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TITLE: AN OPTICAL METHOD FOR DETERMINING THE STATE OF CHARGE OF A LEAD-ACID BATTERY

MASTER

AUTHOR(S): C. R. Derouin, R. E. Bobbett
J. B. McCormick, and W. J. Kerwin

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An optical method for determining the state of charge of a lead-acid battery*

C. R. Derouin, R. E. Bobbett, J. B. McCormick, and W. J. Kerwin**
Los Alamos National Laboratory, E-11, MS 429
Los Alamos, NM 87545

Abstract

An optic device utilizes the index of refraction and critical angle to determine the state of charge of a lead-acid battery.

Introduction

In the past, a basic problem in the application of lead-acid batteries to electric vehicles (and other applications as well) is the lack of a reliable and accurate battery state-of-charge indicator. Open-circuit voltage, voltage under load, and kilowatt-hours used since charged have been tried to determine the state of charge of a lead-acid battery without success. To date, the only reasonably successful instrument is the hydrometer. However, a simple hydrometer does not provide a continuous state-of-charge measurement.

Previous state-of-charge indicators

At Los Alamos National Laboratory, a number of approaches for continuous monitoring of battery acid specific gravity have been considered. The first two approaches described are essentially electronic hydrometers and have been rejected because of difficult implementation, shock, and vibration. The third approach described utilizes the change in the index of refraction of the battery acid vs battery state of charge.

Dynamic hydrometer

The dynamic hydrometer is a float similar to the one used in a normal hydrometer whose position can be continuously monitored with a capacity sensor. This has the advantage that the liquid level in the battery does not affect the reading, only the specific gravity is indicated. The disadvantages are: (a) a float can easily be overdriven (limited) by acceleration, shock, or vibration so as to give an erroneous reading; (b) the five wires connecting to the moving float would have limited life under these conditions; and (c) the high impedance of a small capacity readout can be a problem.

Force transducer

An alternate method is to use an underwater float to produce an upward force (buoyancy effect) proportional to the liquid-specific gravity. The forces are very small (typically 10^{-3} N), and although measurable under static conditions, the effect of acceleration, shock, and vibration would make this instrument useless while driving.

Optical state-of-charge instrument

A third method is to use the linear relation between state of charge and refractive index. The refractive index is utilized by transmitting a light from a point source, such as a light-emitting diode (LED), through glass, quartz, or other transparent medium into the battery where, at the interface with battery acid, it is reflected or refracted depending upon its relation to the critical angle. The critical angle is that angle where total internal reflection is achieved and is determined by the index of refraction of the medium and battery electrolyte. In Fig. 1, it should be noted that there is a sharp change in the intensity of reflected light at the critical angle. In the battery state-of-charge monitor, this effect is used to produce a sharp "edge" and less than 50% on the other. The location of the edge will move as the critical angle varies due to the change in the refractive index of the sulphuric acid. This effect can produce a direct reading of the battery state of charge. The position of the edge is sensed by a photodiode array or other light intensity vs position transducers. The design shown in Fig. 2 is one of several configurations possible. The advantages of this system are: (a) there are no moving parts; (b) only the medium is in the battery acid and vapor; and (c) there is no sensitivity to shock, vibration, acceleration, or motion of the liquid surface. The derivations of the pertinent equations necessary for the application of this concept to the lead-acid battery are described as follows.

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**University of Arizona, Department of Electrical Engineering, Tucson, AZ 85721

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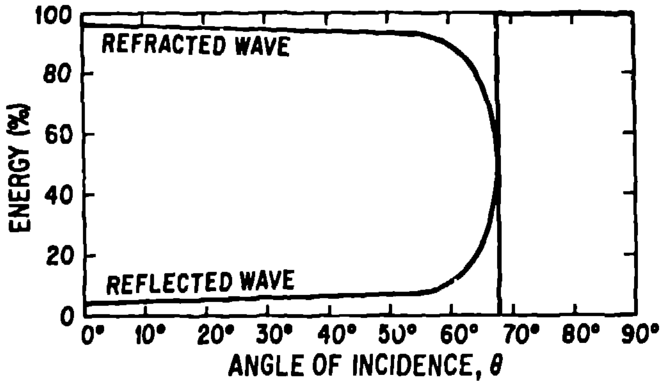

Fig. 1. Reflected energy for a glass, sulfuric acid interface.

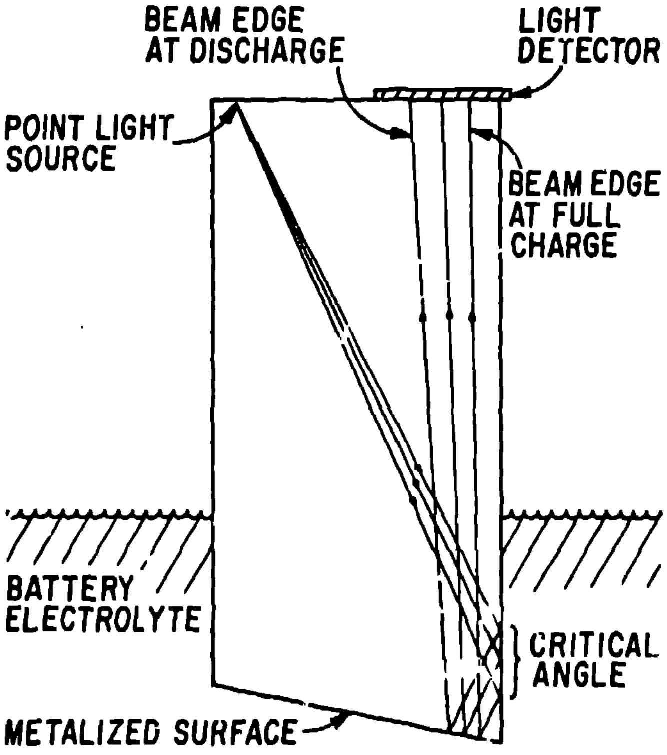

Fig. 2. A typical battery state-of-charge configuration.

Equations

For the lead-acid battery, the equations involved are:

$\eta = 1.333 + 0.00123x$ (1)*

$\rho = 1 + (0.00491x)^{1.117}$ (2)*

$C = 770(\rho - 1.15)$ (3)**

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*Equations (1) and (2) are derived by curve-fitting data from the Handbook of Chemistry and Physics.[1]

**Equation (3) is derived from data by Kordesch.[2]

Solving for C

$$C = 770[8.59(\rho - 1.333)^{1.117} - 0.150] \quad (4)$$

$$C \simeq 5000(\eta - 1.3596) \quad (5)$$

where

η = index of refraction
ρ = specific gravity
C = per cent charge
x = weight per cent H_2SO_4

Equation 5 shows the linear relationship, and it is very accurate (see Fig. 3).

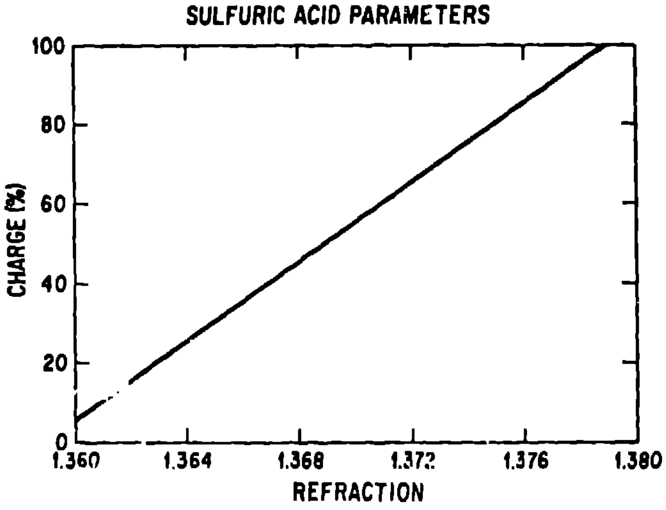

Fig. 3. A plot of the state of charge (density) vs index of refraction.

Therefore, the critical angle is found by putting θ_2 = 90° in the law of refraction:

$$\eta_1 \sin \theta_c = \eta_2 \sin 90° \quad (6)$$

or

$$\sin \theta_c = \frac{\eta_2}{\eta_1} \quad (7)$$

Example

If the battery were 50% charged, then the index of refraction for the H_2SO_4 would be 1.37; and if a glass with an index of refraction of 1.514 at 6700 Å (the wavelength of the monochromatic light source) were used, then the critical angle would be:

$$\sin \theta_c = \frac{1.37}{1.514}$$

$$\theta_c = \sin^{-1} 0.9049$$

$$\theta_c = 64.8°$$

For light at angles greater than this critical angle, 100% total internal reflection is obtained. For light at angles less than this critical angle, the fraction of reflected energy in the two possible polarization directions is:

$$R_{\perp} = \frac{\sin^2(\theta_1 - \theta_0)}{\sin^2(\theta_1 + \theta_0)} \quad (8)$$

$$R_{\parallel} = \frac{\tan^2(\theta_0 - \theta_1)}{\tan^2(\theta_0 + \theta_1)} \qquad (9)$$

The energy reflected when the light beam is 1° less than the critical angle can be calculated by using:

$$\sin \theta_1 = \frac{\eta_0}{\eta_1} \sin \theta_0$$

$$\sin \theta_1 = \frac{1.514}{1.37} \sin 63.8°$$

Then

$$\theta_1 = 82.5$$

$$R_{\perp} = \frac{\sin^2(82.5 - 63.8)}{\sin^2(82.5 + 63.8)}$$

$$R_{\perp} = 33.7\%$$

and

$$R_{\parallel} = \frac{\tan^2(63.8 - 82.5)}{\tan^2(63.8 + 82.5)}$$

$$R_{\perp} = 26\%$$

Equations (8) and (9) are from Stratton.[3]

Conclusions

It should be noted that with proper adjustment of the angles, this instrument can be used for in situ monitoring of many chemical processes in which the index of refraction can be used as an indicator.

References

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3. Stratton, J., Electro-Magnetic Theory, McGraw-Hill 1941.