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INFORMAL REPORT

**BATTERY AVAILABILITY FOR NEAR-TERM (1998)
ELECTRIC VEHICLES**

**Idaho
National
Engineering
Laboratory**

*Managed
by the U.S.
Department
of Energy*

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June 1991

**EG&G Idaho, Inc.
Idaho Falls, Idaho 83415**

**Prepared for the
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Under DOE Contract No. DE-AC07-76ID01570**

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ABSTRACT

Battery Requirements were determined for a wide spectrum of electric vehicles ranging from 2-passenger sports cars and microvans to full-size vans with a payload of 500 kg. All the vehicles utilize ac, high voltage (340-360 V) powertrains and have acceleration performance (0-80 km/h in less than 15 seconds) expected to be the norm in 1998 electric vehicles. Battery packs were configured for each of the vehicles using families of sealed lead-acid and nickel-cadmium modules which are either presently available in limited quantities or are being developed by battery companies which market a similar battery technology. It was found that the battery families available encompass the Ah cell sizes required for the various vehicles and that they could be packaged in the space available in each vehicle. The acceleration performance and range of the vehicles were calculated using the SIMPLEV simulation program. The results showed that all the vehicles had the required acceleration characteristics and ranges between 80-160 km (50-100 miles) with the ranges using nickel-cadmium batteries being 40-60% greater than those using lead-acid batteries.

Significant changes in the design of electric vehicles over the last fifteen years are noted. These changes make the design of the batteries more difficult by increasing the peak power density required from about 60 W/kg to 100-150 W/kg and by reducing the Ah cell size needed from about 150 Ah to 30-70 Ah. Both of these changes in battery specifications increase the difficulty of achieving low \$/kWh cost and long cycle life. This true for both lead-acid and nickel-cadmium batteries.

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BATTERY AVAILABILITY FOR NEAR-TERM (1998) ELECTRIC VEHICLES

INTRODUCTION

The interest of the automobile industry in marketing electric vehicles has increased markedly in the last year due primarily to the emissions rule-making in California, which requires at least 2% of the sales of each company to be electric vehicles in 1998 increasing to 10% of sales by 2003. The performance (acceleration and range) and cost of electric vehicles that can be offered for sale by 1998 are dependent for the most part on the characteristics of the batteries which will be available for use in the vehicles. Even though much effort and resources are being devoted to the development of advanced batteries, it is most likely that the batteries available in 1998 will be based on batteries currently being marketed in limited quantities for electric vehicles. Only lead-acid and nickel-cadmium batteries are at the present time commercially available for electric vehicles and even these batteries are available in a relatively few models (cell sizes and module voltages). Nickel-iron (NiFe) batteries are being considered as near-term batteries by EPRI in their EV program, but NiFe batteries are not presently commercially available even in small quantities. For completeness, NiFe batteries are included in the present study, but to a limited extent. Significant additional development of all the batteries is needed to increase their cycle life to that required in mass marketed vehicles for use by the public.

A study of the available batteries and batteries that can be marketed using the same technologies was made to determine their readiness for use in electric vehicles that are likely to be designed for sale in 1998. It was assumed that those vehicles will utilize propulsion system technology closely related to those presently being developed by Ford and General Electric on the Modular Electric Vehicle Program (MEVP) under contract to DOE or being tested by General Motors in the Impact - that is an ac induction motor,

transistorized inverter, and a single-speed transaxle. Electric vehicles utilizing dc drivelines are still being built and tested (for example the TEVan), but it appears that mass-marketed vehicles will utilize ac driveline systems primarily because of the ease of production and lower cost of the ac motor. Battery packaging requirements were based on those of the ETX-II, MEVP vehicles (Reference 1), ETV-1, and Impact. This array of vehicles (see Table 1) represents all classes from a full-size van to a two-passenger sports car and thus should encompass the complete spectrum of battery sizes required by the auto industry to market various types of vehicles in 1998. For the purpose of comparison of the expected 1998 designs with existing 1990 designs, the TEVan, GVan, and ETX-II (original) powertrains and battery packs are also discussed.

In the study, specific batteries from families of lead-acid and nickel-cadmium batteries marketed by several manufacturers are selected and packaged in each of the 1998 vehicles and the performance of the vehicles simulated using the SIMPLEV computer program (Reference 2). The readiness of the battery technologies for the 1998 vehicles is also assessed relative to cycle life, battery charging, state-of-charge indication, maintenance, and thermal management. The effects of present trends of propulsion system voltage and vehicle acceleration goals on battery requirements for 1998 compared to 1990 are summarized. These trends on battery requirements make the design of a long-life, low-cost battery more difficult.

NEAR-TERM ELECTRIC VEHICLES

VEHICLE CHARACTERISTICS

The design characteristics for a number of electric vehicles that can be considered prototypes for marketing in 1998 are given in Table 1. Also shown in the table are the characteristics of several vehicles that are considered state-of-the art in 1990. The characteristics, which were used in the present study, are based on published information on electric vehicles that have been built and/or are presently under development in the United States. In some cases for the 1998 prototype vehicles, modifications have been made in the electric propulsion systems of the 1990 vehicles to reflect projected advances in electric driveline technology. However, in all cases the basic vehicle geometry and dimensions are unchanged from the original vehicle designs. The performance given for each of the 1998 vehicles is consistent with expected top speed (at least 96 km/h) and acceleration requirements (0-88 km/h in less than 15 seconds) for 1998 electric vehicles. The specifications for the driveline components have been selected accordingly. As a consequence of recent advances in motor and electronics technology, meeting the driveline specifications presents little difficulty except possibly for battery power. Vehicle range is not specified in Table 1 as it depends on both the vehicle and battery characteristics. In this study, range is considered the primary calculated characteristic of each vehicle/ battery combination. For the 1998 vehicles, the approach taken is to fix the vehicle performance and battery packaging constraints and determine the consequences of these specifications on battery requirements and vehicle range for various driving modes.

Table 1. Vehicle Characteristics

1998 Vehicles								
Name	Type	Curb Wgt w/o Bat (kg)	Payload (kg)	Frontal Area (m ²)	C _D	Rolling Resistance	System Voltage	Max Motor HP
Car A	2-passenger car	750	136	1.67	0.28	0.0085	340-360	50
Van A	Microvan	975	212	2.23	0.34	0.0085	340-360	75
Van B	Large Van	1636	455	3.53	0.40	0.0085	340-360	100
ETX-II	Minivan	1227	272	3.25	0.37	0.0085	340-360	75
Impact	2-passenger sports car	636	136	1.58	0.20	0.0085	340-360	75
ETV-I	4-passenger compact	955	136	1.86	0.32	0.0085	340-360	50
1990 Vehicles								
TEVan	Minivan	1375	272	2.97	0.375	0.0095	195	70
DSEP	Minivan	1375	272	2.97	0.375	0.0095	182	73
ETX-II	Minivan	1227	272	3.25	0.370	0.0095	200	70
G Van	Large Van	2200	425	3.35	0.47	0.0100	216	60

BATTERY REQUIREMENTS

Battery system (pack) requirements for each of the vehicles considered in the study are given in Table 2. These requirements apply to all battery types. Battery cell and module characteristics must be compatible with the pack requirements of the vehicle if a particular battery is to be used in that vehicle. In other words, it must be possible to configure a battery pack of the required voltage and planform and height dimensions using available cells/modules of the particular battery before that battery can be used in the vehicle. Since space and voltage requirements vary significantly for the various vehicles, no single cell or module can be expected to be suitable for all vehicles. Hence for each battery type and technology, a family of batteries is needed to meet electric vehicle requirements. Fortunately, in many cases battery companies market a family of designs for each of their battery technologies. Additional module sizes using the same technology would likely be made available if required by particular vehicle designs.

Table 2. Battery Requirements and Constraints

1998 Vehicles							
Name	Max Weight (kg)	System Voltage	Peak Power (kW)	Max. Volume (ℓ)	Max. Pack Dimensions (cm)		
					(L)	(W)	(H)
Car A	350	340-360	45	265	85	96.5	32
Van A	450	340-360	65	365	117	96.5	32
Van B	700	340-360	98	525	170	96.5	32
ETX-II	600	340-360	65	444	185	75	32
Impact	380	340-360	65	185	185	25	40
ETV-I	450	340-360	45	260	190 (a) 76	28 53	28 28
1990 Vehicles							
TEVan	900	208	65	397	210	70	27
DSEP	900	195	65	365	187	75	26
ETX-II	600	200	65	360	185	75	26
GVan	1170	216	55	535	187	110	26

(a) T-shaped battery box; center tunnel and rear-box

COMMERCIALLY AVAILABLE BATTERIES

LEAD-ACID BATTERIES

This study considered both flooded and sealed lead-acid batteries. Only batteries for which a family of cells/modules of a particular design are available were considered in depth. Information on the weight and dimensions of the cells/modules is readily available in brochures and spec. sheets from battery manufacturers. Capacity information at discharge rates appropriate for electric vehicle applications is less readily available, but the required information can in some cases be obtained by direct contact with the manufacturers. Test data from one of the DOE National Laboratories involved with testing batteries for electric vehicles is the best source of battery performance information, but many of the batteries of interest have not yet been tested in one of the laboratories. Hence in this study the batteries were characterized using data from the battery manufacturers, supplemented when possible by data available from the Idaho National Engineering Laboratory (INEL) and Argonne National Laboratory (ANL).

The sealed lead-acid batteries included in the study were those marketed by Johnson Controls, Inc. (Reference 3) and Sonnenschein (Reference 4). The characteristics of these families of batteries are given in Tables 3 and 4 and Figures 1 and 2. All the batteries in the tables are, according to the manufacturers, suitable for use in electric vehicles, even though most of the modules are not presently sold primarily for EV applications. One or two batteries of each manufacturer has been tested at INEL in past work (References 5-7) and were found to be suitable for use in electric vehicles. The Sonnenschein DF6V180 and Johnson Controls GC12V100 have been used in a number of vehicles in recent years and their characteristics are also given in Tables 3 and 4. It is assumed that the technology for each family of a particular manufacturer is essentially the same and that variations in energy

Table 3. Characteristics of Johnson Controls, Inc. Sealed Lead-Acid Batteries

Module ^(a)	Voltage	(Ah)C/3	Weight(kg)	Dimensions (mm)			Volume (ℓ)	Wh kg C/3	Wh ℓ C/3
				L	W	H			
GC6V200	6	130	32.7	321	178	259	14.8	23.7	52
U-1-31	12	23	10.9	198	133	185	4.9	25.1	56
GC12400	12	27	15.0	228	139	205	6.5	21.4	49
GC12550	12	37	18.6	261	173	226	10.2	23.7	43
GC12800	12	57	24.5	331	174	214	12.3	27.7	55
GC12V100 ^(b)	12	66	30.9	331	174	241	13.9	25.4	56
(a) This is the Dynasty series of batteries									
(b) Tested at INEL (Reference 5): C/3 - 68 Ah, 26.9 Wh/kg									

Table 4. Characteristics of Sonnenschein Sealed Lead-Acid Batteries

Module ^(a)	Voltage	(Ah)C/3	Weight(kg)	Dimensions (mm)			Volume(ℓ)	$\frac{Wh}{kg}$ C/3	$\frac{Wh}{\ell}$ C/3
				L	W	H			
DF 6V180 ^(b)	6	150	30.2	245	190	276	12.8	29.3	70
DF 45	12	25	10.4	196	132	180	4.7	28.4	63
DF 75	12	35	12.3	210	175	175	6.4	33.5	65
DF 115	12	50	17.8	278	175	175	8.5	33.1	69
DF 150	12	65	23.1	381	175	190	12.7	32.7	60
DF 180	12	75	30.0	330	170	240	13.6	29.5	65
DF 4DLT	12	90	39.0	514	190	222	21.7	27.2	50
(a) This is the Dryfit Prevailer Marine and RV series of batteries									
(b) Tested at INEL (Reference 7): C/3 - 150 Ah, 28.0 Wh/kg

Figure 1: Peukert Curves for the GC Series of Johnson Controls, Inc. sealed lead-acid batteries.

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Figure 2: Peukert Curves for the Sonnenschein sealed lead-acid batteries.

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and peak power densities (Wh/kg, W/kg) for the different size modules reflect primarily differences in the contribution of packaging to module weight and volume.

A family of flooded lead-acid batteries is available from the Japan Storage Battery (GS) Company (Reference 8). The characteristics of the batteries are given in Table 5 and Figure 3. Several of the E75P and ED150P modules have been purchased by INEL, but have not yet been tested. The flooded lead-acid batteries have somewhat better performance than the sealed batteries, but they require periodic watering. For this reason, sealed batteries are preferred by most electric vehicle manufacturers and users. The characteristics of the Chloride Motive Power 3ET205 tubular plate battery are also given in Table 5. That battery is used in the GVan.

NICKEL-CADMIUM BATTERIES

Some nickel-cadmium batteries are presently commercially available for electric vehicle applications (Reference 9). These are of the flooded type requiring periodic watering. In addition, it is known that at least two companies are planning to market families of sealed nickel-cadmium batteries in the next several years (References 10,11). Two families of nickel-cadmium batteries are considered in this study : (1) a flooded family from Saft (Reference 9) and (2) a sealed family to be marketed by Hoppecke (Reference 11). A Saft nickel-cadmium battery (SEH-5-200) has been tested by INEL and found to have excellent characteristics for use in electric vehicles (Reference 12). The characteristics of the Saft and Hoppecke batteries are given in Tables 6 and 7 and Figures 4 and 5. Characteristics of the large-cell, flooded, nickel-cadmium and nickel-iron batteries are given in Table 8. These batteries are used in the TEVan and DSEP, which operate at lower system voltages than the 1998 prototype vehicles.

Table 5. Characteristics of Flooded Lead-Acid Batteries

Module	Voltage	(Ah) C/3	Weight (kg)	Dimensions (mm)			Volume (ℓ)	$\frac{Wh}{kg}$ (C/3)	$\frac{Wh}{ℓ}$ (C/3)
				L	W	H			
Japan Storage ^(a)									
E75P	12	68	24	304	172	232	12.1	33.7	67
E105P	12	95	35	410	176	249	18.0	32.3	63
E120P	12	108	41	504	182	259	23.8	31.3	54
EDI50P	12	135	42	504	182	259	23.8	38.3	68
Lucas Chloride ^(b)									
3ET205	6	176 (c)	32.5	312	181	235	13.3	32.2	78
(a) Flooded, flat plate construction									
(b) Flooded, tubular plate construction									
(c) Based on INEL tests (Reference 25) of the 3ET205 battery

Figure 3: Peukert curves for flooded lead-acid batteries.

Table 6. Characteristics of Flooded Nickel Cadmium Batteries

Module (a)	Nominal Voltage	Rated (Ah) C/3	Weight (kg)	Dimensions (mm)			Volume (ℓ)	Wh kg	Wh ℓ	C/3
				L	W	H				
STM 5-140	6.1	135	17.5	244	153	262	9.8	47.0		84
STM 5-200 (b)	6.1	180	23.2	244	190	280	13.0	47.5		85
STM 1.40B	1.22	35	1.4	85	45.5	198	.77	30.5		61
STM 1.60	1.22	60	2.0	85	45.5	278	1.08	36.6		68
STM 1.80B	1.22	70	2.5	85	85	198	1.43	34.0		60
STM 1.130	1.22	112	3.7	85	85	278	2.00	37.0		68
(a) This is the SAFT STM series of nickel-cadmium batteries										
(b) Tested at INEL (Reference 12): C/3 - 212 Ah, 55.7 Wh/kg										

Table 7. Characteristics of Sealed Nickel-Cadmium Batteries

Module (a)	Voltage (b)	(Ah) C/3	Weight (kg)	Dimensions (mm)			Volume (ℓ)	$\frac{Wh}{kg}$ C/3	$\frac{Wh}{\ell}$ C/3
				L	W	H			
H 40	6.5	42	6.5	140	115	165	2.66	39.4	96
H 50	6.5	53	7.5	180	115	165	3.41	43.2	95
H 60	6.5	63	8.5	200	115	165	3.79	44.5	100
H 70	6.5	72	9.5	230	115	165	4.36	46.2	101
H 80	6.5	84	10.5	265	115	165	5.03	48.8	102
H 90	6.5	95	11.5	295	115	165	5.60	50.4	103
H 100	6.5	106	12.5	325	115	165	6.16	51.0	105
(a) Hoppecke sealed nickel-cadmium batteries under development - engineering estimates of cell performance									
(b) 5 cells per module

Figure 4: Peukert Curves for the Flooded nickel-cadmium batteries.

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Figure 5: Peukert Curves for sealed nickel-cadmium batteries.

Table 8. Characteristics of large-cell nickel-iron and nickel-cadmium batteries

					Dimensions (mm)						
		Nominal Voltage	Rated (Ah) C/3	Weight (kg)	L	W	H	Volume (ℓ)	WH kg	C/3	Wh ℓ C/3
Eagle Picher Nickel-Iron											
NIF-170		6.2	170	25.0	260	179	245	11.4	42.1		91
NIF-200		6.2	200	25.1	260	179	245	11.4	49.4		107
NIF-220		6.2	220	25.3	260	179	245	11.4	53.9		118
SAFT Nickel-Cadmium											
STM 5-200		6.0	200	24	244	190	280	13.0	50		93
STM 5-140		6.0	140	18	244	153	262	9.8	47		84

COST AND CYCLE-LIFE

Cost and life-cycle information is available for some of the batteries discussed in this section. The information is of limited relevance for batteries to be used in mass-marketed electric vehicles for at least two reasons. First, traction batteries are presently produced in relatively small quantities resulting in prices that are much higher than affordable by the public. This is true even for lead-acid batteries. Second, the cycle life (number of cycles) quoted in the literature from the battery manufacturers pertains to constant-current discharge cycles to at most 80% DOD. Field experience with lead-acid batteries in vehicles and the limited laboratory data available (Reference 13) show that battery life on the FUDS or SFUDS cycles to 100% DOD is much shorter than that found from constant-current discharge testing. The reason for the shorter life of lead-acid batteries on the SFUDS cycle is not presently known and is the object of continuing testing of Sonnenschein sealed lead-acid batteries at INEL.

Available cost and life cycle information for a number of traction batteries is given in Table 9. Of particular interest is the effect of cell size (Ah) on the \$/kWh cost of the battery module. In general, the \$/kWh cost increases as the cell size is reduced. High volume production of the batteries would be expected to significantly reduce the module costs for all cell sizes, but the cost trend with cell size should remain the same. The \$/kWh cost of lead-acid batteries will always be lower than that of nickel-cadmium batteries because of the higher material costs of nickel and cadmium. (There is also the question of the adequacy of the world's cadmium supply if mass-marketed vehicles used nickel-cadmium batteries.) However, the expected longer cycle life of the nickel-cadmium batteries could make their life-cycle costs lower than that of lead-acid batteries in the future.

Table 9. Cost and cycle life information on various batteries

Battery Type	Manufacturer/Module	Capacity (Wh) C/3	Module (a) Cost \$	\$/kWh	Cycle Life (b)
Lead-Acid Flooded	Lucas Chloride 3ET205	1050	275	262	N.A.V.
	Japan Storage				
	E75P	810	330	407	600
	ED150P	1610	590	366	1000
Lead-Acid Sealed	Sonnenschein				
	DF6V180	895	160	179	700(c)
	DF 150	775	110	142	700
	DF 75	420	73	174	700
	DF 45	298	50	168	700
	Johnson Controls				
	GC6V200	775	232	299	500(d)
	GC12V100	785	233	297	500
	GC12550	440	167	380	500
	GC12400	320	131	410	500
	U1 - 31	275	95	345	500
Nickel-Cadmium Flooded	SAFT				
	STM 5-200	1220	752	616	2000(d)
	STM 5-140	825	592	718	2000
	STM 1.130	140	103	735	2000
	STM 1.60	75	58	773	2000
	STM 1.40B	43	35	814	2000
(a) List Price					
(b) Cycle life claimed in brochures from manufacturer					
(c) C/5, 60% DOD					
(d) C/5, 80% DOD					

VEHICLE/BATTERY COMBINATIONS

The battery characteristics given in the previous sections have been used to configure battery packs for the electric vehicles described in Table 1. The first step in configuring a battery pack for a particular battery type and vehicle is to identify a module for which the number of modules required to meet the voltage requirement fits into the planform (length and width) space available in the vehicle. If the weight of the pack is not close to the target weight for that vehicle, the module capacity (Ah) is adjusted (increased or decreased) to meet the target weight. It is assumed that this can be done by changing the battery height while leaving the foot-print (width and length) of the module unchanged. In this way, the performance and range of the various battery/vehicle combinations can be compared on a consistent basis. In nearly all cases, the adjustments in module height needed were not large and should not affect the energy and peak power densities of the modules of a particular technology. The results of the battery configuring are given in Tables 10 and 11 for the lead-acid and nickel-cadmium batteries. For the 1998 vehicles, all of the battery packs are for 340-360 volt systems, which are compatible with the 37.5, 56.3, and 75 kW (50, 75 and 100 Hp) MEVP drivelines used in the vehicles. The results of the SIMPLEV calculations for the various vehicle/battery combinations are given in Tables 12 and 13. The results given in Tables 10-13 are discussed separately for the large vehicles (full-size and mini-vans) and the small vehicles (micro-vans and compact cars). Performance characteristics (References 14-16) given in Table 14 for the TEVan, GVan, and DSEP are based on the batteries for which the vehicles were designed.

LARGE VANS

Batteries in the minivan (ETX-II) and the large van (Van B) are packaged under the floor so that they do not impact the utility of the vehicle. Hence battery height is a critical dimension. With the high system voltages of

Table 10. Battery configurations for 1998 vehicles using sealed lead-acid batteries

1998 Vehicles		Battery Module							Battery Pack (b)		
Name	Type	Model (a)	(Ah)C/3	Wgt (kg)	Dimensions			Volts	Wgt (kg)	Volume (ℓ)	Capacity kWh
					L	W	H				
Car A	2-pass	DF 45	30	10.8	196	132	216	336	303	156	10.0
Van A	Microvan	DF 75	45	16.3	210	175	225	336	455	232	15.0
Van B	Lg. Van	DF 180	70	25.3	330	170	225	336	707	353	23.0
ETX-II	Minivan	DF 180	64	23.1	330	170	205	336	647	322	21.0
Impact	2-pass. Sports	DF 75	38	13.7	210	175	190	336	384	196	12.0
ETV-I	4-pass compact	DF 75	45	16.3	210	175	225	336	455	232	15.0
(a) Sonnenschein sealed lead-acid modules (Table 4)											
(b) 28, 12-Volt modules used in each pack											

Table 11. Battery configurations for 1998 vehicles using sealed nickel-cadmium batteries

1998 Vehicles		Battery Module (b)					Battery Pack (c)				
Name	Type	Model ^(a)	(Ah)C/3	Wgt (kg)	Dimensions			Volts	Wgt (kg)	Volume (ℓ)	Capacity kWh
					L	W	H				
Car A	2-pass	H 40	45	5.8	140	115	177	345	325	160	15.0
Van A	Microvan	H 60	60	7.8	200	115	160	345	434	206	20.0
Van B	Lg. Van	H 90	100	12.9	295	115	175	345	723	335	34.0
ETX-II	Minivan	H 80	85	11.0	265	115	170	345	614	290	29.0
Impact	2-pass. Sports	H 40	45	5.8	140	115	177	345	325	160	15.0
ETV-I	4-pass compact	H 60	60	7.8	200	115	160	345	434	206	20.0
(a) Hoppecke sealed cells (Table 7)											
(b) 5-cell modules - nominal voltage 6.1 V											
(c) 56 modules in each pack											

Table 12. Calculated performance of the 1998 vehicles using sealed lead-acid batteries

1998 Vehicles							
Name	Type	Batt Wgt (kg)	Batt Vol. (ℓ)	Batt Peak Power(W)	0-96 km/h time (sec)	Range (km)	
						FUDS	88.5 km/h
Car A	2-passenger	303	156	42	16	77 125	76 108
Van A	Microvan	455	232	63	15	88 168	77 161
Van B	Large Van	707	353	96	20	76 296	66 279
ETX-II	Minivan	647	322	64	21	100 216	77 227
Impact	2-passenger Sports Car	384	196	63	10	112 115	135 87
ETV-I	4-passenger Compact	455	232	45	20	100 152	97 135

Table 13. Calculated performance of the 1998 vehicles using sealed nickel-cadmium batteries

1998 Vehicles						
Name	Type	Batt Wgt (kg)	Batt Vol. (ℓ)	Batt Peak Power(kW)	0-96 km/h time (sec)	Range (km) energy consumption (Wh/km)
Car A	2-passenger	325	160	46	15	FUDS 130 140 125 108
Van A	Microvan	434	206	64	15	130 122 170 161
Van B	Large Van	723	335	98	20	120 117 297 280
ETX-II	Minivan	614	290	64	21	145 124 214 222
Impact	2-passenger Sports Car	325	160	63	9	150 182 112 86
ETV-I	4-passenger Compact	434	206	45	20	149 150 150 135

Table 14. Batteries and performance characteristics of 1990 vehicles

1990 Vehicles		Batteries				Acceleration		Range (km) Energy Consumption (Wh/km)	
Name	Type	System Voltage	Battery Type	Battery Wgt (kg)	Batt Vol. (ℓ)	Bat Peak Power (kW)	0-96 km/h seconds	FUDS	88.5 km
TEVan (a)	Minivan	208	NiFe NiF-170	750	395	65	28	179 225	169 230
DSEP (b)	Minivan	195	NiFe NiF-200	695	365	65	29	112 296	144 235
GVan (c)	Large Van	216	Lead-acid 3ET205	1160	535	55	12.4 (d)	95(e) 335	150(f) 234
(a) Based on calculated performance (Reference 14)									
(b) Based on measured performance (Reference 15)									
(c) Based on measured performance (Reference 16)									
(d) Acceleration time for 0-48 km/hr									
(e) Range and energy consumption for the J227a C-cycle									
(f) Range and energy consumption for constant speed of 56 km/hr									

present-day powertrains, the Ah cell size of the batteries required is much smaller than in the past for lower voltage systems. This results in a large reduction in the module height and simplifies packaging the batteries under the floor in the vans. The height available in all cases was much larger than needed for the near-term batteries, because the battery space was sized to accommodate the insulating enclosure required for the sodium-sulfur battery. The lead-acid and nickel-cadmium battery packs were sized in all cases by the battery weight limit set for each of the vehicles and considerable additional battery weight could be added if that was desirable without exceeding the space available. The present study indicated that the cell capacities and foot-prints of the available families of sealed Sonnenschein (Table 4) and Hoppecke (Table 7) batteries could be packaged for the vans without difficulty. The modules used in each of the battery packs are given in the Tables 10 and 11. The energy storage capacities of the packs are based on the module capacity claims of the manufacturers, because none of the modules used in the packs has been tested as yet for electric vehicle applications. Modeling of the modules in the SIMPLEV simulations was based on scaling test data obtained at the INEL for larger Sonnenschein lead-acid and Saft nickel-cadmium modules (References 7,12).

The acceleration performance and range of the 1998 vans using sealed lead-acid and nickel-cadmium batteries are given in Tables 12 and 13. The acceleration performance of the vans is 0-96 km/h in 20-21 seconds for both types of batteries with the limiting powertrain component being the inverter/motor, not the battery. The peak power from the batteries is 98kW for the full-size van and 64kW for the minivan. The corresponding battery peak power densities are 138 W/kg for the full-size van and 105 W/kg for the minivan. Both the lead-acid and nickel-cadmium battery packs can provide the required power. The ranges of the full-size van and the minivan are not greatly different, being about 130 km (80 miles) with nickel-cadmium batteries and about 80 km (50 miles) with lead-acid batteries. For the vans the range on the FUDS cycle is slightly longer than that at 55 mph (see Tables 12 and 13). The ranges of the vans using either of the near-term sealed batteries are significantly less than the 100-mile target of the auto industry, but both batteries can provide satisfactory acceleration performance.

The performance and range of the 1990 and 1998 vans are compared in Table 15. The 1998 vans have significantly better acceleration characteristics than the 1990 vans due to the improved electric powertrains and vehicle designs, but the energy consumptions of the 1990 and 1998 vans are comparable for the same vehicle weights. Hence, the range depends primarily on the energy storage capacity of the batteries and only secondarily on the detailed powertrain and vehicle design.

MICROVANS AND COMPACT CARS

Packaging the batteries in the smaller vehicles (that is the microvan and 2- and 4-passenger cars) is more difficult than in the vans where the batteries can be placed under the floor without impacting the utility of the vehicle. In passenger vehicles having both front and back seats, the batteries are placed inside the passenger compartment in a center tunnel, which runs the length of the vehicle, or under the hood and/or in the trunk area fore or aft of the passenger compartment. These packaging arrangements reduce the utility of the vehicle and put a high premium on minimizing battery volume. For small vehicles having only front seats, the batteries can be placed behind the driver's seat, but above the floor level, without significantly reducing the utility of the vehicle. Packaging the batteries in the two-passenger vehicles is nearly as straight-forward as for the larger vans. The characteristics of the smaller vehicles can be found in Table 1. The microvan and Car "A" are two-passenger vehicles, which utilize the low, aft placement of the batteries. The Impact and the ETV-1 utilize the center

Table 15. Comparison of the performance of 1990 and 1998 vehicles

1998 Vehicles			Performance		
Name	Type	Test Weight (kg)	Max. Motor Power (kW)	Acceleration Time (sec) 0-96 km/hr	Energy Consumption (Wh/km)
Van A	Microvan	1620	56	15	FUDS 88.5 km/hr
Van B	Large Van	2815	75	20	170 161
EIX-II	Minivan	2115	56	21	297 280
Car A	2-passenger	1210	37	15	214 226
1990 Vehicles					125 108
TEVan	Minivan	2400	50	28	
DSEP	Minivan	2350	50	29	225 230
					296 235

tunnel approach to battery packaging. Battery packs for these four vehicles were configured (see Tables 10 and 11) using sealed lead-acid and nickel-cadmium batteries. The system voltage is 340-360V for all the vehicles. The microvan and the Impact use the 56.3 kW (75 hp) motor and the ETV-1 and Car "A" use the 37.5 kW (50 hp) motor. The original Impact used two 45 kW (60 hp) motors to drive the front wheels, but it will be seen later that the single 56.3 kW (75 hp) used in the present study yielded sports car acceleration. As shown in Tables 10 and 11, the required height of the batteries for the high voltage systems is only 180-200 mm (7-8 inches). If the vehicle chassis were redesigned to accommodate the battery container, it might be possible to place the battery pack for the near-term batteries under the floor even for a 4-passenger vehicle like the ETV-1, which utilized a T-shaped interior battery enclosure in the original design.

The acceleration performance and range of the small 1998 vehicles using the lead-acid and nickel-cadmium batteries are given in Tables 12 and 13. There are large variations between the various vehicles even for a particular battery type due to differences in vehicle weight and motor power. The Impact has the largest range and fastest acceleration because of its light weight, low CD, and high motor power. The ranges using nickel-cadmium batteries are 35-55% greater than using the lead-acid batteries. The same acceleration performance can be achieved using either of the near-term battery types. The battery peak power density requirements vary from about 100 W/kg for the lower performance vehicles (0-96 km/h in 15-20 seconds) to almost 200 W/kg for the Impact that accelerates from 0 to 96 km/h in 9-10 seconds. The batteries can likely provide this power in the "new condition" and near full charge, but the effect of the 200 W/kg pulses at lower states-of-charge on battery life is a serious concern for both types of batteries.

Available battery families make it possible to package the batteries in all the smaller vehicles without much difficulty. The high system voltage results in small cell sizes and battery height, which is advantageous from a packaging point-of-view. However, the small Ah cells tend to have a lower energy density than larger cells, resulting in ranges that are slightly less than might be expected.

BATTERY SUPPORT SYSTEMS

The battery pack in an electric vehicle is only part of the battery system, which consists of the charger and associated charging algorithms, the state-of-charge meter and algorithms, and the battery maintenance and thermal management functions. These aspects of the battery system are discussed briefly in the following sections.

BATTERY CHARGING

Battery packs without the proper charging equipment and algorithms are of little value as the useful capacity of the battery will be significantly less than rated and the cycle life of the batteries will be short. This is especially true of sealed batteries such as those considered in this study. Unlike flooded batteries, sealed batteries are designed to require only a few percent overcharge and frequent overcharge of even 10-15% can greatly shorten the life of the batteries. Module-to-module variability is a major source of the difficulty in properly charging battery packs. This becomes a serious problem for sealed batteries if the pack is charged rapidly as is desired by vehicle users. Proper charging of the battery over its life-time as it ages requires knowledge of the Ah in and out of the battery during charge and discharge and monitoring of the modules during charging to insure that each module is fully charged without excessive gassing. Implementation requires a microprocessor-controlled charger, which is integrated with the vehicle control microprocessor, and instrumentation of the battery pack to measure the module voltages during charging. The technology to perform this advanced type of battery charging now exists. State-of-the-art electric vehicle powertrains (References 17,18) have the vehicle and battery control system microprocessors integrated and a one-wire battery monitoring technique has been developed (References 19,20), which permits the measurement of battery module voltages and their use to control battery charging. It is unlikely that the simple battery charging techniques presently in common use will be adequate for the sealed batteries that will be used in future electric vehicles.

STATE-OF-CHARGE INDICATORS

Development of reliable state-of-charge indicators for batteries has proven to be difficult and none has been developed for any type of battery that functions satisfactorily for all types of driving and over the life-time of the battery. A number of approaches have been investigated (References 21,22); the most satisfactory approach seems to be to utilize net Ah out as the measure of the capacity used from the battery by defining state-of-charge as the ratio of the Ah out to the expected capacity of the battery. Implementation of this approach requires that battery current be measured and integrated during both charge and discharge of the battery. This is most difficult to do during discharge (vehicle driving) when the battery current changes rapidly during periods of acceleration and deceleration. This type of state-of-charge indication is utilized in the Eaton DSEP vehicles (Reference 17) and is likely to be used in all future vehicles with all types of batteries. Modification of the expected capacity of the battery as it ages can be done by utilizing information from the advanced microprocessor-controlled battery charger, which requires knowledge of the Ah returned to the battery during charging.

BATTERY MAINTENANCE

The reason that sealed batteries are attractive for use in electric vehicles is that battery maintenance can be reduced to near zero. Flooded batteries require periodic watering, which is labor-intensive, and in addition permit explosive hydrogen to accumulate in the battery container and watering system. Considerable work has been done to improve battery watering systems and make them more safe, but there is a clear trend to the use of sealed batteries.

THERMAL MANAGEMENT

From an ideal point-of-view, thermal management (maintaining the batteries in a relatively narrow range of temperature) should be provided as a part of all battery systems to optimize performance and to maximize cycle life. Ambient-temperature batteries exhibit improved performance with increasing temperature, but operation at temperatures in excess of about 45°C can significantly shorten cycle life. Charging batteries at temperatures below about 5°C results in reduced capacity and in addition can damage the battery.

In practice, thermal management is usually provided only when it can not be avoided as it adds to the size, weight, complexity, and cost of the battery system. For lead-acid and nickel-cadmium battery systems, except in extreme climates, it is possible to operate those batteries without thermal management, especially when the vehicles are used under controlled environmental conditions as in fleets. The possible need for significant thermal management of these batteries in mass-marketed electric vehicles needs further study.

ELECTRIC POWERTRAIN TRENDS

The most important trends in powertrain and vehicle design that affect battery requirements are the increase in system voltage and the improvement in the 0-80 km/h acceleration time specification for the vehicles (see Table 16). The system voltage has increased from 108V in the ETV-I (1975) to 192V for the ETX-I and ETX-II (1984-1987) to 340-360V presently being used in the Impact and MEVP programs (Reference 1). Until recently an electric vehicle that could follow the FUDS driving cycle was deemed to have acceptable performance. The 1990 vehicles had 0-80 km/h acceleration times of about 20 seconds. Present vehicle design goals are 0-80 km/h in less than 15 seconds with some vehicles being designed to accelerate from 0-96 km/h in less than 10 seconds. These large improvements in vehicle acceleration performance have been made possible by the recent large advances in motor and electronic technology

Increasing system voltage has significant advantages for the motor and electronic designers as it reduces the peak currents in the system and permits higher motor RPM, resulting in smaller, lighter motors. A study of voltage trade-offs in electric powertrains (Reference 23) in 1980 identified these advantages, but also showed the disadvantages from the battery point-of-view of increasing system voltage. Results taken from Reference 19 are plotted in Figure 6 for lead-acid and nickel-zinc batteries. The results (Wh/kg, Wh/l, \$/kWh) of the computerized design studies, normalized to a 100 V system, indicate that the energy densities decrease slightly with increasing system voltage and that the costs increase significantly with increasing system voltage as the required cell sizes decrease. The cost results shown in Figure 6 are consistent with the increase in \$/kWh given in Table 9 for presently available commercial batteries of small cell size. Increasing system voltage results in a greater number of smaller cells in series to store the same kWh in the battery pack, resulting in a higher pack cost. The results given in Reference 19 are directly applicable to the plate type, near-term batteries

Table 16. Trends in electric powertrain design (1975-2000)

Year	Max Motor Power (kw)	System Voltage	0-80 km/h Acceleration Time (seconds)	Battery Peak Power Density Required(W/kg)
1975-1980	25-30	100 V	20-25	60-65
1985-1990	45-50	200	15-20	80-100
1998	55-75	300-400	10-13	150-200

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Figure 6: Effect of system voltage on the performance and cost of NiZn and lead-acid batteries.

considered in this study; their applicability to batteries such as the CSPL sodium-sulfur battery that are assembled from parallel, series arrangements of small individual cells regardless of the system voltage is less clear. For all battery types, it would be expected that having a greater number of smaller cells/modules in series would be detrimental to battery life, because it would magnify the consequences of cell/module variability, making it more difficult to keep the module capacities balanced during battery charging. The combined effect of reducing battery life and increasing the unit cost (\$/kWh) of the batteries could result in a greatly increased life-cycle cost of the batteries at high system voltages.

Reducing the acceleration time targets for electric vehicles increases the peak power required from the battery pack and thus the peak power density requirement for the battery cells/modules. In developing the SFUDS battery test procedure (Reference 24), it was determined that a cell/module peak power density of about 79 W/kg was required if a vehicle were to follow the FUDS driving cycle. The simulation results obtained in this study (Tables 12 and 13) indicate that for the higher performing electric vehicles presently being designed, battery power densities of 100-200 W/kg are required. The vehicle acceleration performance will degrade as the battery is discharged unless the high power densities are achievable even at low battery states-of-charge (at least as low as 80%). Batteries developed to date do not have power densities in excess of 100 W/kg at low states-of-charge. The high peak power density requirement combined with the need for a larger number of smaller capacity cells to satisfy a high system voltage seems certain to make it more difficult to meet the battery cycle life targets of 500-1000 cycles on the SFUDS test cycle.

The effect of system voltage and vehicle acceleration performance on battery cost and cycle life should be considered as part of the vehicle/powertrain design process. This is not easy to do as much of the battery data to examine these tradeoffs is available only after a new battery technology has been developed and tested. Nevertheless, there is little doubt that the recent trends cited make the task of the battery designer more difficult and may even limit the choices available for advanced batteries.

SUMMARY

In this study, battery requirements were determined for a wide spectrum of electric vehicles ranging from 2-passenger sports cars and microvans to full-size vans with a 500 kg payload capacity. All the vehicles utilize ac, high voltage (340-360 V) powertrains and have acceleration performance (0-80 km/h in less than 15 seconds) expected to be the norm in 1998 electric vehicles. Lead-acid and nickel-cadmium batteries were considered in the study as they are likely to be the only types of batteries available in large quantities in 1998. Battery packs were configured for each of the vehicles, using families of sealed lead-acid and nickel-cadmium batteries which are either presently available in limited quantities or are being developed by battery companies which market a similar battery technology. It was found that the battery families available encompass the Ah cell sizes required for the various vehicles and in most cases available modules could be used, if necessary, with little sacrifice in vehicle range or performance. Packaging the ambient temperature, sealed batteries in the vehicles using high system voltages was not difficult as the individual modules were relatively small in footprint and height.

The acceleration performance and range were calculated for each of the vehicles, using the SIMPLEV simulation program. The results showed that all types of electric vehicles can be built with good acceleration characteristics -0-96 km/h (0-60 mph) in 15-20 seconds or less -- without difficulty using either lead-acid or nickel-cadmium batteries. The peak power density required of the battery pack is 100-150 W/kg. The ranges of the vehicles are primarily dependent on the energy storage capacity (Wh/kg) of the battery as the energy consumption (Wh/km) of the vehicles in the various driving modes is almost independent of the battery type. The ranges of the vehicles are between 80 and 160 km (50 and 100 miles) with the range using nickel-cadmium batteries being 40-60% higher than that using lead-acid batteries. The range results indicate it will be more difficult to achieve a 100-mile (160 km) range for the vans than for the passenger cars, because of the higher aerodynamic drag of the vans.

There have been significant changes in the design of electric vehicles in the last fifteen years. The most important of these trends that affect battery requirements are the increase in system voltage from 100 V to 350 V and the improvement in the 0-80 km/h (0-50 mph) acceleration times from 20-25 second in 1975 to 10-13 seconds for 1998 vehicles. These trends make the design of the battery more difficult by increasing the peak power density required from about 60 W/kg to 100-150 W/kg and by reducing the Ah cell size needed from about 150 Ah to 30-70 Ah. Both of these changes in battery specifications increase the difficulty of achieving low \$/kWh cost and long cycle life. This true for both the lead-acid and nickel-cadmium batteries.

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