Journal of Power Sources, 42 (1993) 237–246

Development of automotive battery systems capable of surviving modern underhood environments

John R. Pierson* and Richard T. Johnson

Johnson Controls Battery Group, Inc., 5757 North Green Bay Avenue, P.O. Box 591, Milwaukee, WI 53201 (USA)

Abstract

The starting, lighting, and ignition (SLI) battery in today's automobile typically finds itself in an engine compartment that is jammed with mechanical, electrical, and electronic devices. The spacing of these devices precludes air movement and, thus, heat transfer out of the compartment. Furthermore, many of the devices, in addition to the internal combustion engine, actually generate heat. The resulting underhood environment is extremely hostile to thermally-sensitive components, especially the battery. All indications point to a continuation of this trend towards higher engine-compartment temperatures as future vehicles evolve. The impact of ambient temperature on battery life is clearly demonstrated in the failure-mode analysis conducted by the Battery Council International in 1990. This study, when combined with additional failure-mode analyses, vehicle systems simulation, and elevated temperature life testing, provides insight into the potential for extension of life of batteries. Controlled fleet and field tests are used to document and quantify improvements in product design. Three approaches to battery life extension under adverse thermal conditions are assessed, namely: (i) battery design; (ii) thermal management, and (iii) alternative battery locations. The advantages and disadvantages of these approaches (both individually and in combination) for original equipment and aftermarket applications are explored.

Introduction

The underhood engine compartments of today's aerodynamic automobiles are densely packed with mechanical, electrical and electronic devices. Many of the devices, including the high-performance, transverse-mounted internal combustion engine, generate heat during operation. Transfer of heat out of the engine compartment is extremely limited because of constrained air movement due to the close-packed nature of the devices, combined with the down-sizing or elimination of grilles. The high temperatures that result present an extremely hostile environment for thermally-sensitive components, particularly the battery. This trend is likely to continue (Fig. 1). Unless appropriate countermeasures are developed in design, thermal protection and/or placement of the battery, product life will become unacceptably short at a time when vehicle and component reliability and warranty are being emphasized by vehicle manufacturers. The situation is obviously aggravated both in those geographic regions of the world where ambient temperatures are highest, and in drive cycles characterized by low speeds and short trips with extensive idle time.

---

*Author to whom correspondence should be addressed.

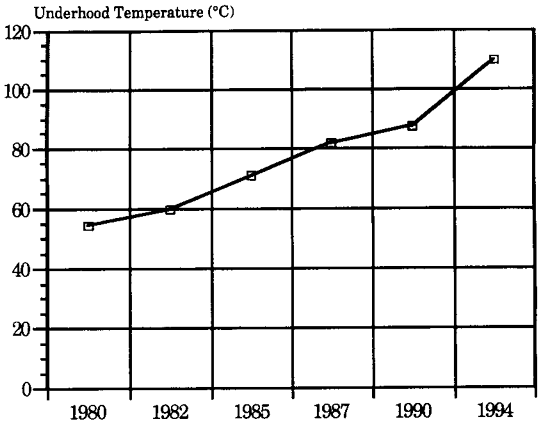


Fig. 1. Trends of underhood temperatures in passenger automobiles.

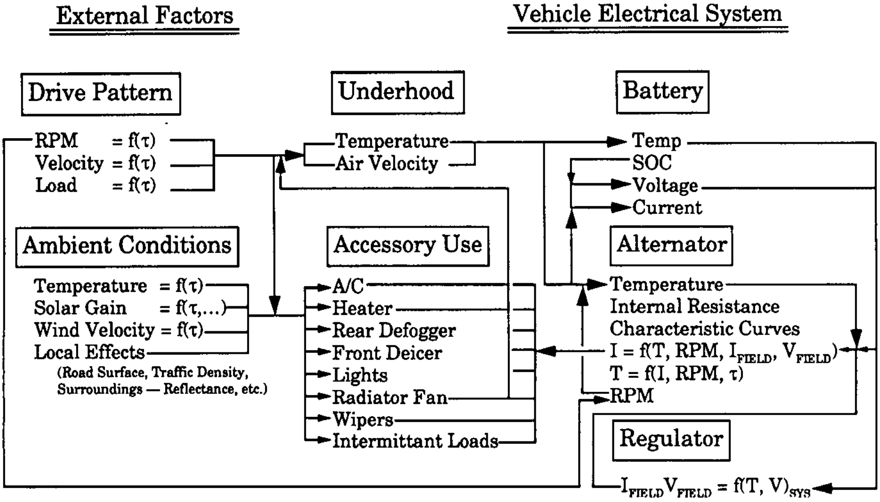


Fig. 2. System interdependencies.

The importance of a systems approach

Lead/acid batteries are predestined to fail based on the fundamental thermodynamics of the reactions occurring during their use. More importantly, from the view of thermally-activated reactions, the thermodynamics of specific failure or wearout mechanisms continue to drive those reactions during the much more prevalent periods of nonuse that are typical of automobile service. The primary controlling factors of battery life, exclusive of design, are temperature, depth-of-discharge and conditions of recharge. The dynamic response of a battery to the varied electrical and thermal parameters of its environment is the determinant of life in a vehicle. A simplified schematic of the various interactions that affect a battery in the vehicle electrical power system is shown in Fig. 2.

Battery design and material selection have always been the primary tools used to overcome the basic thermodynamics through control of, or adjustment to, the kinetics of the various wearout mechanisms. This approach has been very effective in improving life, while increasing performance per unit weight and volume, under the relatively constant operating environment that was experienced between the introduction of alternators in the early 1960s and the aerodynamic vehicle packaging and increasing electrical loads of the mid 1980s. Selective use of these tools allowed battery designers to maintain reasonable battery life into the 1990s. Unfortunately, however, given the drive of automobile designers towards improved aerodynamic styling, enhanced vehicle performance and 'cab-forward' or increased cabin volume design, at the expense of underbonnet space, the approach used in the past has been showing limitations. These limitations are expected based on the exponential dependencies of battery failure mechanism kinetics upon temperature, depth-of-discharge and charge voltage. Battery manufacturers are left with no other choice than to delve more deeply into battery/system interactions in order to understand them better and to generate solutions for these evolving application problems [1, 2].

Battery failure modes

The Technical Committee of the Battery Council International (BCI) has commissioned a series of studies to establish how long batteries live and what causes their ultimate failure. The data developed in the most recent study, i.e., 1990 [1], are cut multiple ways and include life as a function of climate, and life as a function of failure mode by climatic zone. The age of batteries removed from service ranged from an average of 52 months in the Northwest and Northeast (mean temperature 10 °C) to 31 months in the desert Southwest (mean temperature 24 °C) of the USA. Thermally-activated failure modes such as 'open circuits', 'short circuits', 'plate/grid related' and 'worn out/abused' all occurred significantly sooner in high-temperature locations than in more moderate climates. Similar independent field reliability (junk-bin) studies conducted by Johnson Controls Battery Group, Inc. (JCBGI) have correlated extremely well with the BCI findings.

Junk-bin studies

Junk-bin studies were conducted in numerous geographic segments to develop a complete picture of wasted battery age, failure modes, water-loss characteristics, effect of power density on life, and original equipment versus aftermarket comparisons. The results have yielded an insight into battery and system design.

The JCBGI studies included five geographic segments, with a typical sample size of 1000 batteries per segment. Battery group size, manufacturer, manufacturing date code, open-circuit voltage, cell specific gravity, and water loss were all included in the data gathered. A random sample of 10 to 15% of the batteries was torn down at JCBGI's Battery Quality Assurance Laboratory to determine battery failure mode.

A comparison of 'junk' battery life for the JCBGI and BCI studies is shown in Table 1. The JCBGI studies show that, within the same group size, batteries with high power density are adversely affected by high temperatures to a greater degree than those of lower power density. It was further found that nonsealed batteries were being watered in the southern climates, that temperature is a major driving force for

TABLE 1

Life expectancy (in months) of automotive batteries in the USA

Region in USA	BCI	JCBGI
Southwest	31	32.6
Southeast	40	37.6
Central	47	46.7
Northeast	52	54.2

battery failure, and that the design of the vehicle electrical system plays a role in battery life.

Battery design

Recent trends in automotive battery design, particularly in the USA, have stressed lightweight and high power density characteristics, sometimes at the expense of life at elevated temperatures. This 'cold-cranking race' has resulted in the marketing of some products with exceptional cold-weather performance but with marginal longevity, particularly in worse-case climate, vehicle and drive-cycle circumstances.

Design options

Thorough analysis of the dominant failure modes of batteries in high-temperature applications yields some insight into the opportunities for extending the useful life of the product.

Positive grid deterioration is addressed by increasing the cross section of the grid wires and placement of the wires in a tapered radial configuration [3] that mirrors the pattern of current flow during operation. Open-circuit corrosion of the positive grid [4], as well as water-loss characteristics of the battery during operation, are optimized by selecting appropriate grid materials, namely, 1.4 wt.% antimony positive and 0.1 wt.% calcium negative grid alloys. Trace materials that impact deleteriously on gas generation or water-loss performance must be avoided in all materials [5].

Both the weight and the density of the paste that is applied to the positive grid are increased to enhance the cycling capability and to reduce the propensity for active-material shedding during operation.

Thin backweb envelope separators with thick ribs provide for a suitable reservoir of electrolyte for electrochemical reaction and heat transfer. Envelope separator construction permits minimization of container mud space and plate feet, and thus allows the element to be placed deep in the container cell under a maximum head of electrolyte.

A patented hydrostatic pump [6] is inserted into each cell of the battery in order to force the circulation of the electrolyte and, thereby, to minimize stratification during charge/discharge and to facilitate the transfer of heat from the element. The mixing action achieved through the use of the pump is shown schematically in Fig. 3.

The benefits of circulating the electrolyte of a lead/acid battery are well understood. The authors of numerous articles, e.g., refs. 7 and 8 have described increases in life

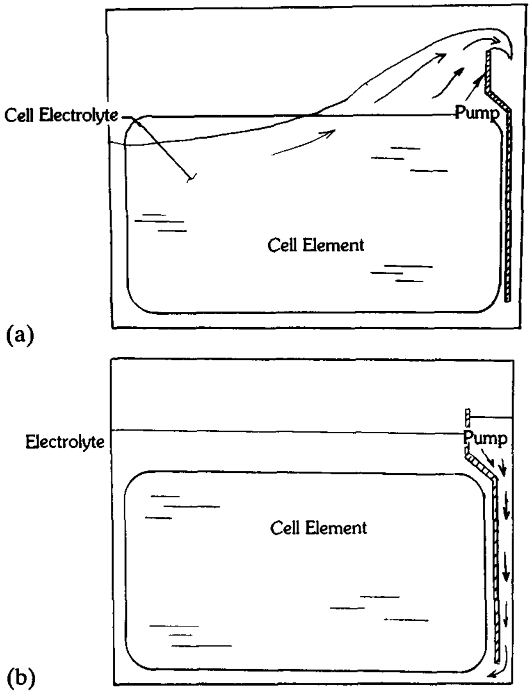


Fig. 3. Schematic of electrolyte pump operation: (a) wave cresting into the pump mouth; (b) equilization flow of liquid.

and performance associated with electrolyte circulation. The improvements have generally been linked to cycling applications that, in contrast to popular thinking, do occur in the environment of today's automotive batteries. The advent of greater electrical demand in late-model vehicles has placed the battery in a situation where it will discharge both during idle periods and in city driving service.

Laboratory life tests

Accelerated laboratory-test regimes for simulating battery life have been developed by various organizations worldwide (e.g., SAE, DIN, JIS). Results using these test methods, while meaningful for comparative purposes, do not accurately mirror the failure modes encountered in elevated-temperature environments. As a consequence, several vehicle manufacturers have either developed their own life tests or have specified that the SAE J240 [9] test be run at temperatures that are substantially higher than the normal 40 °C [10].

One test that is becoming a common means for evaluating battery life in elevated-temperature conditions is the 75 or 80 °C SAE J240 test. The test is conducted as specified in SAE J240 with one exception, the temperature of the battery is raised to 75 or 80 °C. This modification results in large changes in battery cycles to failure. Data that contrast the results of 40 °C tests with those of 80 °C tests are given in Table 2. A reduction of 18 to 40% is seen for the conventional batteries listed.

The batteries showing the greatest reduction in life at 80 °C are the high cold-cranking, thin-plate designs; the reduction is 69 to 82%. Careful attention to the

TABLE 2

Performance of automotive batteries under SAE J240 test

Battery description		J240 Cycles to failure	
	Group 24	40 °C	80 °C
Mfr A	Conventional design	2850	2350
Mfr B	Conventional design	2800	1675
Mfr C	Conventional design	2900	2260
Mfr B	High power density design	9660	1750
Mfg C	High power density design	5140	1610

TABLE 3

Performance of advanced-design automotive batteries under SAE J240 test

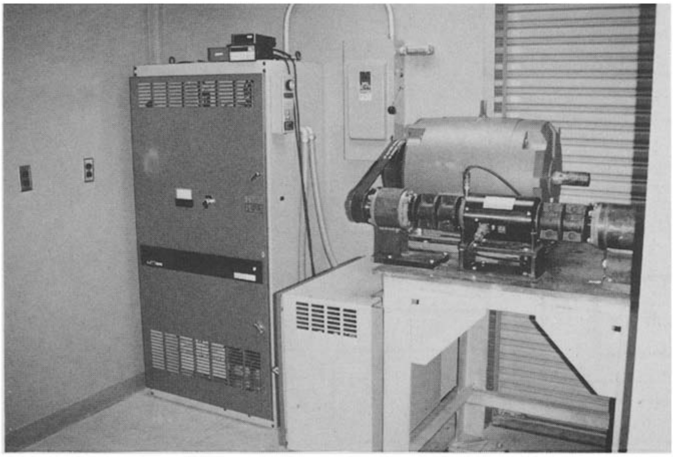
Battery description Group 24	J240 cycles to failure	
	40 °C	80 °C
Design A	6400	3860
Design B	3510	2500
Design C	8940	2470
Design D	9460	5850

design factors referenced previously has allowed battery designers to increase the life expectancy under 80 °C J240 conditions to as much as 5850 cycles, compared with a life of 9460 cycles at 40 °C, see Table 3.

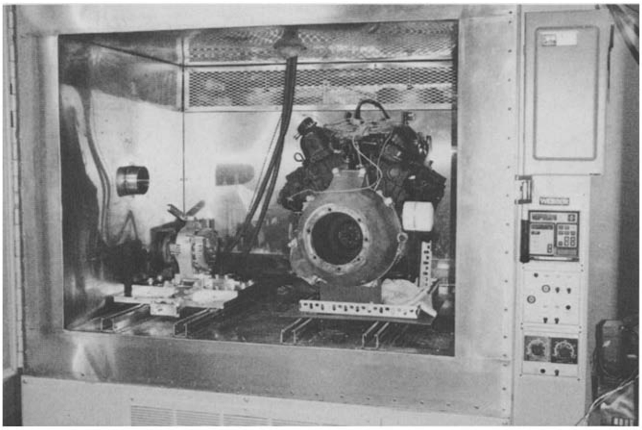
System simulation

Another powerful tool for evaluating battery performance, along with the battery/vehicle system interaction, is simulation of the electrical and temperature underhood environment of the battery. In this approach, the vehicle-operating conditions (as recorded in instrumented test vehicles) are recreated in sufficient detail to include all of the significant effects that act upon the battery. In the most complete demonstration of this method, several individual vehicle electrical components are also included in a controlled-temperature chamber along with the battery. Figure 4 shows a simulation setup with an engine block for a cranking load and an alternator/regulator included inside the chamber with an external electrical motor to drive the alternator. Components and additional simulated loads are controlled by a computer and are based on the measured drive revolutions per min, underhood temperatures and electrical load resistances. Representative drive patterns can be used, and combined in place of specific drive data, in order to monitor the behavior under varied drive conditions.

Once individual vehicle components have been characterized in this system, they can be modelled as electrical load and power source components as a function of the drive inputs. The effects of controlled variations and modifications to the components on the overall system can then be quickly considered. Simulation of component behavior



(a)



(b)

Fig. 4. (a) (b) Equipment for simulating the electrical/temperature underhood environment of automotive batteries.

allows combination into a less complex system with a real battery, a power supply and electrical load resistance equipment as hardware. This test system will still effectively recreate the vehicle-operating conditions for the battery. It is based on the known behavior of other electrical components as a function of drive pattern engine speed, temperature and measured load characteristics. Figure 5 shows a schematic diagram of simulator components. The four major components are: (i) the battery enclosed in a temperature-controlled chamber ranging from −40 to 100 °C; (ii) the alternator/regulator or power supply capable of up to 250 A charging; (iii) vehicle electrical loads or equivalent resistances that handle up to 500 continuous amperes; (iv) the computer-controller that imposes drive patterns.

Some of the system behavior that is studied with simulation equipment includes the effects of high-temperature driving on battery charge-voltage and gassing, battery state-of-charge and cycle depth under severe drive conditions with limited alternator capacity, and battery charge acceptance when cold. Simulation is able to identify system

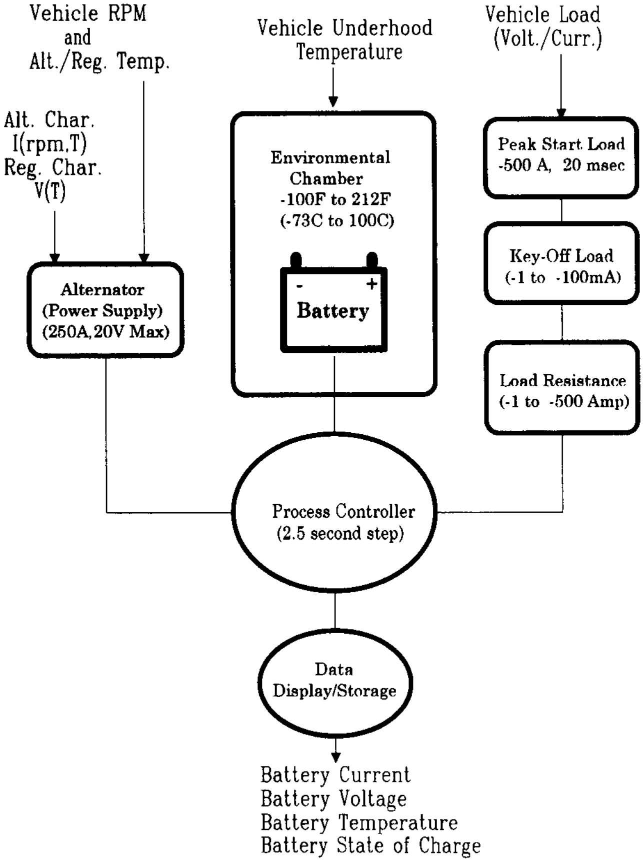


Fig. 5. Vehicle electrical system simulator components.

demands and battery performance within the vehicle environment under a range of operating conditions. It is also able to determine the sensitivity of the vehicle electrical system in component sizing and drive pattern as it affects the battery.

Field testing: thermal protection

Johnson Controls' Battery Group performs numerous field-test programs to establish the effect of the electrical and thermal environment of the battery on its life. Test sites have ranged from Death Valley, California (summer: maximum ambient temperature: 52 °C) to Bemidji, Minnesota (winter: minimum ambient temperature: −38 °C). The tests focus on measuring the temperature and the electrical capacity response of batteries to various drive cycles, electrical system changes and thermal protection methods.

Thermal management

A number of vehicle manufacturers have recognized the temperature problem and, accordingly, have designed plastic heat shields to cover the battery and protect

TABLE 4

Calculated life of automotive batteries under hot-climate conditions—months to 50% battery population failure (based on thermally-activated wearout mechanisms only)

System	Average temperature (°C)	Months
Baseline system	39	9
Ram air	38	13
Fan-forced	34	20
Run-after, fan-forced	20	65

it from the hostile underhood environment. These passive devices have some utility in shielding batteries from the extreme heat generated in the engine compartment, but have little effect during prolonged high-temperature soak periods after the vehicle is turned off.

Numerous methods of managing the thermal environment of the battery were tested and analyzed. These included standard conditions, passive protection methods such as shielding and insulation, and active methods such as vehicle-drive-motion ram air, fan-forced air, and run-after fan-forced air. The coefficients developed were used in a life-prediction model to develop estimates of battery life for various thermal protection methods. Table 4 shows an example of calculated battery life, for the various protection methods, under hot climate drive-cycle conditions. When temperature is known to be the life-limiting factor, estimates based upon test results have shown that by providing suitable protection, such as that patented by JCBGI [11], the long-term reliability of batteries can be improved substantially.

Alternative battery location

One solution to the problem that is utilized by some vehicle manufacturers is to simply remove the battery from the engine compartment and locate it in an alternative location, i.e., trunk, passenger compartment, etc. While this solves the thermal problem, the benefits must be weighed against the additional cost of copper cabling, state-of-charge sensing of the battery and battery-temperature sensing for voltage regulation purposes. Remote locations might dictate the use of valve-regulated, lead/acid battery technology.

Conclusion

The hostile thermal conditions experienced in present vehicles will result in unacceptably short battery life, unless a system's approach is employed to address the problem through battery design optimization, thermal management of the battery, and/or removal of the battery from the engine compartment.

References

1 J. H. Hoover, Failure modes of batteries removed from service, Paper presented to *Battery Council International 102nd Convention, San Francisco, CA, 1990.*

2 J. R. Pierson and R. T. Johnson, *J. Power Sources, 33* (1991) 309–318.
3 J. R. Pierson and C. E. Weinlein, in J. Thompson (ed.), *Power Sources 9, Research and Development in Non-Mechanical Electrical Power Sources,* Academic Press, London, 1983, p. 49.
4 R. T. Johnson and J. R. Pierson, in L. J. Pearce (ed.), *Power Sources 11, Research and Development in Non-Mechanical Eletrical Power Sources,* International Power Sources Symposium Committee, Leatherhead, UK, 1987, p. 1.
5 J. R. Pierson, C. E. Weinlein and C. E. Wright, in D. H. Collins (ed.), *Power Sources 5, Research and Development in Non-Mechanical Electrical Power Sources,* Pergamon, London/New York, 1975, p. 97.
6 W. C. Delaney, *US Patent No. 4 963 444* (June 1990) (to JCI Corporation).
7 T Sagawa, K. Takahashi and M. Tsubota, *GS-News, 44* (2) (1985) pp. 8–13.
8 W. H. Tiedemann and G. L. Wierschem, *Ext. Abstr. Cycling Behavior of Lead/Acid Batteries for Electric Vehicles, Hollywood, FL, Oct. 5–10, 1980,* Vol. 80-2, The Electrochemical Society, p. 278.
9 *Life Test for Automotive Storage Batteries, SAE J240, June 1982,* 1992 SAE Handbook, Vol. 2, pp. 20–50, (SAE Recommended Practice), Society of Automotive Engineers, Inc.
10 J. R. Pierson, Designing and developing batteries for tomorrow's vehicles—North America, Paper presented to *100th Convention of the Battery Council International, Osaka, Japan, 1988.*
11 M. S. Inkmann, R. T. Johnson, N. C. Karolek, J. A. Kondrakiewicz, B. M. Lenhardt and D. W. Saari, *US Patent No. 5 031 712* (July 1991) (to JCI Corporation).