Electric Vehicle Application Handbook
For Genesis® Sealed-Lead Batteries

Fourth Edition

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Preface

This, the fourth edition of the electric vehicle handbook has been created with a view to include updated Genesis® battery information for EV users. Readers will also be interested to know that the product line has been extended by the addition of a larger Genesis® size to the family. The 12V, 65Ah battery is the largest single module that has been manufactured by Hawker Energy Products Inc., and complete ***preliminary*** information on this new battery is included in this edition.

It is hoped that this edition will be at least as useful to its reader as its three predecessors. We at Hawker Energy Products Inc. are very proud of the capabilities of this unique battery, and will continue to provide updated information to designers and users of the Genesis® line of sealed-lead batteries.

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Introduction

Although the Genesis® battery was originally conceived to be a high-rate discharge battery, many electric vehicle (EV) designers and users have found that, when applied properly, these batteries are capable of delivering up to 500 cycles at 80% depth of discharge (DOD) at the three (3) to five (5) hour discharge rate. These excellent numbers make Genesis® an ideal choice for many existing and future EV applications.

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Why use Genesis® in electric vehicles?

There are several answers to this question. Some are listed below:

- ***Greater cycle life*** — Genesis® achievable cycle life is remarkable for sealed-lead batteries. A conventional sealed-lead battery would typically have a cycle life to 80% DOD anywhere between 200 and 300 cycles. By using Genesis® batteries, the EV manufacturer is able to experience almost double life expectancy, very high power density, plus all the advantages of a sealed chemistry.

- ***Existing product*** — Genesis® batteries are in commercial production **TODAY** as an off-the-shelf product. The EV manufacturer does not have to wait for prototypes to be converted to production status and to demonstrate consistent reliability.

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♦ ***Low internal resistance*** — The extremely low fully charged internal resistance of 4.5mΩ to 10mΩ per 12V module is another distinct advantage of Genesis® batteries. These resistances are 33% to 50% of those of conventional sealed-lead batteries. Because of such a low internal resistance, the voltage profile of the Genesis® battery under discharge is relatively flat, enabling the voltage to stay at a higher level longer during discharge.

♦ ***Opportunistic charging*** — Another advantage of having very low internal resistance is that it allows high currents to be pumped back into the battery pack during regenerative braking. Such a scheme enables "opportunistic" charging of the battery. This topic is explored in greater detail later in the section titled **Opportunistic charging and Extended time charging**.

♦ ***Fast recharge capability*** — Provided that the charger has the requisite power handling capability, Genesis® batteries may be recharged to better than 95% state of charge (SOC) **in under one (1) hour using only a single level constant voltage charge**. The later section on opportunistic and extended time charging sheds more light on this aspect of Genesis® batteries.

♦ ***Dry cell classification*** — All Hawker Energy Products Inc.'s batteries (including Genesis®) are dry by design and have been tested and determined to be in compliance with section 173.159 (d) of the United States Department of Transportation (USDOT) regulation. They are exempted from other shipping requirements of 49CFR, sub-chapter 173.159, and as of September 30, 1995, all shipments are classified as unregulated "nonspillable wet electric storage batteries." All batteries and shipping containers are marked "**NONSPILLABLE**" or "**NONSPILLABLE BATTERY**."

- ***Mounting flexibility*** — The Genesis® battery may be installed in any orientation without sacrificing any performance attributes.

- ***High-rate discharge capability*** — Genesis® batteries are ideally suited for hybrid electric vehicles (HEV) due to their extraordinary short duration, high-rate discharge capability. This helps greatly in providing brief bursts or *pulses* of very high magnitudes to accelerate the HEV without causing the battery voltage to drop too low. A separate section later in this handbook is devoted to more discussions on using Genesis® batteries in HEV applications.

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Discharge characteristics of Genesis® batteries

The next five graphs and their accompanying tables describe in considerable detail the discharge characteristics of the complete line of Genesis® batteries. Note, however, that these graphs and charts provide full discharge performance information only to one specific end of discharge voltage (EODV) and one temperature (25°C).

Should the reader be interested in similar information to other EODV values, or for other information not contained in this guide, they are urged to consult the ***Genesis® Application Manual***. For a copy of this very comprehensive manual, please contact your local Hawker Energy Products Inc. representative or the near-est authorized value added center. You may also order your copy by calling (800) 964 – 2837 (in the United States) or (660) 429 – 6437 from outside the United States.

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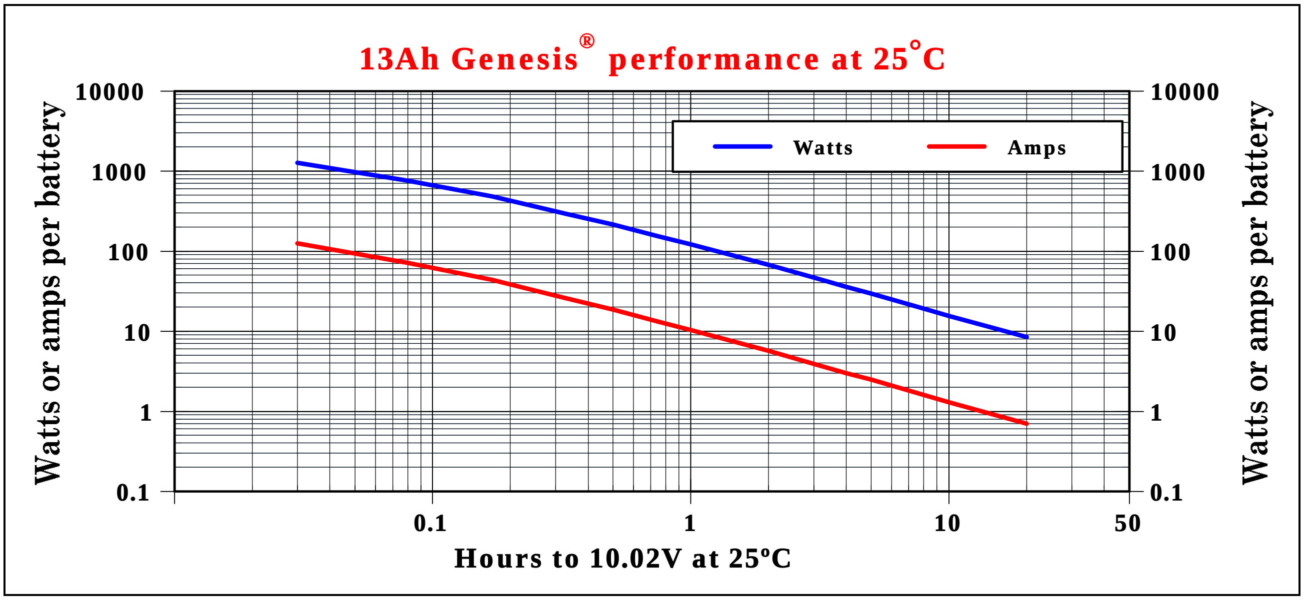

Run time to 1.67 vpc	Watts	Amps	Capacity (Ah)	Energy (Wh)	Energy and power densities			
					Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	1268	123.9	4.10	42.30	665.20	22.20	264.10	8.80
5 min	758	70.8	5.90	63.20	397.90	33.20	158.00	13.20
10 min	482	43.6	7.30	80.30	252.80	42.10	100.40	16.70
15 min	361	32.2	8.05	90.30	189.50	47.40	75.25	18.80
20 min	292	25.7	8.60	97.20	153.00	51.00	60.75	20.25
30 min	214	18.6	9.30	106.80	112.10	56.00	44.50	22.25
45 min	154	13.2	9.90	115.65	80.90	60.70	32.10	24.10
1 hr	121	10.4	10.40	121.20	63.60	63.60	25.25	25.25
2 hr	67	5.7	11.40	134.40	35.30	70.50	14.00	28.00
3 hr	47	3.9	11.70	140.40	24.60	73.70	9.75	29.25
4 hr	36	3.0	12.00	144.00	18.90	75.55	7.50	30.00
5 hr	29	2.5	12.50	147.00	15.40	77.10	6.10	30.60
8 hr	19	1.6	12.80	153.60	10.10	80.60	4.00	32.00
10 hr	16	1.3	13.00	156.00	8.20	81.85	3.25	32.50
20 hr	8	0.7	14.00	168.00	4.40	88.15	1.75	35.00

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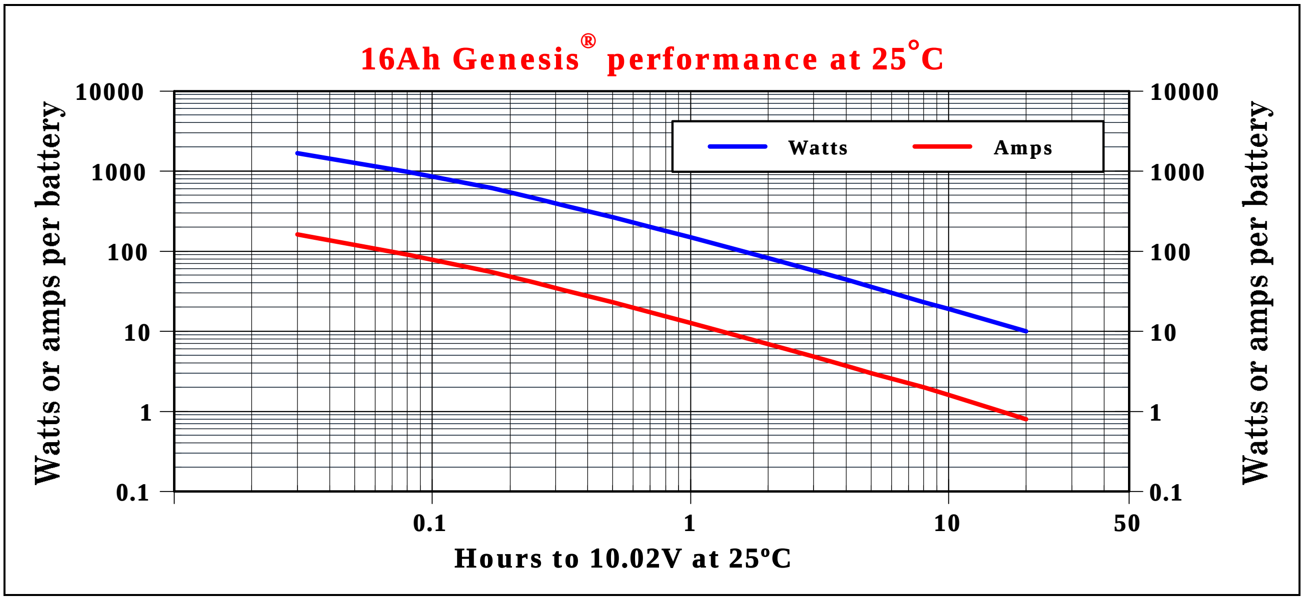

Run time to 1.67 vpc	Watts	Amps	Capacity (Ah)	Energy (Wh)	Energy	and	power	densities
					Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	1660	159.9	5.30	55.30	705.40	23.50	267.80	8.90
5 min	967	89.3	7.40	80.60	410.90	34.25	156.00	13.00
10 min	605	54.3	9.05	100.80	257.00	42.80	97.55	16.30
15 min	450	39.8	9.95	112.50	191.20	47.80	72.60	18.15
20 min	361	31.7	10.60	120.40	153.50	51.20	58.30	19.40
30 min	263	22.8	11.40	131.40	111.70	55.80	42.40	21.20
45 min	188	16.2	12.15	141.30	80.05	60.00	30.40	22.80
1 hr	148	12.6	12.60	148.20	63.00	63.00	23.90	23.90
2 hr	82	6.9	13.80	163.20	34.7	69.30	13.20	26.30
3 hr	57	4.8	14.40	171.00	24.20	72.65	9.20	27.60
4 hr	44	3.7	14.80	175.20	18.60	74.40	7.10	28.30
5 hr	36	3.0	15.00	180.00	15.30	76.50	5.80	29.00
8 hr	23	1.9	15.20	187.20	9.90	79.50	3.80	30.20
10 hr	19	1.6	16.00	192.00	8.20	81.60	3.10	31.00
20 hr	10	0.8	16.00	204.00	4.30	86.70	1.65	32.90

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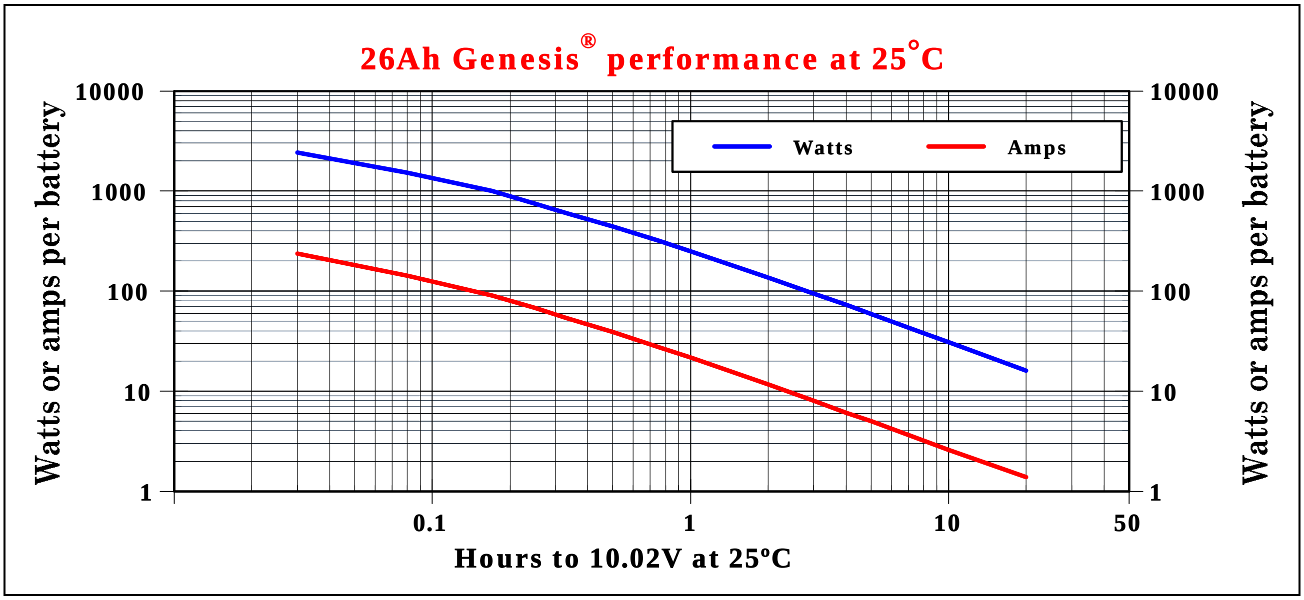

Run time to 1.67 vpc	Watts	Amps	Capacity (Ah)	Energy (Wh)	Energy and power densities			
					Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	2419	235.8	7.90	80.60	654.50	21.80	228.20	7.60
5 min	1532	143.4	11.95	127.65	414.50	34.50	144.50	12.0
10 min	995	90.7	15.10	165.90	269.40	44.90	93.90	15.65
15 min	751	67.4	16.85	187.65	203.10	50.80	70.80	17.70
20 min	607	54.1	18.0	202.40	164.30	54.80	57.30	19.10
30 min	444	39.0	19.50	222.0	120.15	60.10	41.90	20.90
45 min	319	27.8	20.85	239.40	86.40	64.80	30.10	22.60
1 hr	251	21.7	21.70	250.80	67.90	67.90	23.70	23.70
2 hr	137	11.7	23.40	273.60	37.0	74.0	12.90	25.80
3 hr	95	8.0	24.0	284.40	25.65	77.0	8.90	26.80
4 hr	73	6.1	24.0	290.40	19.65	78.60	6.85	27.40
5 hr	59	5.0	25.0	297.0	16.10	80.40	5.60	28.0
8 hr	38	3.2	25.60	307.20	10.40	83.10	3.60	29.0
10 hr	31	2.6	26.0	312.0	8.40	84.40	2.90	29.40
20 hr	16	1.4	28.0	324.0	4.40	87.70	1.50	30.60

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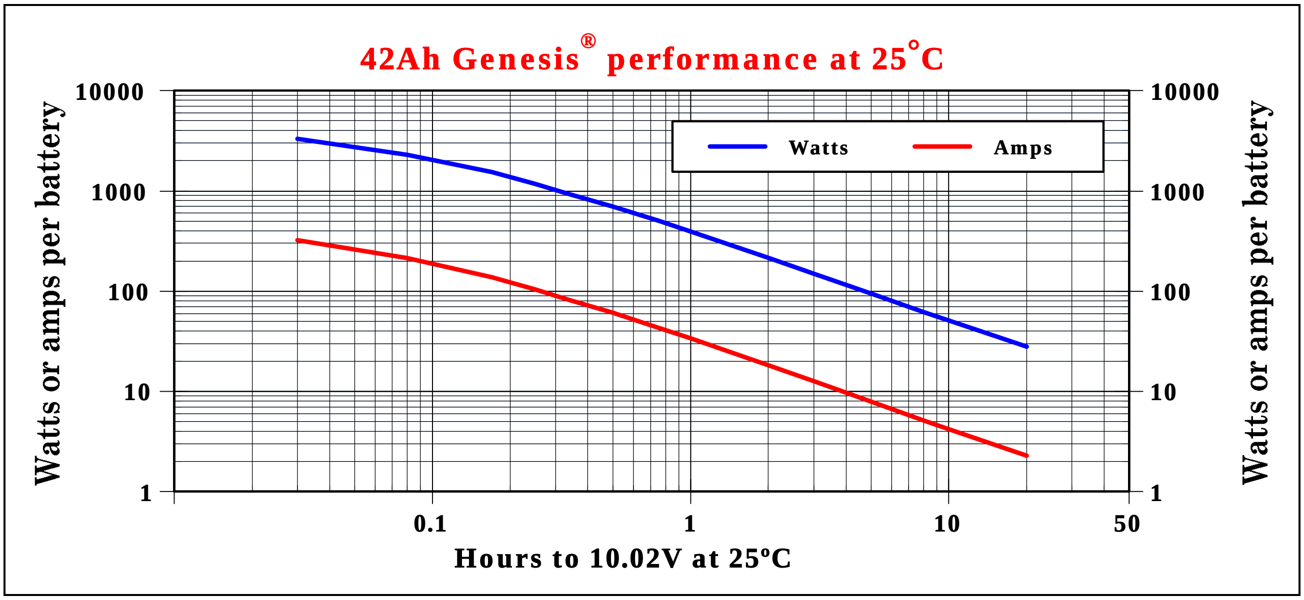

Run time to 1.67 vpc	Watts	Amps	Capacity (Ah)	Energy (Wh)	Energy	and	power	densities
					Watts per liter	Wh per liter	Watts per kilogram	Wh per kilogram
2 min	3317	322.3	10.70	110.60	593.0	19.80	225.70	7.50
5 min	2291	212.0	17.70	190.95	409.60	34.10	155.90	13.0
10 min	1540	138.4	23.10	256.6	275.20	45.90	104.70	17.50
15 min	1173	104.1	26.0	293.25	209.70	52.40	79.80	19.95
20 min	953	83.8	27.90	317.6	170.30	56.80	64.80	21.60
30 min	698	60.8	30.40	348.9	124.70	62.40	47.50	23.70
45 min	502	43.3	32.50	376.65	89.80	67.30	34.20	25.60
1 hr	394	33.8	33.80	393.6	70.35	70.35	26.80	26.80
2 hr	215	18.2	36.40	429.6	38.40	76.80	14.60	29.20
3 hr	149	12.6	37.80	448.2	26.70	80.10	10.20	30.50
4 hr	115	9.7	38.80	460.8	20.60	82.40	7.80	31.35
5 hr	94	7.9	39.50	471.0	16.80	84.20	6.40	32.0
8 hr	62	5.1	40.80	494.4	11.05	88.40	4.20	33.60
10 hr	51	4.2	42.0	510.0	9.10	91.20	3.50	34.70
20 hr	28	2.3	46.0	564.0	5.0	100.80	1.90	38.40

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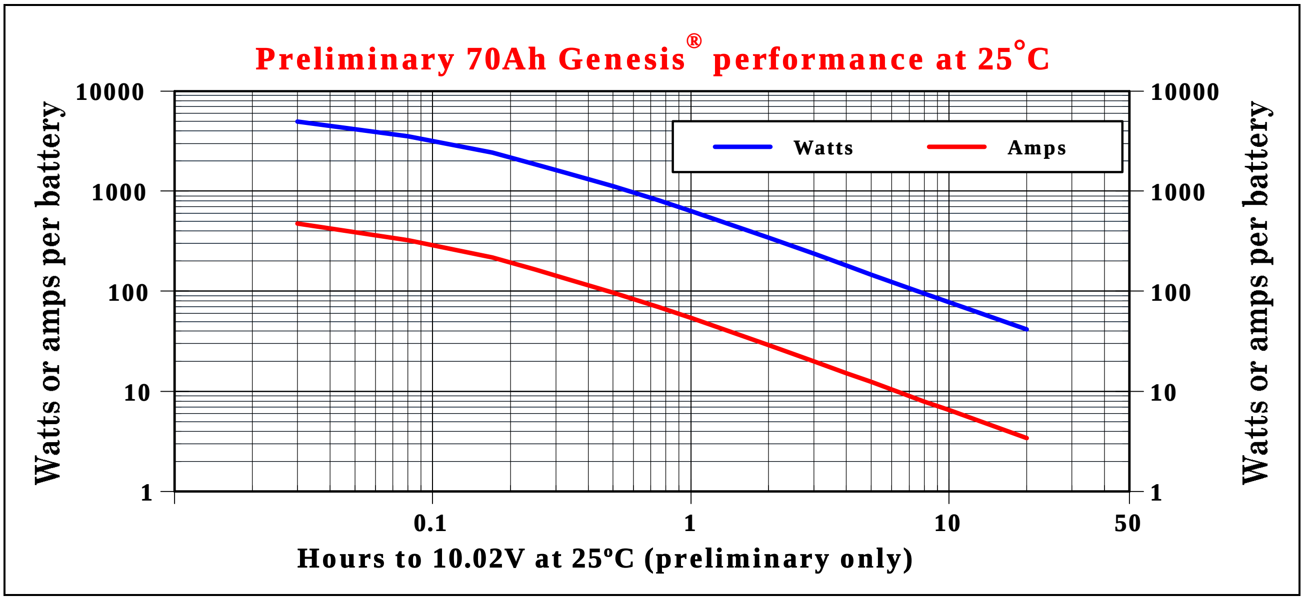

Run time	Watts	Amps	Capacity	Energy	Energy	and	power	densities
to 1.67 vpc			**(Ah)**	**(Wh)**	**Watts/lit.**	**Wh/lit.**	**Watts/kg.**	**Wh/kg.**
2 min	4938	476.2	15.9	165	504.6	16.8	180.9	6.0
5 min	3525	325.6	27.1	294	360.2	30.0	129.1	10.8
10 min	2416	217.2	36.2	403	246.8	41.1	88.5	14.7
15 min	1858	164.8	41.2	464	189.8	47.5	68.0	17.0
20 min	1517	133.4	44.5	506	155.1	51.7	55.6	18.5
30 min	1118	97.2	48.6	559	114.2	57.1	40.9	20.5
45 min	806	69.5	52.1	605	82.4	61.8	29.5	22.1
1 hr	633	54.2	54.2	633	64.7	64.7	23.2	23.2
2 hr	343	29.1	58.2	686	35.1	70.1	12.6	25.1
3 hr	237	20.0	60.0	711	24.2	72.7	8.7	26.0
4 hr	182	15.2	60.8	727	18.6	74.3	6.7	26.6
5 hr	148	12.4	62.0	738	15.1	75.4	5.4	27.0
8 hr	95	7.9	63.2	763	9.7	78.0	3.5	28.0
10 hr	77	6.5	65.0	774	7.9	79.1	2.8	28.3
20 hr	41	3.4	68.0	828	4.2	84.6	1.5	30.3

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Other Genesis® specifications

Item	13Ah	16Ah	26Ah	42Ah	70Ah[1]
			Model		
Capacity (Ah) at :					
10 hr rate	13.0 (1.3A)	16.0 (1.6A)	26.0 (2.6A)	42.0 (4.2A)	65.0 (6.5A)
5 hr rate	12.5 (2.5A)	15.0 (1.5A)	25.0 (5.0A)	37.0 (7.2A)	62.0 (12.4A)
3 hr rate	11.7 (3.9A)	14.4 (4.8A)	22.5 (7.5A)	32.3 (10.7A)	60.0 (20.0A)
1 hr rate	10.4 (10.4A)	12.7 (12.7A)	21.0 (21.0A)	30.0 (30.0A)	54.2 (54.2A)
Max. dimensions, in. (mm)					
L	3.29 (84)	3.01 (77)	6.92 (176)	6.53 (166)	6.62 (168)
W (terminal side)	6.91 (176)	7.15 (182)	6.57 (167)	7.78 (198)	13.02 (331)
H	5.12 (130)	6.62 (168)	4.96 (126)	6.72 (171)	6.93 (176)
Weight, lbs (kg)	11.8 (5.4)	13.4 (6.1)	23.0 (10)	35.0 (16)	60.0 (27.3)
Cycle life at 25°C					
@ 15 min rate	250 for 100% DOD and 2.45 vpc charge for 16 – 24 hrs[2].				
	350 for 80% DOD and 2.45 vpc charge for 16 – 24 hrs.				
@ 3 to 5 hr rate	400 for 100% DOD and 2.45 vpc charge for 16 – 24 hrs.				
	500 for 80% DOD and 2.45 vpc charge for 16 – 24 hrs.				
Operating temperature	– 40°C to + 60°C, depending on packaging selected				
Int. resistance[3]	10mΩ	7.0mΩ	5.0mΩ	4.5mΩ	3.5mΩ (est.)
Short circuit level	> 1,200A	> 1,800A	> 2,400A	> 2,600A	> 3,500A (est.)

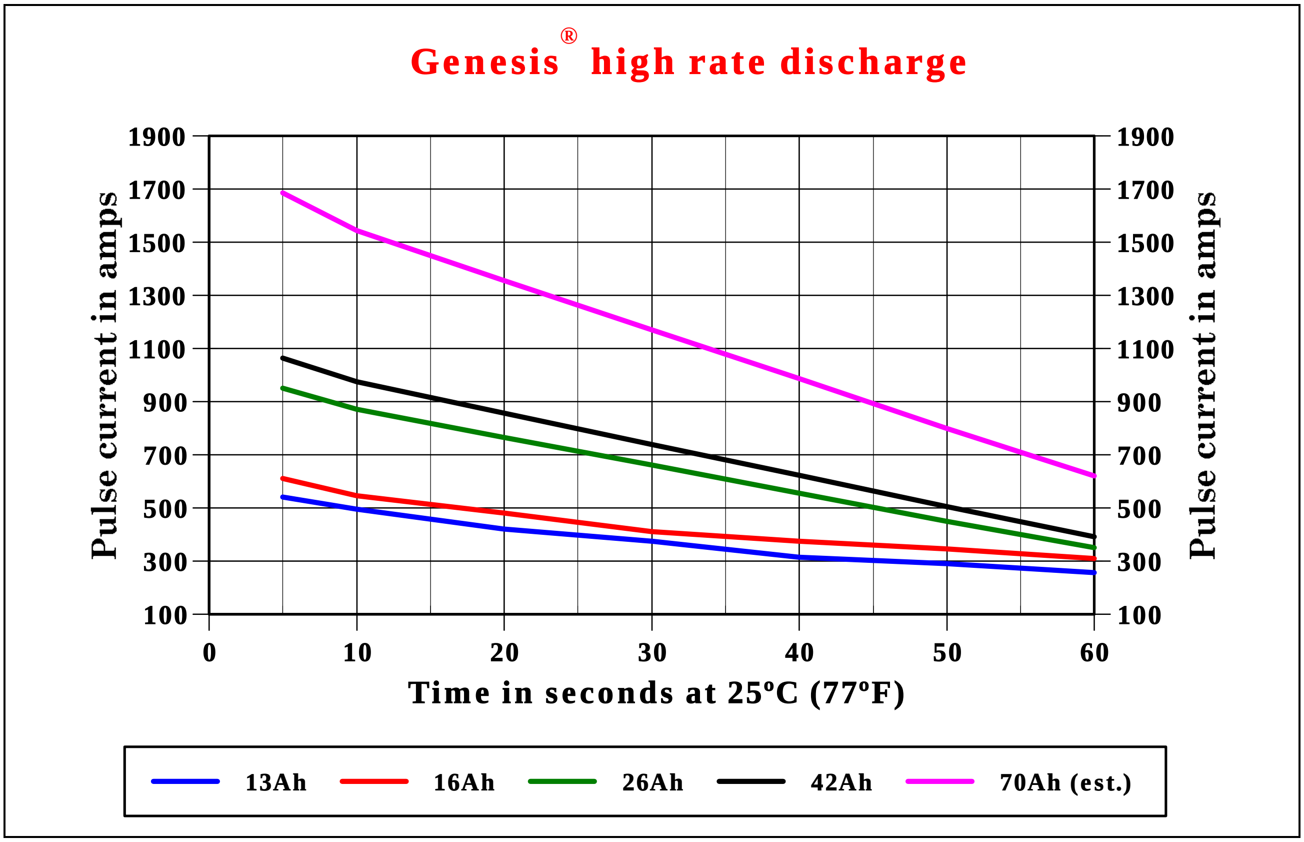
[1] Preliminary data only

[2] The current limit or the initial inrush current must be as high as possible

[3] For a fully charged 12V battery when measured using a H-P 4328A milliohmmeter

Pulse discharge capabilities

The graph titled ***Genesis® high rate discharge*** shown below demonstrates the extraordinary short duration (pulse) discharge capabilities of these batteries. Note that the discharge figures are shown for an ambient temperature of 25°C and to an EODV of 7.00V per 12V battery. Provided that the EV's electronics can tolerate such a low battery voltage, this graph illustrates how Genesis® batteries may be used to provide brief bursts of very high currents to help in rapid acceleration situations.



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Two points should be kept in mind when using this battery for such extreme high-rate discharges. First, sufficient time must be given between two successive discharges to allow the terminals to cool down. Second, the graph reflects the capabilities of ***fully charged*** batteries. Unless the batteries are fully charged, one must not expect them to meet these numbers. Finally, all of these numbers are for an ambient temperature of 25°C; if the temperature is significantly different from 25°C, the graph shown above must be appropriately modified.

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Optimizing battery performance and cycle life

To obtain the best performance and maximum cycle life from the Genesis® battery, attention must be paid to ***(a) adequate charging***, ***(b) monitoring of the battery system*** and ***(c) proper installation of the battery pack***.

Owing to the extreme sensitivity of battery performance to charging conditions, particularly in cyclic applications such as EVs, we will devote considerable time and space to discussing the charging requirements in an EV environment.

To obtain maximum life from a sealed-lead battery, its charging scheme must be optimized with respect to the specific application. While there are several methods to effectively recharge a sealed-lead battery, a full recharge must put in a few more ampere-hours than what was taken out on the previous discharge. Typically this is in the neighborhood of 5% to 10% additional ampere-hours; however, we have seen Genesis® batteries deliver excellent cycle life with as little as

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2% to 3% overcharge when the initial (inrush) current in the charge cycle is of the order of $1C_{10}$ or higher.

This statement is particularly relevant to EVs because of the cyclic nature of the battery's duty cycle. A sealed-lead battery is negatively affected by both overcharge and undercharge — the difference lies in the time scale in which the detrimental effects show up. Since the results of undercharge appear much faster than those due to overcharge, the issue of undercharge is of critical importance in EV applications.

In a cyclic application, undercharging is generally more likely than overcharging, and therefore the battery is likely to fail prematurely. This makes proper charging of the EV battery extremely critical. We have seen batteries in cyclic applications fail due to undercharge in less than thirty cycles. This is disastrous, considering that the cycle life of Genesis® batteries is about 500 for 80% DOD cycles.

THE IMPORTANCE OF ADEQUATE CHARGING IN ELECTRIC VEHICLES CANNOT BE OVEREMPHASIZED

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Charging Genesis® batteries in an EV environment

(I) BATTERY CHARGING WAVEFORM QUALITY CONSIDERATIONS

The quality of the charging current waveform is an important factor that must be considered when designing a charging system. Poor waveform quality may have a significant impact on battery cycle life, even when the charging regime is otherwise an effective one.

Average (AVE) and Root Mean Square (RMS) Values

A good quality waveform should have an AVE value that is sufficient to meet the control limits required by the chosen charging algorithm. **The AVE value of the waveform is an important consideration due to the fact that it is the AVE value of the waveform that is responsible for putting the ampere-hours into the battery.**

The root mean square (RMS) value of a waveform is frequently used in electric power measurements. The RMS value of a waveform describes a measure of equivalent energy transport or dissipation into a standard resistive load.

This makes it conceptually possible to dissipate 100 watts of power in a 1Ω resistor using either a purely sinusoidal 10 amperes RMS or a pure 10 amperes of DC. However, that same sinusoidal 10A RMS waveform, when connected to a battery, will **return zero ampere-hours, regardless of how long the charger**

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is left connected to the battery. This is due to the fact that the AVE value of a sinusoidal waveform is zero.

Ripple Values

One measure often used to qualitatively describe the DC power supply output is the percentage of ripple contained in the output voltage waveform over a range of electrical load conditions.

It is recommended that the total variation of the DC supply, including load regulation effects, is **less than ±2% (peak-to-peak) of the nominal charging voltage**. This means that for a system being charged at 2.45 volts per cell (vpc), the absolute limits of voltage variation are from 2.401 to 2.499 vpc.

(II) CONSTANT VOLTAGE (CV) CHARGING

One of the most effective methods of recharging a sealed–lead battery is a single value constant voltage (CV). Genesis® batteries may be charged at **14.7V to 15V per battery, with the highest possible current limit, in about sixteen (16) hours from a fully discharged (100% DOD) condition at 25°C**.

If the DOD is less than 100%, the time required to complete the charge will be correspondingly less. For example, if the batteries were only 50% discharged, they may be charged in 8 to 10 hours using a CV of 15V per battery, with a **minimum** current limit of $0.33C_{10}$[4]. We recommend a **minimum** current limit in

[4] The "C_{10}" rate is the charge or discharge current in ampere–hours that is numerically equal to the rated capacity of a cell in ampere–hours. The Genesis® 26Ah battery would have a C_{10} rate of 26A; the $0.33C_{10}$ rate would be 8.67A

the $1C_{10}$ to $2C_{10}$ range to achieve a full charge in 16 hours from a 100% DOD condition when using a single level CV charge.

This high charge voltage must not be applied to the battery any longer than is necessary to complete the charge. This may be achieved by using a simple timer to either shut off the charger or reduce the charge voltage to about 13.65V per battery, at 25°C, after the charging process is complete.

(III) CONSTANT CURRENT (CC) CHARGING

An alternative charging scheme is to use a constant current (CC) to accomplish the recharge. While this method typically completes the charging process in a shorter time period, greater care must be taken to control the charging. Unlike the CV method where the battery itself regulates the charge current at any point in the charge cycle, the CC method continues to inject a set current regardless of the battery's state of charge. That is why one needs to exercise greater care when implementing a CC charge regime. In addition, the maximum charge current in a CC scheme must not exceed $0.2C_{10}$ amperes. This is in sharp contrast to a CV charger where one can use as high a current limit as one can have because the battery self-regulates the charge current.

The CC charge termination may be triggered either by the elapsed time (timer) or by sensing the cell voltage. To use a timer to determine the point at which charging is complete, the user must have complete knowledge of the ampere–hours taken out of the battery in the previous discharge cycle, A_{dis}. Multiplying A_{dis} by about 1.05 to 1.10[5], one arrives at the number of ampere–hours that must be replaced to charge the battery, A_{cha}. Finally, one divides A_{cha} by the charge current to compute the time required to complete the recharge.

Clearly, this requires more sophisticated circuitry for successful implementation. A simpler approach is to monitor the battery voltage as it gets charged. This voltage hits a peak when 100% of previously discharged capacity, A_{dis} has been returned. However, it would be a mistake to terminate the charge at this point — the battery still needs an additional 5 % to 10% for a full recharge.

(IV) COMBINATION CV/CC CHARGING

In many instances, a combination of CC and CV charging is employed. This allows the designer to cut down the charge time significantly and not increase the chances of damaging the battery permanently. Typically, the charger starts out as a CC charger (sometimes referred to as the **bulk charge mode**), replacing a large portion of the discharged capacity relatively rapidly because the battery has a high charge acceptance efficiency when it is in a low state of charge.

The charger continues in the CC mode until the battery voltage reaches its peak. In most chargers, this peak is sensed when the battery voltage stops rising. This serves as a signal to trigger the charger to switch to a CV mode. The charger now needs to obey the Ah Rule and put in about 10% of previously discharged capacity.

[5] This accounts for the 5% to 10% overcharge factor discussed earlier

In the CV mode, the charger applies a constant 2.45 to 2.50 vpc (14.7V to 15V per battery), and the charge current drops gradually. While it is almost impossible to predict the end of charge current (EOCC) with reasonable accuracy, a good indicator of charge completion may be found in observing the magnitude of the charge current. If three successive hourly readings of the charge current are substantially the same, it may be inferred that the battery pack is fully charged. Typically, the EOCC will be in the $0.001C_{10}$ to $0.002C_{10}$ ampere range at 25°C.

(V) FAST CHARGE ALGORITHM

In-house testing of Genesis® batteries using a special IUI (CC/CV/CC) algorithm has yielded excellent cycle life, while dramatically reducing the charge time from sixteen (16) hours to only six (6) to eight (8) hours for batteries that have been 80% to 100% discharged.

To obtain maximum life from a sealed–lead battery, its charging scheme must be optimized. Based on the application, the charging parameters would vary.

While there are several effective methods to recharge a sealed–lead battery, a full recharge must put in about 5 to 10% more capacity (ampere–hours) than what was taken out. Thus, for every ampere–hour discharged, one must return between 1.05 and 1.10Ah. For example, if the Genesis® 38Ah battery is fully discharged, then the ampere–hours needed to fully charge the battery would be 39.9 to 41.8Ah.

In a cyclic application, undercharging is typically more likely than overcharging, and therefore the battery is likely to fail prematurely. This fact makes proper charging of a cyclic battery a critical issue. We have seen batteries in cyclic applications fail due to undercharge in less than thirty (30) cycles. This is a disastrous result, considering that one can expect at least 500 cycles to 80% depth of discharge (DOD) from a properly charged Genesis® battery. The importance of adequate charging in a cyclic environment cannot be overemphasized.

It should be noted that in all the steps outlined below, it is preferable to have a temperature compensated charger, and that the coefficient of temperature compensation should be about ±18mV/battery/°C variation from 25°C. The charge voltage must be reduced for ambient temperatures in excess of 25°C and increased for temperatures lower than 25°C.

Figure 1 illustrates one IUI fast charge profile. Region A is a constant current mode, and continues until the battery terminal voltage reaches between 14.7V and 15.0V (Figure 1 uses a 14.7V peak). The time to reach this peak, T1, is noted and becomes the starting point for triggering the subsequent trip points on the charge cycle.

Region B commences as soon as the voltage peaks at 14.7V, at which point the charger switches to a constant voltage (CV) mode at 14.7V, and it continues in this mode until time (T1+ 1.5T1), or 2.5T1 hours. As an example, if time T1 in Region A is 1 hour, then the corresponding time for Region B is 2.5 hours.

At the end of 2.5T1 hours, the charger switches to a CC mode (Region C in Figure 1), with the current limited to $0.05C_{10}$. In addition to the limitation on the charge current, two other constraints must be designed into the charger. First, the battery voltage must not be allowed to exceed 15.6V, and second, the CC charge must be terminated after no more than one (1) hour. The length of time that the battery sees this CC charge is ideally 0.5T1, but no more than 1 hour. **In other words, (T3 – T2) = 0.5T1 ≤ 1**.

In practice, the battery voltage in Region C will rise to the 15.6V ceiling in less than one hour; however, **CHARGING MUST CONTINUE IN THE CV MODE AT 15.6V PER BATTERY**. At the end of time T3 hours from the commencement of charging, the charger is shut off or switched to float.

In some instances, the charger designer may desire a float voltage setting in order to provide an extended (over the weekend, for example) slow charge. If this is the case, there should be a one (1) hour rest after the CC mode before the charger switches into the float mode. This rest period is depicted as Region D in the charge profile. We recommend that the temperature compensated float charge (Region E) be set at 13.62 vpc at 25°C.

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While this is clearly a more complex charger design, having a charger that accommodates Region E is very important in applications where the battery is frequently undercharged, such as hybrid electric vehicles (HEV). In these cases, Region D serves to provide a slow, long overcharge that neutralizes the negative effects of any prior undercharge.

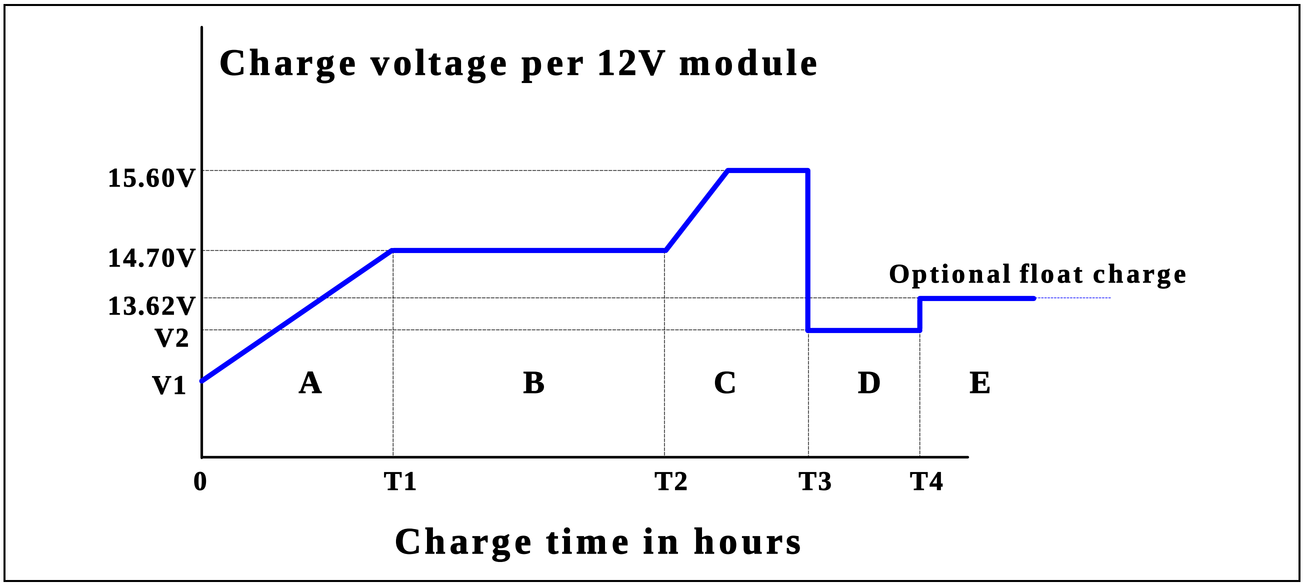

Figure 1 : Graphical representation of fast charge algorithm (not to scale)

The various time relationships shown in Figure 1 are summarized below:

T1 = time taken for battery terminal voltage to reach 14.7V (Region A)

T2 = (T1 + 1.5T1) = 2.5T1 (Region B)

(T3 – T2) = 0.5T1 ≤ 1 hour (Region C)

(T4 – T3) = 1 hour (Region D)

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V1 is the battery OCV at the commencement of the charge cycle while V2 is the battery terminal voltage as it approaches a full charge.

Using the minimum current limits of $0.4C_{10}$, where C_{10} is defined as the rated capacity of the battery expressed in amperes[6], and a charge voltage of 14.7V per 12V module (2.45 vpc), chargers must have the following **MINIMUM** power ratings in order to successfully utilize the algorithm given.

IT IS VERY IMPORTANT TO NOTE HERE THAT THESE MINIMUM POWER NUMBERS ARE THE CHARGER OUTPUT RATINGS AFTER ACCOUNTING FOR THE OVERALL EFFICIENCY OF THE CHARGER

Battery	Min. charger output rating
Genesis® 12V, 13Ah battery	**80W per module**
Genesis® 12V, 16Ah battery	**95W per module**
Genesis® 12V, 26Ah battery	**155W per module**
Genesis® 12V, 42Ah battery	**225W per module**
Genesis® 12V, 70Ah battery	**415W per module**

Consider, for example, an application that uses twenty five 12V, 26Ah batteries in series to get a 300V, 26Ah battery. If the charger has to recharge the batteries from a 80% to 100% DOD in six hours using the algorithm shown, the

[6] Thus for a 26Ah battery C_{10} = 26A and $0.4C_{10}$ would be 10.4A.

table indicates that its **MINIMUM OUTPUT** power rating must be 3.875kW (25 modules X 155W per module).

One final note before we conclude our discussion on charging. It is always good practice to prevent seriously overcharging the batteries in the event of a charger malfunction. This could happen, for example, if the charger failed to shut off after the charge portion defined by region B was completed (see Fig. 1) and continued to drive energy into the batteries at 15.6V per battery.

As a safety feature, we recommend designing in an ampere–hour counter that is capable of turning off the charger as soon as a cumulative threshold ampere–hour value is exceeded. If the charger fails, it will continue to feed energy into the batteries, and it is suggested that when **200% OF ITS RATED CAPACITY (52Ah FOR A BATTERY RATED AT 26Ah FOR OUR EXAMPLE OF A 300V BATTERY PACK) HAVE BEEN REPLACED, THE CHARGER MUST BE SHUT OFF. IN ADDITION, CHARGING MUST DISCONTINUE AS SOON AS THE BATTERY CASE TEMPERATURE REACHES 55°C (131°F)**.

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Additional comments on fast charging

The IUI algorithm described above is necessary when the inrush current (or current limit) is between $0.4C_{10}$ and $1C_{10}$ amperes. If, however, the current limit is greater than $1C_{10}$, the one-hour charge defined by Region B in Figure 1 can be eliminated.

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Taken together, the preceding paragraph illustrates an extremely important fact about Genesis® batteries in highly cyclic conditions such as electric vehicles — **IF THE CHARGER INRUSH CURRENT IS LOWER THAN 0.40C10, ONE SHOULD NOT EXPECT TO FULLY CHARGE THESE BATTERIES FROM A DEEPLY (80% TO 100%) DISCHARGED CONDITION IN ONLY SIX (6) TO EIGHT (8) HOURS. IN OTHER WORDS, 0.4C10 IS THE MINIMUM INRUSH CURRENT THAT IS REQUIRED FOR THE IUI ALGORITHM TO BE EFFECTIVE.**

The fast charge algorithm was developed in response to battery usage patterns dictated by ***(i) using the vehicle in two shifts per day in fleet operations*** and ***(ii) EV America guidelines that require batteries be fully charged in less than 12 hours using an input AC supply of 208V, 40A maximum***. Finally, the IUI algorithm has been extensively tested in the field with satisfactory results. Based on user experience as well as in-house testing, we are continually refining the basic algorithm.

Mathematically, T2 = *f*(T1), and once this relationship is defined, we have what we may rightfully term a ***universal charge algorithm (UCA)***. The time to get fully charged becomes directly linked to the DOD on the previous cycle, hence the term "universal."

While preliminary test results have indicated that the relationship between T1 and T2, as described in Figure 1 (T2 = 1.5T1), is acceptable we at Hawker Energy Products Inc. are currently actively working towards further defining the relationship between T1 and T2 as well as on fine tuning the algorithm not only in terms voltages, currents and times for the different regions but also in including various safety-oriented features.

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Hybrid electric vehicle (HEV)

The superior high rate discharge capabilities of Genesis® batteries make them a popular choice for a HEV that depends on the battery pack for high bursts of power to provide rapid acceleration. Ragone plots for the 13Ah, 16Ah, 26Ah, 38Ah and 70Ah batteries, showing the relationship between power and energy densities, are given below.

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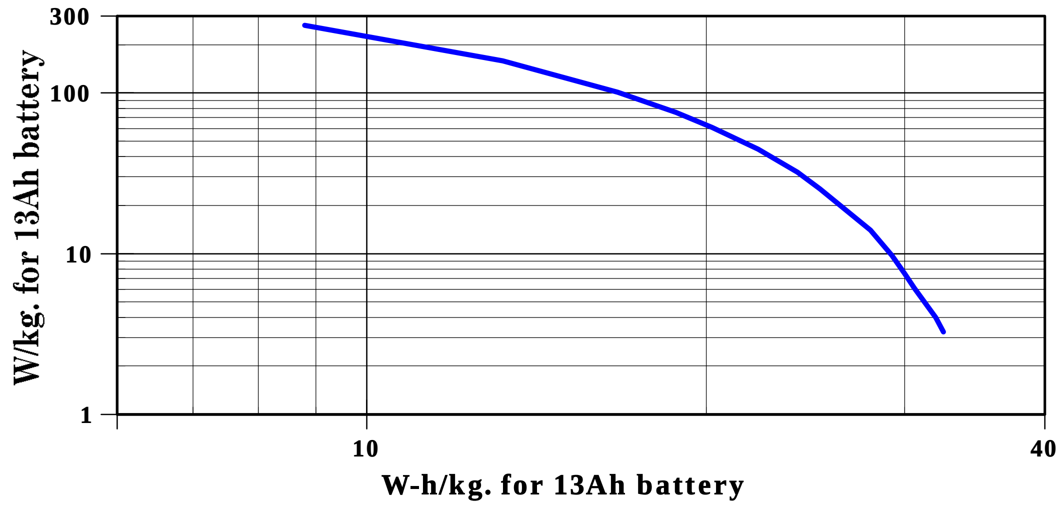
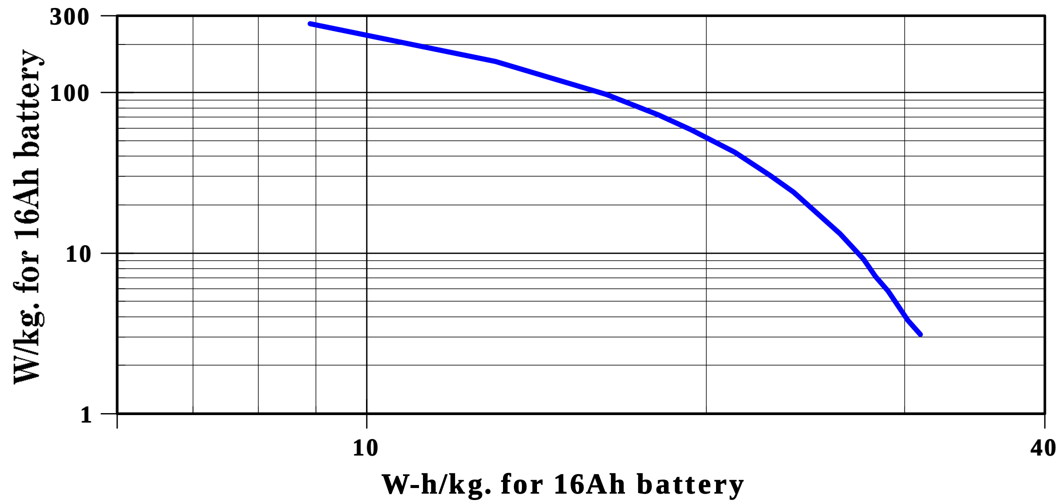
13Ah Genesis® Ragone plot



16Ah Genesis® Ragone plot



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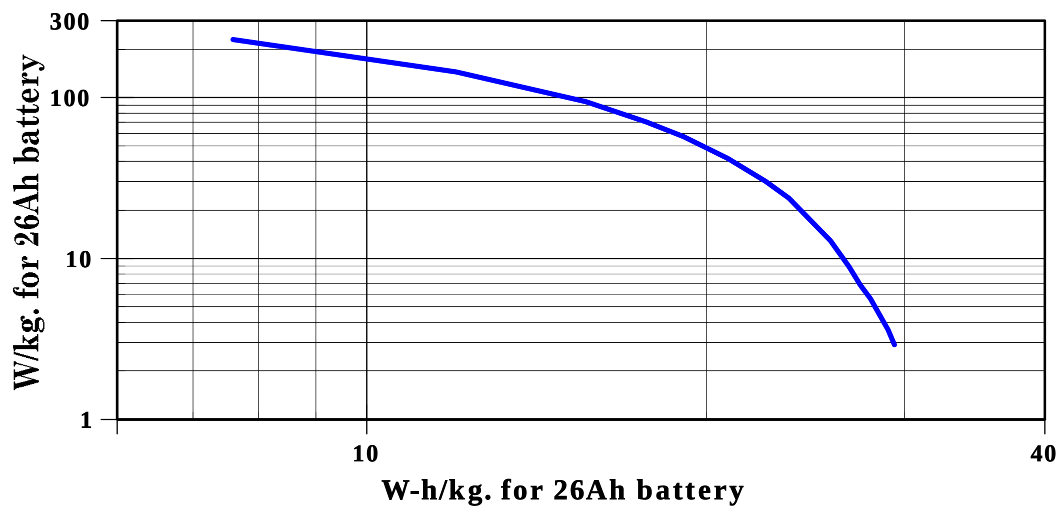
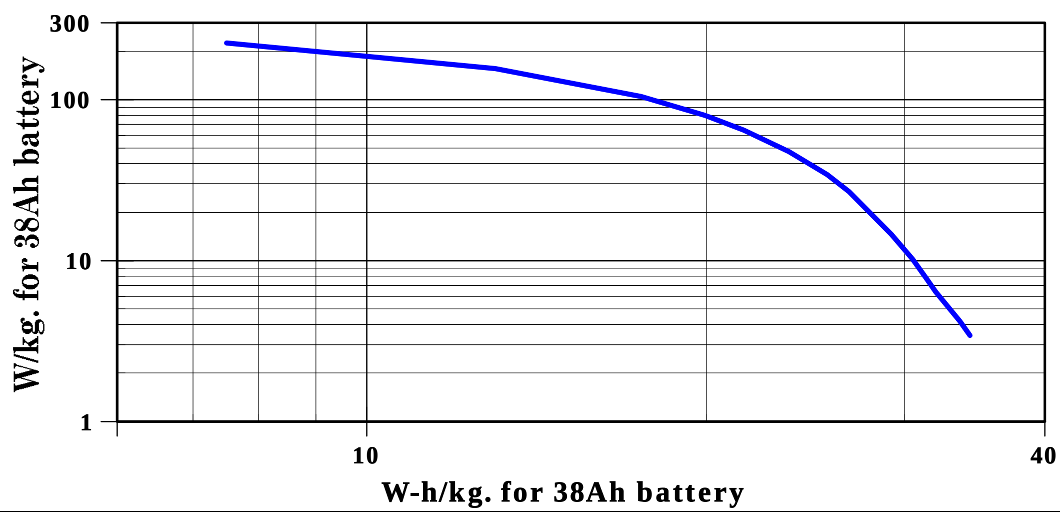
26Ah Genesis® Ragone plot



42Ah Genesis® Ragone plot



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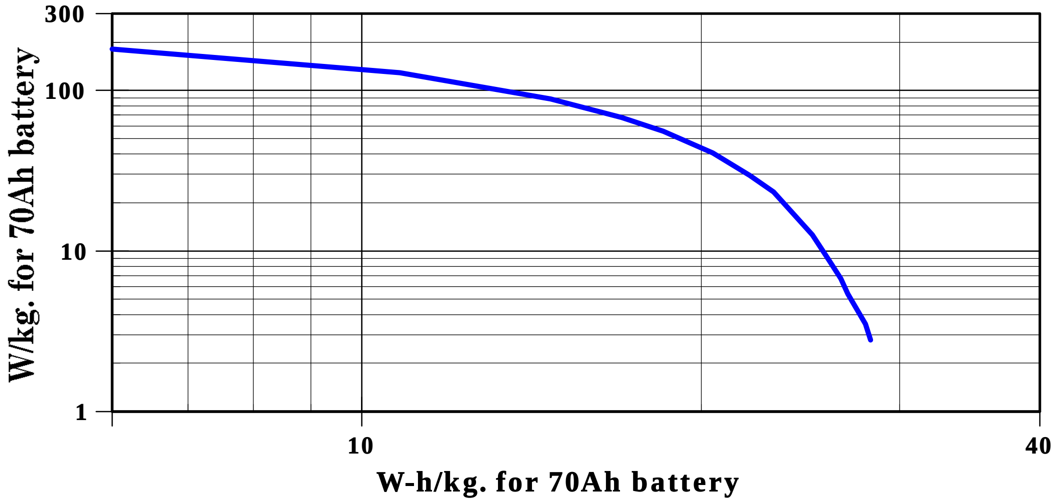
70Ah Genesis® Ragone plot (preliminary only)



Many HEV designs typically cycle the batteries between 20% and 80% states of charge. This type of "short cycling" (equivalent to a systematic undercharge) leads to premature loss of capacity. This is due to the fact that it is critically important that batteries be fully charged, at least periodically. In most HEV designs, since the batteries are never fully charged, the inevitable result is early failure.

To avoid this situation, we strongly recommend the use of an off-board charger that would be able to periodically recharge the batteries fully. Simply stated, if the battery is not adequately charged, cycle life expectancy will be compromised.

An off-board charger for a HEV does not require a great deal of sophistication, provided that at least sixteen (16) to twenty four (24) hours are available for the extended charge that would eliminate the ill effects of short cycling. A constant voltage (CV) charge at 14.7V to 15.0V per battery, with as high an inrush as possible but **not less than 0.4C_{10}**, should be adequate. The battery should be placed on charge, for example once every week, for 16 to 24 hours on this CV charger. **However, if at least 16 hours are not available to accommodate an extended charge, the HEV user must fall back on the IUI algorithm that will complete the charge in six hours**.

After 16 to 24 hours on charge, the charger should be shut off. A better option is to automatically switch to a float voltage (13.62V at 25°C per battery) at the end of the 16 to 24 hour charge. Either option is most strongly recommended for HEVs that are designed to have their batteries oscillate between varying states of discharge.

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Thermal management of EV battery systems

As explained earlier, owing to the tight packing of individual battery modules in an EV installation, the twin questions of heat generation and heat dissipation may be overlooked. Good thermal management of the battery system is critical to the system's long term performance and reliability.

Other factors making EV battery thermal management an issue that must be considered during the EV design phase includes one or more of the following:

- *Extended periods of overcharge at $C_{10}/10$ amperes or higher*
- *Fast charging*
- *High discharge current*
- *High or low ambient temperatures*

While liquid or gaseous cooling media can be circulated within the battery compartment, there are several obvious disadvantages, such as necessary plumbing to convey the coolant and the additional weight of these items that must be carried by the EV. Moreover, space constraints are a severe handicap when designing such a cooling system.

(I) PHASE CHANGE MATERIAL (PCM)

An alternative method of thermally managing the batteries is via the use of *phase change materials* or PCM. These materials absorb and store thermal energy for later release. This is accomplished through a change in the material's physical state — for example, from solid to liquid. In contrast to liquid or gaseous cooling, PCM offers the following advantages:

- *A high latent heat of fusion and material density, allowing energy storage packs to be compact*

- *Once the phase change temperature is reached, heat is absorbed isothermally, maintaining a constant temperature*

- *The process is reversible — on cooling, the absorbed thermal energy is released isothermally, helping to maintain the battery at an elevated temperature, a significant consideration for low ambient temperature operation*

- *Peripheral equipment such as pumps, plumbing and heat exchangers are not needed, nor are there any moving parts that require maintenance*

Although PCM offers some advantages for battery thermal management, it is up to the user to determine if the benefits of such a system outweigh the additional cost to implement it.

Second, successful implementation of battery thermal management using PCM requires reconversion from one phase to another. Thus, adequate temperature swings are needed, both in magnitude as well as duration, in order to insure that reconversion does in fact occur.

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Opportunistic charging and extended time charging

In most EV applications, it is highly unlikely that the battery will get sufficient time to be fully charged every time it is used. As indicated earlier, undercharging a battery rapidly leads to capacity loss, and unless the issue of repeated undercharge is adequately addressed, the results can be catastrophic. There are two solutions to this potential problem — ***(i) opportunistic charging*** and ***(ii) extended time charging***.

(I) OPPORTUNISTIC CHARGING

As the name implies, this term applies to those systems that allow brief, but incomplete, charges for the batteries. Typically, this would include regenerative braking, where short bursts of energy are returned to the battery every time the vehicle is either braked or the foot taken off the accelerator. Another situation would be where the operator is able to plug in the battery charger for a short time before driving away again.

While neither of these situations is enough to complete a recharge, they are useful in returning vital ampere-hours to the battery. Moreover, every time the battery is opportunistically charged, the time required to complete the full charge is correspondingly reduced.

The pure lead-tin technology of Genesis® batteries lends itself extremely well to opportunistic charging. The graph below shows the fast charge characteristics of

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these batteries when charged using a CV at 14.7V or 2.45 vpc, at various levels of inrush current. Table I shows the time taken for 100% of previously discharged capacity to be returned to the battery at the three levels of inrush magnitude.

Note that charging must not be terminated when 100% of discharged capacity is returned; an additional 5% to 10% overcharge must be replaced to complete the full recharge.

Table I

Capacity returned	Inrush	current	magnitude
	$0.8C_{10}$	**$1.6C_{10}$**	**$3.1C_{10}$**
60%	44 min.	20 min.	10 min.
80%	57 min.	28 min.	14 min.
100%	90 min.	50 min.	30 min.

This table indicates that when the Genesis® battery is charged at 14.7V with an inrush current of $0.8C_{10}$ the time taken to return 100% of discharged capacity is 90 minutes; if the inrush is double to $1.6C_{10}$ the time to return 100% of discharged capacity drops to 50 minutes.

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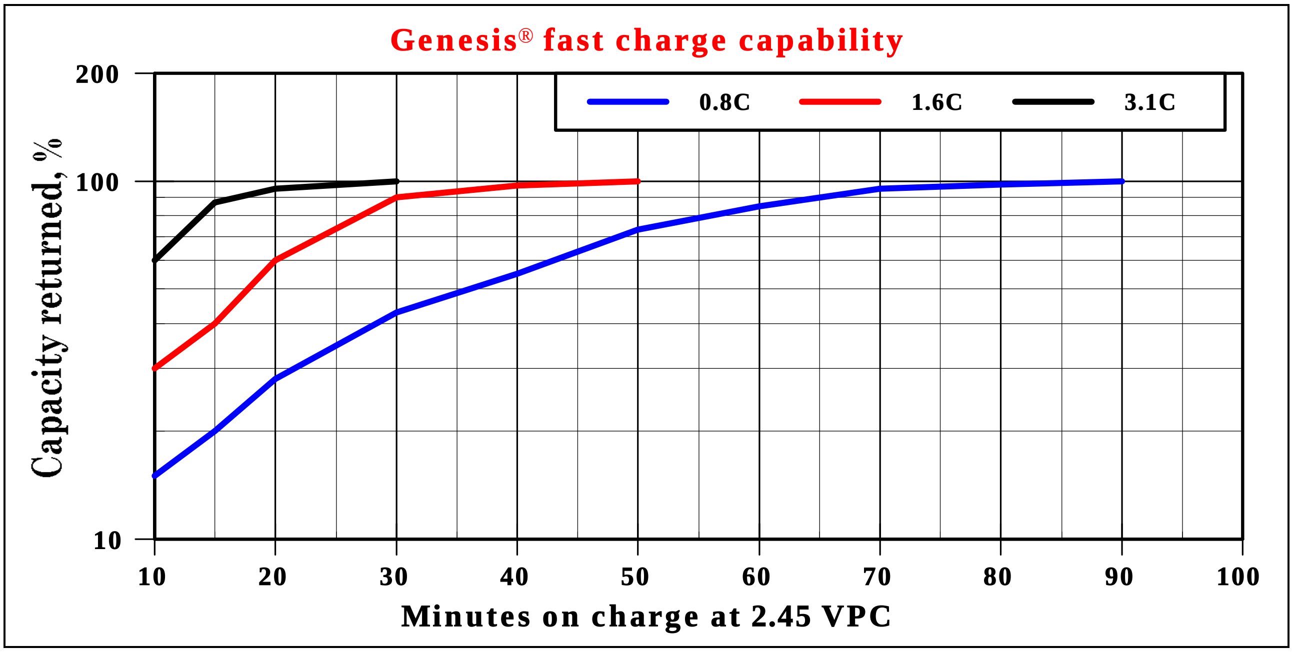

An important consideration in any fast charging scheme is the temperature rise experienced by the battery. **Hawker Energy Products Inc. recommends that charging be discontinued when the battery case temperature reaches 55°C**.

(II) EXTENDED TIME CHARGING

The rationale for this concept is to neutralize the ill effects of undercharging the battery pack may have been subjected to prior to the application of an extended time charge. The idea is to provide a slow charge over a longer time period, such as a weekend.

Referring back to Figure 1 for the fast charge profile, Region D, labeled as "**Optional float charge**" implements this concept. Should the charger have this feature, however, **it is extremely important to insure that the charger allows at least one hour rest**.

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Battery pack configuration

In order to meet system power requirements, it is frequently necessary to put several battery modules in a series-parallel configuration. Although the design of Genesis® product is very well suited for these types of configurations, it is prudent to take into account several considerations when designing a particular system.

(I) SERIES STRINGS

When series strings are used, statistics dictate that individual cells in the string will, at some point in their life cycle, have reduced capacity compared with the majority of the cells. If the battery is discharged to a specific string end of discharge voltage (EODV), the low capacity cells will be driven to voltages that are significantly lower than the overall string EODV.

Each time this occurs, low capacity cells will driven down further and further below the string EODV. Ultimately the low capacity cell can be driven to negative voltages (cell reversal). Thus, once this process of capacity imbalance begins, it is self perpetuating. It should be kept in mind that individual cells could begin their service life with capacity differences due to minor variations that are inherent in any manufacturing process.

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Ignoring for the moment capacity differences due to manufacturing variances, the most common cause for cell-to-cell imbalances is undercharging. Adequately charged cells tend to maintain consistent capacities from cell to cell. However, cells do not respond uniformly to undercharging; that response is determined by the charge efficiency of individual cells, which in turn is influenced heavily by factors such as temperature variations across a long string of batteries or due to slight differences in manufacturing.

If the charge is incomplete, this difference in charge efficiencies will lead to capacity variations from cell to cell. On the other hand, if charging is adequate, differences in charge efficiency are fully neutralized by overcharge, enabling all cells to be brought up to their full potential capacities.

Short battery strings[7] that are charged using constant voltage power sources tend to regulate the current so that all cells in the string receive the charge capacity they need. In long strings, however, if some cells reach a full state of charge earlier than others due to charge efficiency discrepancies then only those cells that are near or at a full state of charge will tend to regulate the current.

This will cause cells that are not charged to be deprived of current they need to attain full charge. Clearly, cyclic applications exacerbate this scenario due to repetitive charging, and this is an area that system designers must take into consideration when developing charging schemes for long series strings.

[7] While there is no accepted definition of a short string, a string comprised of 24 or more cells in series (48V and higher) may be considered to be a long string

One popular technique that is frequently used to reduce cell imbalance in long strings is called ***equalization***. As the name implies, the goal is to equalize the capacities of the individual cells that comprise the long string. An equalizing charge may consist of an extended charge at cyclic voltages (14.7 to 15.0V Genesis® products), low ($0.05C_{10}$) constant current charging for about 24 hours or short charge periods at elevated voltages, as illustrated by Region C in Figure 1.

All of these methods provide adequate overcharge, insuring all cells in the string reach their full potential capacities. While the frequency of these equalization charges depends on the specific application, for a cyclic application such as an EV, a weekly equalization is recommended. The key to a successful equalization schedule is to prevent cell-to-cell imbalances from progressing to a point where it corrupts the performance of the overall string.

Sizing the battery system such that the DOD of the string, such as with an EODV cutoff, is well controlled complements the positive impact of a well executed equalization scheme. The shallower the DOD the less likely it is that one or more cells in the string will be driven to damaging low voltages. Designing battery systems to prevent deep DODs will invariably extend battery life, provided of course that other critical areas such as charging are properly implemented.

(II) PARALLEL STRINGS

Parallel strings add a new twist to the issue of balancing cells in a single string. In addition to insuring that individual cells in a series string get fully charged, the system designer now has to be concerned about seeing to it that each string also gets adequately charged. In an ideal situation, each string would charge separately and the charge parameters would also be controlled separately. In most applications, however, this is impractical.

If the effective resistance to charging is different between strings then the charge distribution between strings will also be different, with one string potentially getting the lion's share of the charge current. Moreover, if the charge current magnitude is marginal then the string/s deprived of charge current will be degraded quickly as a result of inadequate current and/or insufficient total ampere-hours. **IN OTHER WORDS, LOW LEVEL CONSTANT CURRENT CHARGING MUST BE AVOIDED WHEN CHARGING PARALLEL STRINGS**.

An important design criterion when using parallel strings is to make sure that the resistance of the separate strings, including cables and connectors, is very similar. In extreme cases it may even necessitate the installation of extra cabling to equalize string resistances.

Multiple string systems also require the incorporation of blocking diodes that will prevent strings from discharging into each other. For example, a short circuit in one string can cause an adjacent string to discharge into it a very high rate.

If the available charge current is adequate (***$0.4C_{10}$ amperes per string or higher***), battery systems with multiple parallel should provide good service. In fact, parallel strings provide the benefit of system redundancy so that if one string fails, the other strings will support the load for at least a portion of the designed service time.

The real key to successfully using multiple strings lies in high charging currents, proper charge voltages and sufficient charge time — in other words, correct charge parameters are critical to obtaining adequate service life from a series-parallel battery system. If the charge current available is high enough, all strings will get enough charge current to even out significant capacity imbalances.

Imbalances during discharge of a parallel system are generally less severe because the string with a higher resistance will simply deliver less than its appropriate share of the total load current. As long as the strings are reasonably healthy, these differences in load sharing will be minimal. If a string does develop a problem, it will be reflected in a drop in its share of the load current and this could be used as a signal to check out the system and implement remedial action.

In conclusion, therefore, battery systems will provide good, reliable service life regardless of its specific configuration (short string/long string/series-parallel) as along as the charging parameters are correctly matched to the application.

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Concluding remarks

It should be evident to the reader that if proper care is taken regarding *(1) charging*, *(2) monitoring* and *(3) installing Genesis® batteries in an EV application*, these batteries will deliver satisfactory performance for today's electric vehicles.

The fact that many EV designers and manufacturers are giving serious consideration to Genesis® bears ample testimony to the true capabilities of this remarkable battery.

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