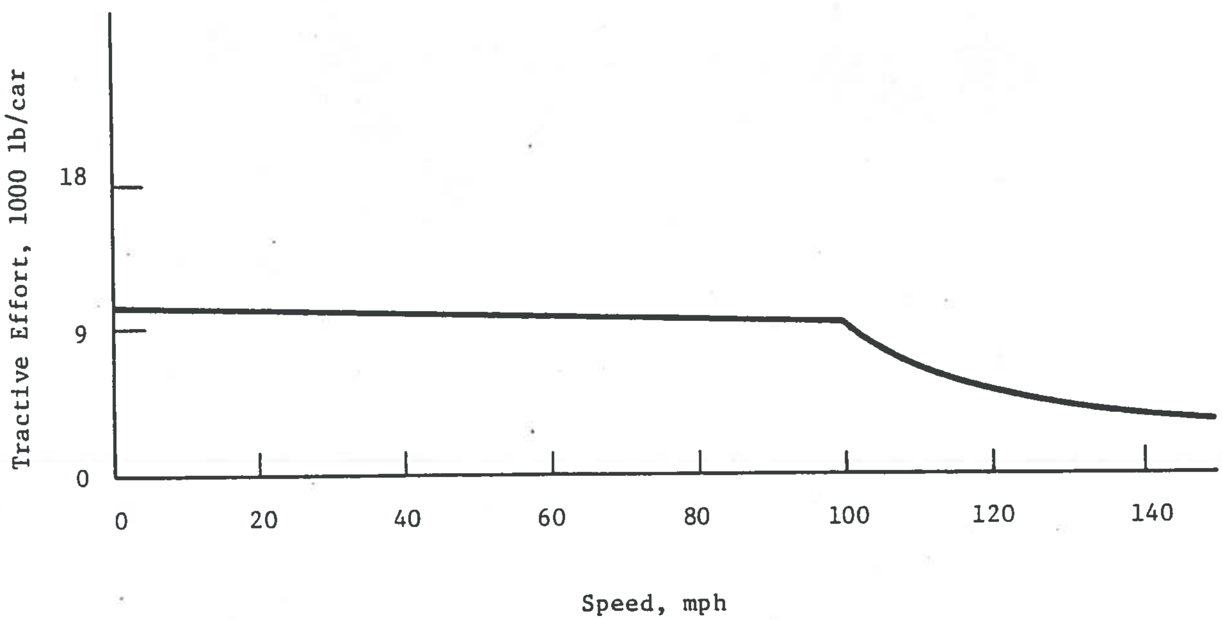
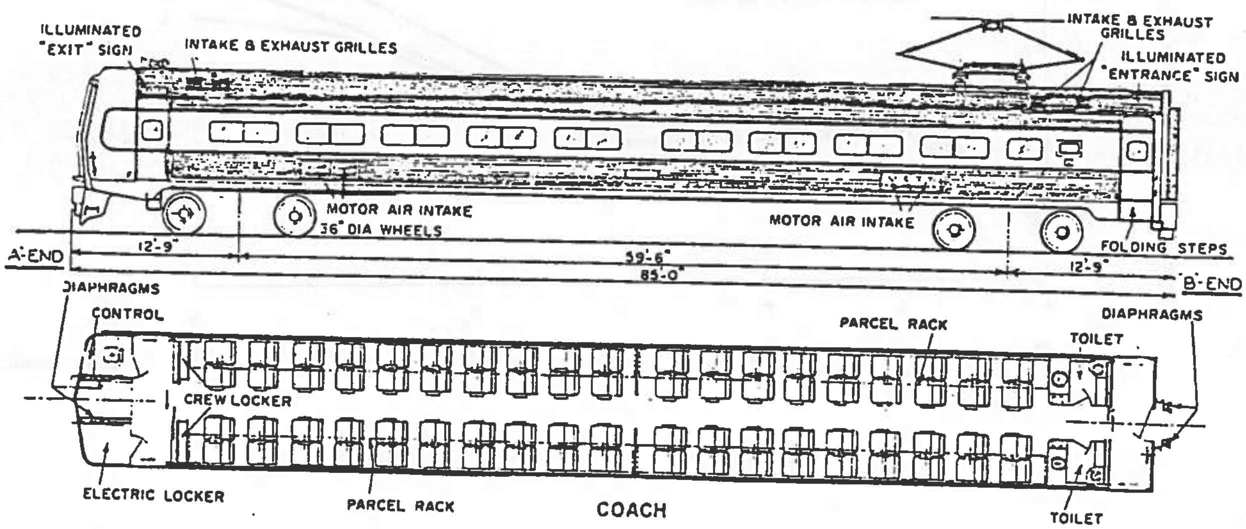


FIGURE A-5. SPEED-TRACTIVE EFFORT CURVE
METROLINER CAR*

*Based on Reference 2.

Item	Weight Lbs.
Transformer	12,000
Thyristor Rectifier Equipment	2,200
Smoothing Reactor	2,700
Pantograph	600
Surge Arrester	100
Total Car Weight	176,000

A. Partial Weight List - Estimated



B. Dimensions

FIGURE A-6. METROLINER COACH CAR

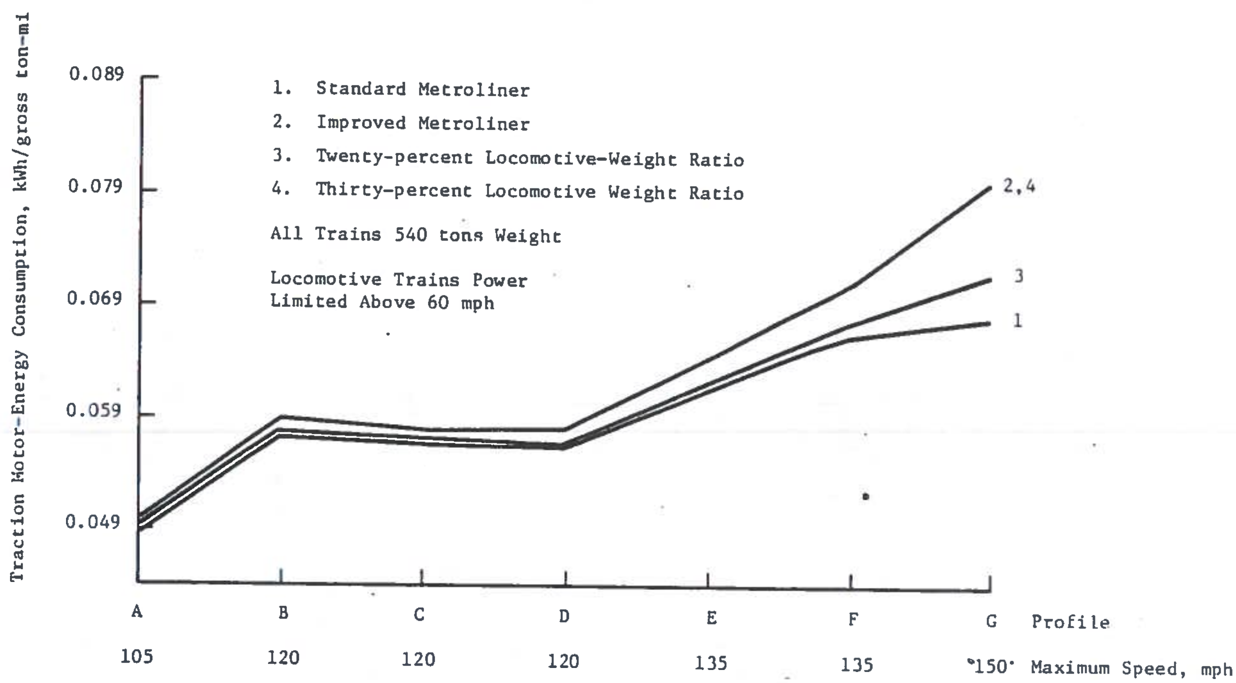


FIGURE A-7. ENERGY CONSUMPTION, NEW YORK-WASHINGTON*

*Based on Ref. 2 , Page 21, -226 mi trip, 90% motor/ gear efficiency

TABLE A-1. SD40 - WEIGHT LIST

Item	Weight Lb
16-645E3 Diesel Engine	32,500
Starter Motor	80
Starter Motor Bracket	60
Engine Governor	120
Turbocharger	1800
AR10 Main Generator Assembly	16,000
Auxiliary Generator And Blower Assembly	1000
Inertial Air Filter	600
Inertial Filter Screen	35
Inertial Filter Compartment And Hatch	4700
Inertial Filter Hatch (Less Filters)	500
Fuel Tank 3200 Gal.	6650
Fuel Tank 4000 Gal.	9940
Truck Assembly (Single Shoe; Solid Bolster)	57,200
Traction Motor	6000
Axle	1325
Wheel	1015
Gear 62 Tooth	409
Bearing - Inner Race	33
Air Compressor	2325
Air Compressor Shaft	136
Air Compressor Shaft Guard	68
Air Compressor Coupling	48
Lube Oil Cooler	845
Lube Oil Filter	675
Fuel Pump Assembly	81
Fuel Suction Strainer	8
AC Cabinet Assembly	250
Fuel Filter	60
Temperature Switch Manifold	20
Load Regulator Vane Motor	36
Dynamic Brake Fan Assembly	760
Dynamic Brake Resistor Grid	385
Dynamic Brake Grid Shorting Contactor	35
Fan Grill Assembly	190
Radiator Fan Assembly	700
Radiator Core	325
Cab Heater	71
Storage Battery	289
SCR (Generator Excitation)	29

TABLE A-2. AEM7 - ESTIMATED WEIGHT LIST

Carbody - cab - underframe shell	37,275
"H" coupler with MS488-6A draft gear	3,876
Air brake equipment in cabs	1,315
Air brake rack equipped ("A" end)	0
Air brake rack equipped ("B" end)	863
Air reservoirs (60,000 cu. in.)	1,180
Paint	900
Additional piping (thin wall to heavy wall)	350
Toilet (Prime)	120
Bell	69
Air dryer (underframe mounted)	270
Horn (2 total)	70
Hoses and jumper cables	200
Window guards	150
Provision for air conditioning	50
Miscellaneous (terminal lugs, etc.)	100
Sand (10.6 cu. ft. total)	1,060
Antenna for power source changeover	0
Power source detector-roof mounted transformer	110
Automatic changeover equipment - transformer motor for changeover	52
Pantographs (Stemmann) (Faiveley)	1,500
Main circuit breaker	485
Bushings (8 insulators, high voltage hoses, high voltage bushing, power cable)	485
Lightning arrestors (15 and 25 kv)	198
Transformer/reactor set (copper windings) (aluminum windings)	25,904
Earthing transformer	100
High voltage cabinet and earthing device	331
Filter contractors (PF Equipment)	0
Auxiliary transformer	771
Thyristor converter	8,377
Electronic control cabinet (Y2)	661
Motor modules with inertial filters	3,852
Electric cabinet	1,279
Filter capacitors (16 total) with box and structure	0
Compressor/separator rack (includes oil cooler)	2,300
Auxiliary compressor and dryer with rack	93
Auxiliary converter and head end power	0
Throttle	110
Console	93
Signals (headlights, signal lights, alerting lights, classification lights)	154
Support F3 (center console in cab)	397
Cab heaters with ducting	165
Battery (Exide RT140 - 8 trays)	856
Receptacles	198
Cable and duct	3,003
Pipes and duct	221
Erection material	661
Thyristor converter air filter box (4 element)	220

TABLE A-3. TYPICAL TRAIN SCHEDULE-BOSTON TO NEW YORK CITY

Km	Mi	Train Number		191	171	173	193	67
		Train Name		Morning Liberty Express	The Colonial	The Patriot	Evening Liberty Express	The Night Owl
		Frequency of Operation		Daily	Daily	Daily	Daily	Daily
		Type of Service		✓ [illegible]	✓ [illegible] [illegible]	✓ [illegible]	✓ [illegible]	[illegible] [illegible] [illegible]
0	0	**Boston, MA** *(South Sta.) (ET)*	Dp	5 45 A	7 20 A	9 15 A	5 00 P	10 10 P
2	1	**Boston, MA** ÷ *(Back Bay Sta.)*		R 5 50 A	R 7 25 A	R 9 20 A	R 5 05 P	R 10 15 P
19	12	Route 128, MA		6 05 A	7 38 A	9 34 A	R 5 18 P	10 28 P
70	44	**Providence, RI**		6 40 A	8 20 A	10 15 A	5 55 P	11 08 P
114	71	Kingston, RI ÷			8 48 A			F 11 35 P
141	88	Westerly, RI ÷		7 22 A	9 06 A			F 11 54 P
155	96	Mystic, CT • *(Mystic Seaport)*			9 17 A			
171	106	New London, CT ÷		7 47 A	9 31 A	11 22 A	6 55 P	12 17 A
199	124	Old Saybrook, CT		8 07 A	9 54 A			
34	21	Framingham, MA •						
71	44	Worcester, MA						
158	98	**Springfield, MA**						
171	106	Thompsonville, CT • *(Enfield)*						
180	112	Windsor Locks, CT •						
189	117	Windsor, CT •						
199	124	**Hartford, CT**						
216	134	Berlin, CT *(New Britain)*						
228	142	Meriden, CT ÷						
238	148	Wallingford, CT ÷						
258	160	**New Haven, CT**	Ar	9 01 A	10 44 A	12 33 P	7 57 P	1 15 A
252	157	**New Haven, CT**	Dp	9 11 A	10 55 A	12 43 P	8 07 P	1 30 A
280	174	Bridgeport, CT			(17) 11 13 A			(17) 1 50 A
315	196	Stamford, CT			(17) 11 36 A	(17) 1 35 P	(17) 8 48 P	(17) 2 18 A
330	205	Rye, NY			(17) 11 49 A			
373	232	**NEW YORK, NY** *(Penn. Sta.)*	Ar	10 45 A	12 45 P	2 25 P	9 45 P	3 13 A

APPENDIX B
REPORT OF NEW TECHNOLOGY

The work described herein reports for the first time the results of a study in which the characteristics of batteries and fuel cells were compared with the requirements of railroad motive power equipment to determine if batteries and/or fuel cells are viable sources of railroad-propulsion energy. The study results support the conclusion that batteries and fuel cells can be used as alternative energy sources, and that further in-depth analysis must be conducted to establish technical and economic feasibility.

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