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Advancing electric-vehicle development with pure-lead–tin battery technology

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Abstract

Electric-vehicle (EV) development continues to make solid progress towards extending vehicle range, reliability and ease of use, aided significantly by technological advances in vehicle systems. There is, however, a widespread misconception that current battery technologies are not capable of meeting even the minimum user requirements that would launch EVs into daily use. Existing pure-lead–tin technology is moving EVs out of research laboratories and onto the streets, in daily side-by-side operation with vehicles powered by conventional gasoline and alternative fuels. This commercially available battery technology can provide traffic-compatible performance in a reliable and affordable manner, and can be used for either pure EVs or hybrid electric vehicles (HEVs). Independent results obtained when applying lead–tin batteries in highly abusive conditions, both electrically and environmentally, are presented. The test fleet of EVs is owned and operated by Arizona Public Service (APS), an electric utility in Phoenix, AZ, USA. System, charger and battery development will be described. This gives a single charge range of up to 184 km at a constant speed of 72 km h^{-1}, and with suitable opportunity charging, a 320 km range in a normal 8 h working day. © 1997 Published by Elsevier Science S.A.

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1. Introduction

Electric vehicles (EVs) may be particularly well suited to fleet applications and commuter/town cars, but for EVs to be practical in fleets, it is necessary to have technical feasibility and commercial viability that meets the user's needs and affordability. The EV must first be safe, reliable and cost effective, with consistency of the battery system being the key to determining the usefulness as a fleet vehicle. The EV battery system should be a totally functional, tamper-proof, energy-storage system that is comprised of a battery pack, thermal management and electronic control.

Since performance characteristics of the battery pack affect directly the vehicle's performance, the battery characteristics of prime importance to be considered for the EV should include [1]:

1. peak specific power (W kg^{-1}) to provide adequate vehicle acceleration and hill climbing;
2. specific energy (Wh kg^{-1}) to provide an acceptable driving range;
3. battery cost and life which determines replacement/recycling period and total life-cycle cost;
4. high tolerance to overcharge, undercharge and over-discharge;
5. high tolerance to constant and rapid deep discharges and to regenerative braking current acceptance, even when the battery is at a high state-of-charge (SOC), i.e., 80% or above;
6. a low rate of self-discharge to accommodate times when the EV is parked off-charge;
7. the restoration of cell balance must be easy to achieve during each full recharge;
8. internal resistance of the battery should experience minimal change with depth-of-discharge (DOD);
9. the battery should have minimal degradation of specific power during battery life;
10. a low internal resistance to allow for rapid deep discharge and safe, repeated, fast charging;
11. operation in climate extremes, maintaining high level of specific energy and peak specific power levels.

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12. battery design must be inherently safe and meet required international and federal standards, and
13. zero maintenance while in service.

An EV battery in fleet service should retain the above characteristics with minimal degradation right up to end-of-useful life. The end-of-life is defined in USABC Electric Vehicle Battery Test Procedures Manual Rev 2. [2] as:

1. when the net delivered capacity of a battery is less than 80% of its rated capacity when measured on the DST (reference performance test), or
2. when the peak power capability (determined using the Peak Power Test) is less than 80% of the rated power at 80% DOD.

Few battery types retain all the above characteristics at minimum necessary performance levels throughout useful battery life to allow application in EV fleets. Furthermore, while there is much laboratory data and results published at cell and module levels for individual attributes for many battery technologies, including those identified as 'advanced' battery technologies, there is limited performance data showing end-of-useful battery life for sealed recombinant EV battery packs operating in the harsh environment of 'real world' EV driving.

2. Pure-lead–tin battery technology

The Genesis® pure-lead battery uses valve-regulated lead/acid (VRLA) technology in a special form developed for high cycle life and high specific power [3].

The batteries (Fig. 1) are constructed with grids manufactured from pure-lead–tin strip as the current-collector with specially formulated positive and negative active-materials. The plates are separated with an absorptive glass mat (AGM) material designed to avoid the effects of acid stratification. The pure-lead–tin grid combines good cycling behaviour with high corrosion resistance and thus enables the battery to be constructed with very thin plates in order to achieve high power density. This, in turn, improves charge acceptance for rapid recharge and for regenerative braking. High integrity seals and a Bunsen valve venting system are used to ensure reliable operation.

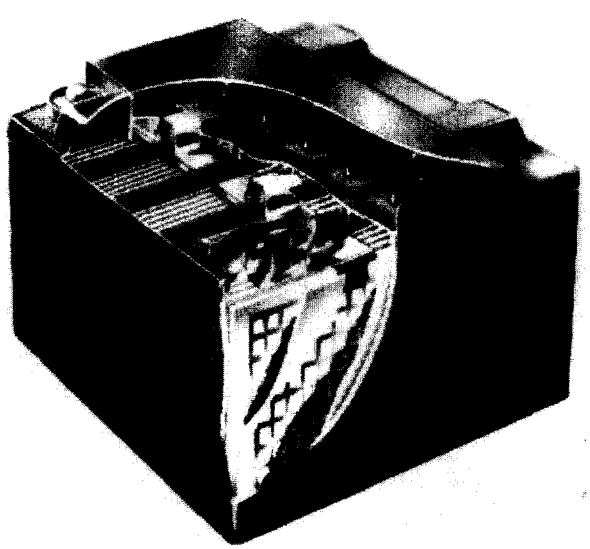

Fig. 1. Genesis® battery cutaway view.

3. Genesis® batteries in an electric vehicle fleet

Hawker Energy Products is working with Arizona Public Service (APS) on a Charger Test Project to evaluate the affect of various charger types and charge algorithms on battery life [4]. APS is a site operator for the US Department of Energy (DOE) EV Test Program.

The success of the Charger Test Project emphasizes the importance of having a fully operational battery charger infrastructure in place that can support both overnight charging (to keep the battery healthy) and daily opportunity (fast) charging, to assure efficient use and extend the driving range of EVs in fleets. From a battery perspective, the Charger Test Project also serves the purpose of field testing the battery performance characteristics mentioned above, in 'real world' EV operating environments, to the end-of-useful battery life.

During the period from April to December 1995, a Hawker Genesis® 24 kWh battery pack installed in APS Vehicle No. 07 137, exceeded 22 400 km in city/freeway driving, without a significant loss in battery performance. During this period, No. 07 137 was driven to 80 and 100% DOD on daily service routes in the Phoenix area, and remained in service through the hot summer months, with daily high ambient temperatures above 38 °C and low ambient temperatures above 29 °C. The robustness of the Genesis® battery to tolerate hot weather operation was confirmed, since the battery did not have the benefit of thermal management and was repeatedly subjected to fast charging that included multiple daily charging.

In November 1995, No. 07 137 achieved a driving range of 301 km in a single day (8 h continuous service). To achieve the 301 km driving range, the battery pack was opportunity charged three times during the 8 h workshift; each charge period lasted between 20 and 25 min to return 80 to 90% of capacity to the battery pack. Previous fast charging of the Genesis® battery at the 6*C* rate (in a laboratory environment) showed that 80% capacity was returned in 8 min.

The Genesis® battery being field-tested in the APS Charger Test Project is a Hawker standard production battery type G12V190W15SP. Field testing of an improved lower weight version of this Genesis® battery began early in 1996. Table 1 lists specifications for Genesis® Battery Model G12V190W15SP.

The EV test fleet used in the APS Charger Test Program is comprised of eight APS EVs each equipped with Hawker Genesis® pure-lead–tin technology batteries. This

Table 1
Specifications for GENESIS® battery model G12V190W15SP

Specific energy@$C_{3/3}$	33 W kg^{-1}
Specific power@30 s	250 W kg^{-1}
Cycle life@100% DOD	400 cycles
80% DOD	500 cycles
Cost	$150/kWh
Luternal resistance@100% SOC	4.5 MΩ
Dimensions (mm)	166(L)×198(W)×171(H)
Weight	14.7 kg

paper will address the range results from two of the eight test EVs, No. 07 137 and No. 07 139. Both vehicles are GM Chevrolet S-10 Pickup trucks converted to electric drive by US Electricar (USE S-10). Each vehicle has a built-in 1.5 kW conductive charger integral with a GM–Hughes power control unit (PCU). The 24 kWh Genesis® batteries in these two APS EVs are wired in series-parallel (two parallel strings of twenty-six 12 V, 38 Ah modules) to make a nominal 312 V, 76 Ah battery pack. The USE S-10 and its specifications is shown in Fig. 2. Ref. [5].

3.1. Range testing

At about 3200 km or less, most of the USE S-10 EVs (approximately 175 vehicles) in fleet service with utilities and state agencies were experiencing significant reduction in driving range.

The drivers of S-10 EVs in the APS fleet experienced similar reductions in vehicle range. The immediate 'cause' (not effect) of the reduction in driving range was attributed to the battery pack—not the charger, not the inverter, not the motor, and not even the driver. After a quantitative analysis by Hawker engineers on the above components in No. 07 137, it became clear that the battery was not the cause of reduction in driving range, but rather the low-power, 1.5 kW integral charger and primary charge algorithm. Whenever the battery pack voltage was lower that the a.c. input peak voltage, the integral charger would initially trickle charge before initializing a full power recharge, which would then require between 18 to 30 h to recharge the battery pack from 80 to 100% DOD. Thus, since daily work schedules in utility fleets are typically 8 h or more, there was insufficient time to recharge fully during the week. Additionally, the Genesis® battery was operating in a non-ventilated battery compartment.

Fig. 2. US Electricar S-10: (i) motor type: a.c. induction, 3-phase, 4-pole matched to the inverter; (ii) power control unit: 50 kW, 3-phase, d.c.–a.c. inverter; (iii) accessory power: 12 V d.c., 100 A supply; (iv) built-in charger: 110 V a.c., 15 A, single-phase, 110/220 V a.c.

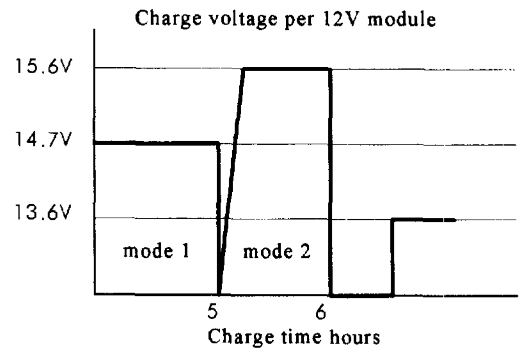

Fig. 3. Six-hour charge algorithm. Mode 1: constant voltage, 2.45 V per cell (382 V), current limit at $C/2.5$ range, time 5 h. Mode 2: constant current at $C/20$ rate, time 1 h at 2.60 V per cell (406 V), temperature compensation ±3 mV per cell per °C from 25 °C.

It was evident that the Genesis® batteries in No. 07 137 and in other USE S-10 electric vehicles in fleet use were being undercharged due to the low-power integral charger, coupled with an inadequate charge algorithm, and as a result the batteries were liable to fail prematurely. For practical EV fleet operations, recharge times should not exceed 8 h. A Hawker recommended, 6 h charge algorithm with temperature compensation is shown in Fig. 3.

As a result of the undercharging problem, a Charger Test Project was established by APS to evaluate the affects of different chargers and charge algorithms on battery life and to validate EV range by 'on-road' range testing. The range testing determines the maximum range that the vehicle can achieve when driven at 72 km h^{-1} constant speed, and confirms the useable energy available from the battery pack.

To begin the range test, the batteries must be fully charged (100% SOC). The electric vehicle, when loaded with two 75 kg occupants or equivalent, must have a minimum driving range of 80 km at a constant speed of 72 km^{-1}. From a standing start, the EV is accelerated under its own power to a speed of 72 km h^{-1} and maintains this speed until an average lap speed of at least 69 km h^{-1} cannot be maintained. Final speed, time and odometer reading are recorded.

In April 1995, No. 07 137 was range tested at a constant speed of 72 km h^{-1} but delivered a range of only 59 km, which was 47% below its previous October 1994 range test at 72 km h^{-1}, and below the minimum driving range of 80 km at constant speed of 72 km h^{-1} required by EV America Program. In Table 2, the average driving range of 134.4 km for No. 07 137 includes the driving period up to April 1995 at 3504 km, and before discovery that the Genesis® battery pack was being undercharged from the

Table 2
EV range testing: constant speed 72 km^{-1} h with 24-kWh Genesis@battery in vehicle No. 07137

Month	Range (km)	Odometer
October 1994	113.1	new
April 1995	60.3	3.504
May 1995	153.3	4.221
July 1995	153.3	6.107
August 1995	166.1	10.470
November 1995	141.1	17.443
December 1995	154.6	21.699
Average	134.4	21.699

vehicle's low-power, integral 1.5 kW charger with an inadequate charge algorithm. In May, at 3840 km, the 1.5 kW integral charger was by-passed and APS added a GM–Hughes 6.6 kW inductive charge port to the vehicle [6]. Charging connectors were also added for fast charging with a Norvik 150 kW conductive charger. At the same time, a new charge algorithm developed by Hawker was modified and programmed into the GM–Hughes 6.6 kW inductive charger. The Norvik charger was also programmed with the new Hawker charge algorithm.

3.2. *Vehicle driving range restored*

Vehicle No. 07 137 was now ready to be fast charged with the Norvik 150 kW charger (Fig. 4), followed with an overnight equalization charge on the GM–Hughes inductive charger.

At 4221 km and after the five fast charges with the Norvik charger [7], No. 07 137 was range tested at a constant speed of 72 km h^{-1} and delivered a range of 153.3 km. Once again, the high tolerance of the Genesis® battery towards abusive conditions (in this case repeated undercharging) was confirmed and the battery's capacity recovered fully when adequate charging was applied. The daily usage of No. 07 137 in November is graphed in Fig. 5.

Once the problem of undercharging was corrected and adequate ventilation provided to the battery compartment,

Fig. 4. Norvik 150 kW charging [7].

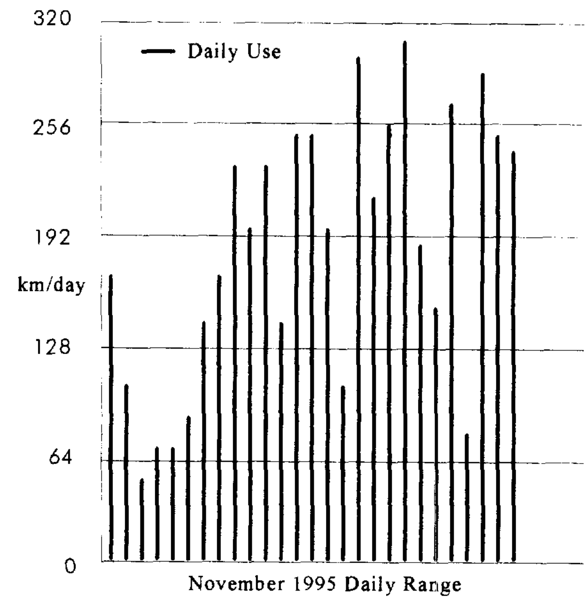

Fig. 5. Vehicle No. 07 137 daily driving range during November 1995.

No. 07 137 was returned to service. From May to the end of December 1995, No. 07 137 was driven for 19 200 km and received 365 fast charges that included 61 multiple fast charges and over 100 overnight charges. The Genesis® battery pack maintained its high energy and power levels throughout.

4. Inductive charging with Genesis® batteries

Unlike Vehicle No. 07 137 which is fast charged from a Norvik 150 kW conductive charger, No. 07 139 is charged only with the GM–Hughes 6.6 kW inductive charger. No. 07 139 came equipped with the GM–Hughes 1.5 kW integral charger, but was modified by APS for inductive charging. Some consider inductive charging as the safest technology available, since the system does not use metal-to-metal connections and can be used in all weather conditions. The 24 kWh Genesis® battery pack in No. 07 139 had also experienced undercharging for the first 1280 km because the battery had been charged with a similarly installed 1.5 kW integral charger.

Table 3
Modified charge algorithm for GM-Hughes inductive charger using 24-kWh genesis@battery

Mode 1:	Constant voltage@2.45 V per cell
	Current limit@20 A
	Charge time of 8 h
Mode 2:	Constant current@0.05C
	+ 750 mA to 2.55 V per cell
	Charge time of 1.5 h

Table 4
Vehicle No. 07139 range testing: constant speed 72 km^{-1} h with 24-kWh Genesis@battery

Month	Range (km)	Odometer
October 1994	113.1	new
May 1995	162.9	1.458
July 1995	172.5	2.750
August 1995	166.1	4.219
December 1995	127.1	5.235
Average	148.8	

Since No. 07 139 would be inductively charged only, a new charge algorithm was developed by Hawker for the GM–Hughes inductive charger. This regime was also modified to match the lower charge voltage ceiling in the GM–Hughes charger. In addition, the GM–Hughes 6.6 kW inductive charger can deliver only 60% of the power required to recharge the Genesis® battery pack in under 8 h from 80 to 90% DOD; consequently, the time 'on-charge' (in the new algorithm) was increased to 9.5 h. The modified charge algorithm is described in Table 3. As of the end of December 1995, the Hughes inductive charger with the new charge algorithm has maintained the health of the battery in a safe and reliable way.

Although No. 07 139 has been driven less miles than No. 07 137, its Genesis® battery delivered an average driving range of 148.8 km when road tested at a constant speed of 72 km h^{-1}. The results of range testing No. 07 139 are given in Table 4.

5. Conclusions

1. From 1995 'on-road' EV experience, it has been found that acute undercharging is far more likely to occur in an EV than chronic overcharging. Therefore, it is critical to have adequate charging at all times and to use a complimentary timed and implemented algorithm matched to the charge power available. Failure to return a full recharge regularly, together with time to properly balance all cells individually, will only lead to premature and costly battery failure and/or loss of vehicle range and usage.

2. EV chargers should be programmable on-site, using a hand held PC.

3. Adequate thermal management of the battery pack is essential. It will enhance fast charging by limiting the increase in battery pack temperature, and thus will allow more multiple fast charges in a work day and will extend the driving range to above 192 km per day.

4. Careful attention should be paid to battery-terminal/intercell connections. Unwanted voltage drops and heating should be avoided by sizing connections to carry expected EV power requirements. Bolted connections should have lock washers and tightening torque controlled to manufacturer's specification. A single loose intercell connector is a sure path to destruction of the battery pack.

5. The 24 kWh Genesis® battery pack, wired in series-parallel, can be repeatedly fast charged and deep discharged without apparent loss in performance. End-of-useful battery life has yet to be determined.

6. Parallel strings provide a redundant mode and allow the vehicle to return to the fleet depot under its own power. This avoids having to tow the vehicle, as happens with a discrete series-only string failure.

7. Always keep the battery appropriately 'on-charge' when the EV is not in operation.

8. An EV powered by pure-lead–tin technology can meet the needs of a high percentage of commuters in urban areas like Los Angeles, where clean air attainment is critical [8]. Typical commuting ranges are shown in Fig. 6.

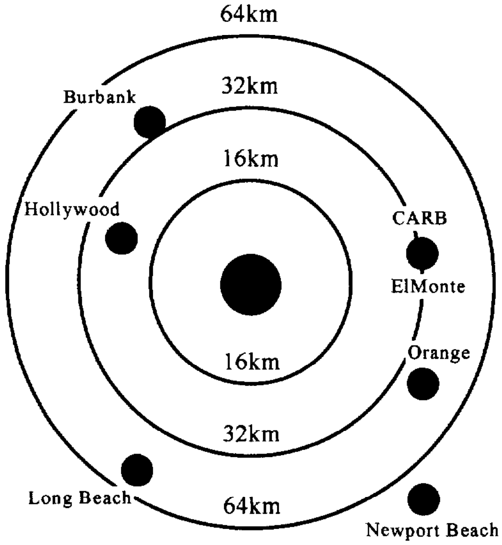

Fig. 6. Los Angeles basin where 70% of the population commute for a daily round trip of less than 64 km [8].

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