U.S. CONSUMER PRODUCT SAFETY COMMISSION

DIRECTORATE FOR ENGINEERING SCIENCES

PRELIMINARY TEST RESULTS ON

LITHIUM BATTERIES

USED IN RESIDENTIAL SMOKE ALARMS

JUNE 28, 2002

Arthur Lee
Electrical Engineer
Division of Electrical Engineering
Directorate for Engineering Sciences

PRELIMINARY TEST RESULTS ON LITHIUM BATTERIES
USED IN RESIDENTIAL SMOKE ALARMS
JUNE 28, 2002

BACKGROUND

During a national campaign to introduce smoke alarms to U.S. households in the 1980s, due to their low cost and availability, most householders installed battery-powered smoke alarms. A 1998 National Fire Protection Association (NFPA) report estimated that three-quarters of U.S. residences had at least one working smoke alarm.[1] Although current building codes for new construction and renovations require smoke alarms to be hard-wired with a battery as a back-up power supply, the majority of smoke alarms installed today are still battery powered.

Two studies, conducted in 1983 and in 1992, concluded that the main cause of non-operational smoke alarms is a dead or missing battery. The 1983 study for the International Association of Fire Chiefs Foundation examined 314 fires where the smoke alarm did not sound; 69 percent of the incidents were attributed to dead batteries, missing batteries, and other power source problems.[2] The U.S. Consumer Product Safety Commission (CPSC) conducted a *National Smoke Detector Project* to survey smoke alarm operability in 1992. The study concluded that an estimated 20 percent of U.S. households did not have an operational smoke alarm.[3] The CPSC report indicated that missing batteries, dead batteries, and disconnected batteries were the main causes for non-operational smoke alarms. The CPSC report also stated that the main reasons batteries were removed from smoke alarms were because of annoying alarm activation from cooking and continuous alarming. Some of the incidents reported as continuous alarming may be attributed to "chirping," indicating a low battery.

In 1992, the Centers for Disease Control and Prevention (CDC) funded a Small Business Innovative Research (SBIR) grant on an *Extended Life Smoke Detector Investigation*. The research investigated whether lithium anode primary cells could power a residential smoke alarm for up to 15 years. The report concluded that powering a residential smoke alarm up to 15 years was feasible.[4]

[1] Marty Ahrens, *U.S. Experience with Smoke Alarms and Other Fire Alarms*, Quincy, MA: National Fire Protection Association, October 1998, pp.17.
[2] Raymond E Hawkins, *An Evaluation of Residential Smoke Detectors Under Actual Field Conditions – Final Phase*, Washington: International Association of Fire Chiefs Foundation, March 1983, p. 17.
[3] Charles L. Smith, *Smoke Detector Operability Survey – Report on Findings*, Bethesda, MD: U.S. Consumer Product Safety Commission, November 1993.
[4] Victor M. Serby P.E., VMS Consulting Engineers, *Extended Life Smoke Detector Investigation* for Centers for Disease Control, SBIR Phase I Grant 1R43 CE000014-01

In recent years, the market has offered battery-powered residential smoke alarms with long-life batteries of up to 10-years. The batteries are lithium 9-volt batteries that contain three 3-volt cells in series (as shown in Figure 1). The 9-volt lithium battery is still packaged in a standard 9-volt battery housing (ANSI 1604), which requires no or minor modifications to existing battery-operated smoke alarms. The 9-volt lithium batteries are also sold separately to allow consumers to replace their existing alkaline batteries with long-life batteries.

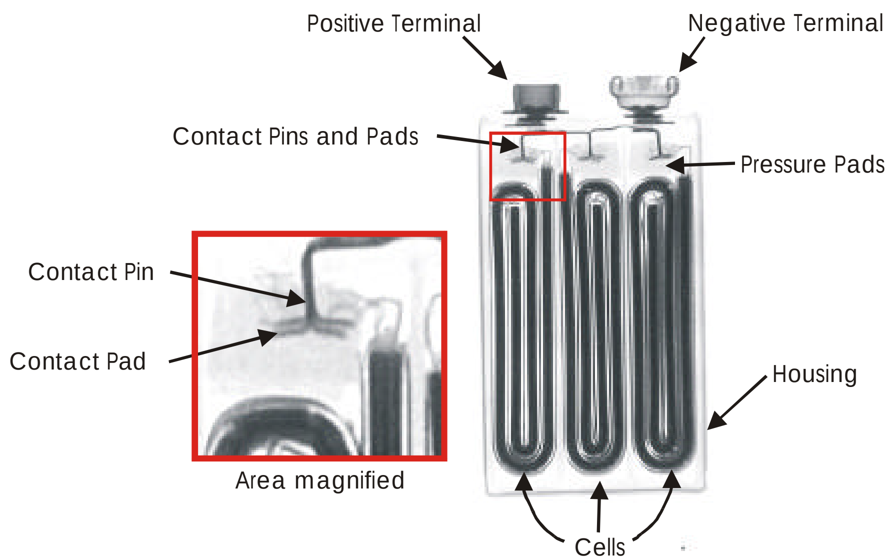


Figure 1. X-Ray of a 9-Volt Lithium Battery in an ANSI 1604 Housing

In June of 1999, Oregon was the first state to require all single-station ionization smoke alarms sold in the state to have 10-year batteries. Similarly, New York, Pennsylvania, New Hampshire and Florida are considering legislation requiring 10-year smoke alarms.

The CDC has programs that fund a number of states to provide smoke alarms. From 1998 to 2000, in a 3-year funded program, CDC recommended, but did not require, that the states install the 10-year smoke alarms. In a new 5-year funded program, it is required that the states install the 10-year smoke alarms, unless a special agreement is reached. In the past two years, the funded states and CDC have had a large number of consumer complaints and/or call backs to replace their new smoke alarms because of low battery chirping. In some cases, low battery chirping occurred within a few months after installation. CDC has summarized the extent of the problem as follows;

- State of Michigan purchased 1,200 smoke alarms; 570 of the alarms exhibited premature low battery chirping.
- State of New York purchased 7,806 smoke alarms. The number of smoke alarms that exhibited premature low battery chirping is unknown, but all the batteries were replaced in the 7,806 units due to premature chirping in some units.

- State of Oklahoma installed 23,828 smoke alarms. The state office activated 906 smoke alarms and, within 1 month, over 300 of those were chirping. Approximately 200 additional units that prematurely chirped were identified in the field, and approximately 100 replacement batteries were used in those units.
- State of Minnesota reported 393 smoke alarms that exhibited premature low battery chirping.
- State of Pennsylvania replaced 200-300 batteries.
- State of Washington had 248 smoke alarms with premature low battery chirping.

The CPSC has also received several complaints of premature low battery chirping associated with 10-year smoke alarms. CPSC field investigators have collected some samples. In addition, CPSC staff requested that CDC provide some of their incident units for analysis. Together, CDC and CPSC collected 63 smoke alarms and 67 lithium batteries from the field for testing and analysis.

TESTING

Testing was conducted in two phases. The first phase was to test and analyze the samples from the field. The second phase was to conduct long-term testing of newly purchased lithium and alkaline batteries that were installed in smoke alarms.

Phase I – Test and Analysis of Samples from the Field

CDC and CPSC Field Investigators provided field samples for testing and analysis. Sixty-three smoke alarms and 67 lithium batteries were provided to CPSC staff for testing.

The procedure was to measure and monitor the voltage of each battery under no load, stand-by (smoke alarm powered and waiting), and during its “test battery” conditions. Every smoke alarm performs a low battery test approximately every 30 to 40 seconds depending on the manufacturer. The low battery test is conducted when a load is placed on the battery for a short period. The smoke alarm easily accomplishes this by flashing an LED light. When the LED flashes, it places a load on the battery and, at that point, the smoke alarm tests for low battery voltage. Typical low battery thresholds are set around 7.6 volts, but this varies by manufacturer. The smoke alarm emits a chirping sound when it has detected a low battery condition. The “test battery” condition will be referred to as the LED test load for the remainder of the document.

All the battery voltages were first recorded under no load conditions using a digital multi-meter. The batteries were then tested under LED test load and standby conditions. The same smoke alarm (sample 00-800-2400-06) was used to test all the batteries, since this provided the same test conditions for each battery. Standby and LED test load voltage measurements (the grounding terminal waveform for the LED and the battery voltage waveform) were recorded with a digital oscilloscope. The setup is shown in Figure 2.

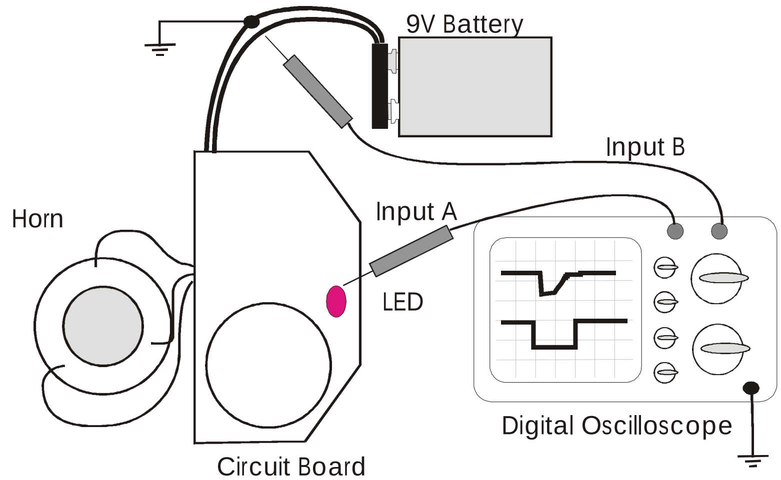


Figure 2. Test Setup for Phase I

The 67 lithium batteries were installed in the test smoke alarm. Forty-seven of the 67 batteries indicated low battery by causing the test smoke alarm to chirp.

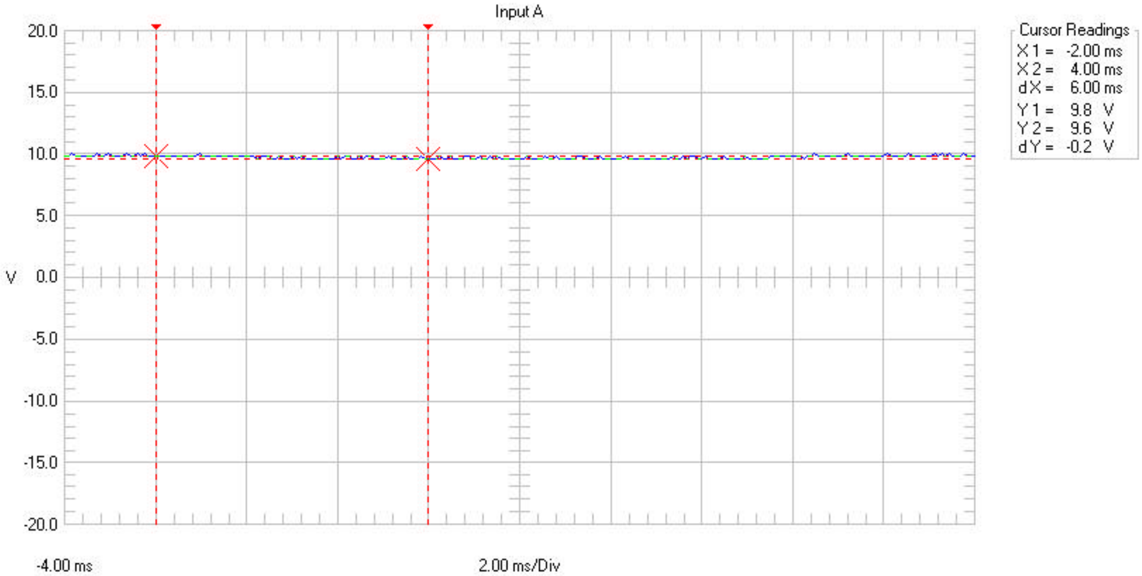
Sixteen batteries did not cause a low battery chirp and the alarm sounded when the smoke alarm's test button was pressed. Two of the 67 batteries had a no-load reading of 0 volts. Two batteries either had a damaged terminal or were shorted. In summary,

- 67 lithium batteries were tested
- 47 caused a low battery chirp
- 16 batteries did not cause a low battery chirp and functioned when tested
- 2 batteries measured 0 volts
- 2 batteries were either damaged or shorted.

The 47 batteries that caused a low battery chirp had a no-load voltage of at least 8.75 volts. The maximum no-load voltage measured was 10.06 volts and the average no-load voltage was 9.90 volts. The 47 batteries also had stand-by voltages of at least 8.60 volts. The maximum stand-by voltage measured was 10.20 volts and the average stand-by voltage was 9.79 volts. During the LED test load, the minimum voltage measured was 5.60 volts. The average and maximum voltages measured were 6.95 and 7.60 volts, respectively. In summary,

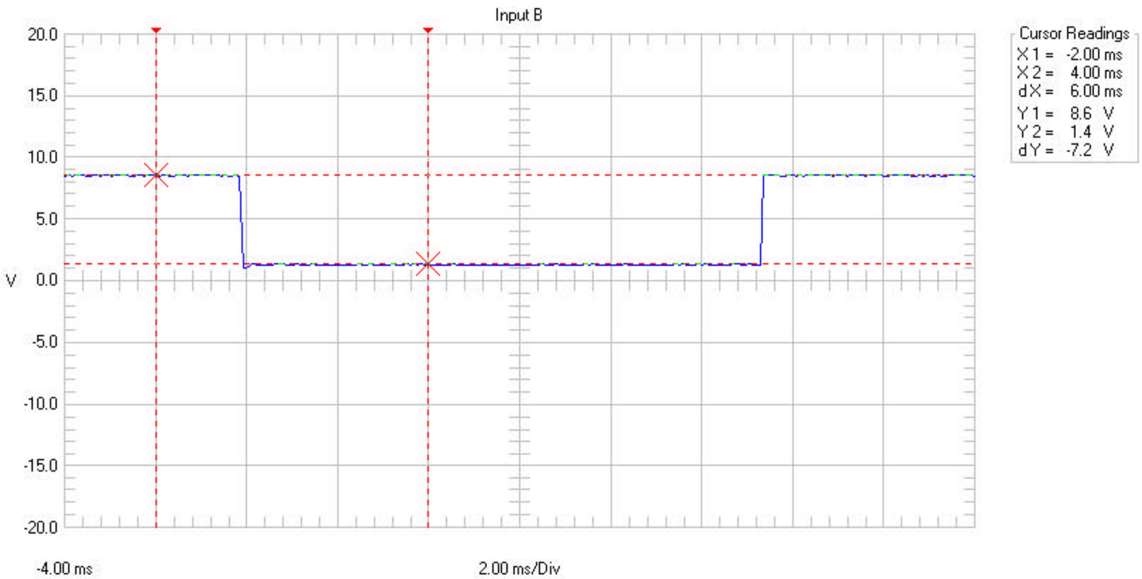
- 47 batteries were tested (those that caused a low battery chirp)
- The minimum no-load voltage measured was 8.75 volts
- The minimum stand-by voltage measured was 8.60 volts
- Under LED test load, the minimum voltage measured was 5.60 volts; the maximum was 7.6 volts

Figures 3a and 3b show how a typical (good) battery responds when the LED test load is applied. Figure 3a shows the battery response when the LED test load is applied on the battery. There is very little or no voltage change. Figure 3b shows when the LED test load is applied and its duration. When the voltage drops from 10 volts to near zero corresponds to the application of the LED test load. The duration of the LED test load was approximately 11 ms (evidenced by the voltage stepping up to 10 volts again).



sample 8327-26

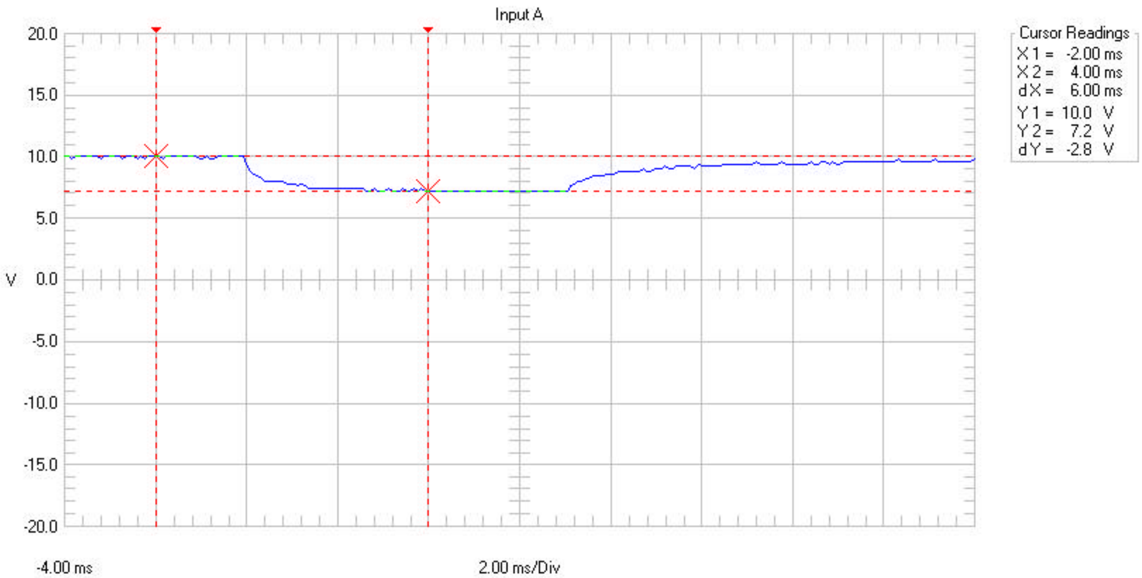
Figure 3a. Response on Battery Voltage when LED Test Load Applied (Good battery)



sample 8327-26

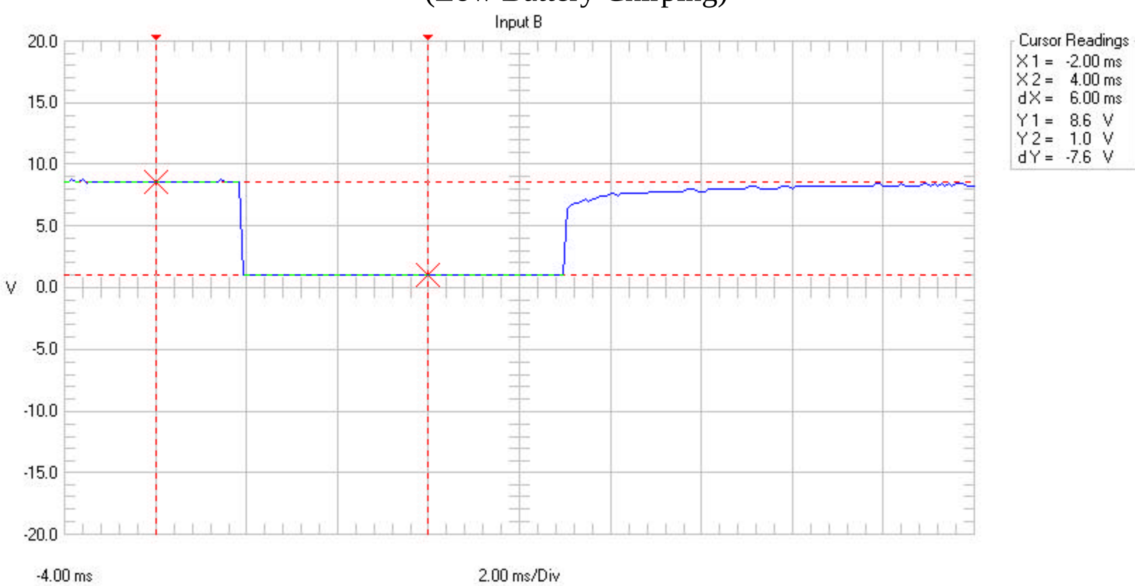
Figure 3b. Application and Duration of LED Test Load

The 47 batteries that caused a low battery chirp had significant voltage drops when an LED test load was applied as compared to their stand-by voltages. Figures 4a, 4b, 5a, and 5b show typical voltage drops below the 7.6 volt threshold even when the battery had a no-load voltage of 10 volts. Figure 4a shows a drop in voltage from a stand-by voltage of nearly 10 volts to 7.2 volts when the LED test load was applied. Figure 4b shows the duration of the LED test load. The duration of the LED test load had a shorter period, approximately 7 ms, when compared with Figure 1b. When the LED test load was applied, it pulled the battery voltage below the low battery threshold for chirping (around 7.6 volts or less).



sample 8327-21

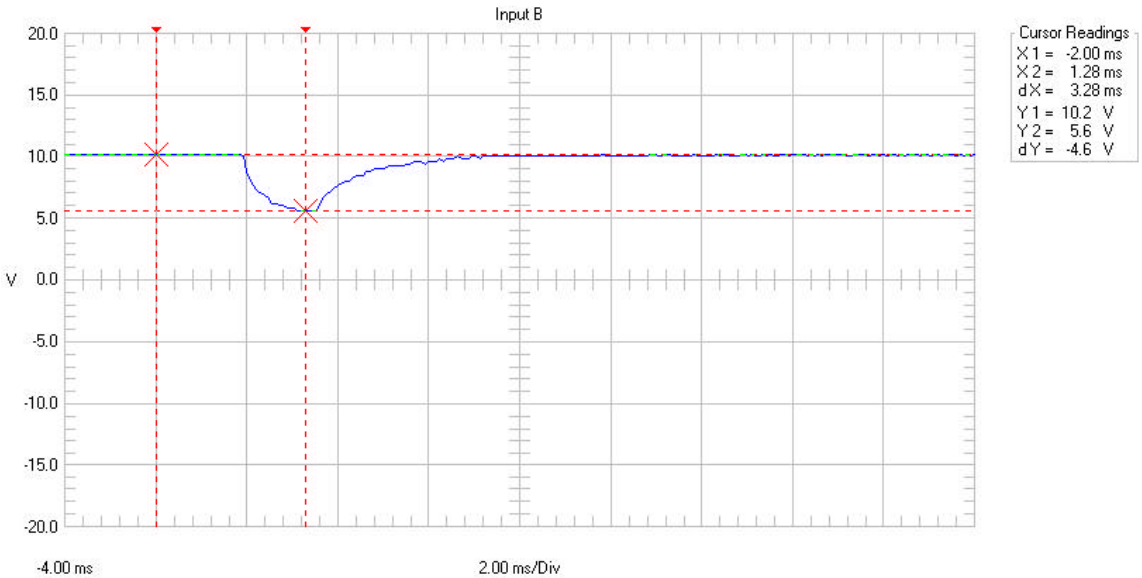
Figure 4a. Response on Battery Voltage when LED Load Applied (Low Battery Chirping)



sample 8327-21

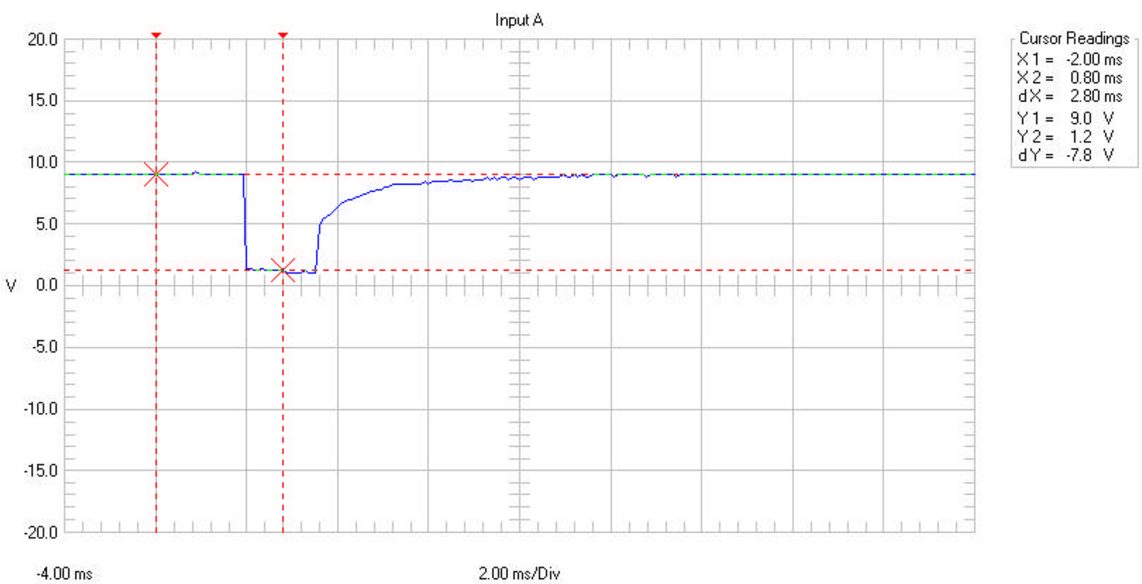
Figure 4b. Application and Duration of LED Load

Figure 5a shows a drop in voltage from a stand-by voltage of over 10 volts to 5.6 volts when the LED test load was applied. Figure 5b shows the duration of the LED test load. The duration of the LED test load had an even shorter period, 1.5 ms, when compared to Figures 3b and 4b.



sample 5500-03

Figure 5a. Response on Battery Voltage when LED Test Load Applied (Low Battery Chirping)



sample 5500-03

Figure 5b. Application and Duration of LED Test Load

All 47 batteries that caused a low battery chirp when installed in the test smoke alarm had similar voltage waveforms for the LED test load and the battery. The larger drop from standby voltage to LED test load voltage causes a shorter LED pulse duration.

Similar tests conducted with an alkaline battery with a low voltage of 7 volts still produced a LED test duration of approximately 11 milliseconds. The batteries that cause a premature low battery chirping apparently cause the smoke alarm timing circuitry to run abnormally. The LED test load signal period, normal approximately 11 ms., decreases as the battery worsens or the delta voltage between the stand-by and LED test load voltages increases.

Samples of the 63 smoke alarms were tested using a 9-volt alkaline battery. The sample of smoke alarms did not produce any unusual drop in voltage in the alkaline battery during the LED test load nor did they emit a low battery chirp. The smoke alarms do not appear to be the direct cause for the premature low battery chirping.

One of the batteries that caused a smoke alarm to emit a low battery chirping was x-rayed. The x-ray did not reveal any cause that would explain the premature low battery chirping. Figure 6 shows the x-ray of sample 8326-01. In the x-ray, the individual 3-volt cells can be identified.

Figure 6. X-Ray of Battery Sample 8326-01

Phase II – Long Term Testing

In Phase II, newly purchased lithium and alkaline batteries were installed in smoke alarms of 2 different manufacturers. The smoke alarms used for this testing were samples collected in the field by CPSC and/or CDC. Five lithium and 10 alkaline batteries were purchased locally. Three of the 5 lithium batteries and 5 of the 10 alkaline batteries were installed in the smoke alarms. The remaining batteries were stored with no load as control samples. Testing began in July 2001.

The test procedure was to test each smoke alarm once a week using the test button and to record the voltage waveforms for the battery and LED test load once a month. The same smoke alarm and setup used in Phase I testing was used to record the voltage waveforms. The initial average voltages for the lithium and alkaline batteries were 9.63 and 9.43 volts, respectively. Table 1 lists the no load, stand-by, and LED test load voltages for each battery at the beginning of the long-term testing.

Table 1. No Load, Stand-by, and LED Test Load Voltages

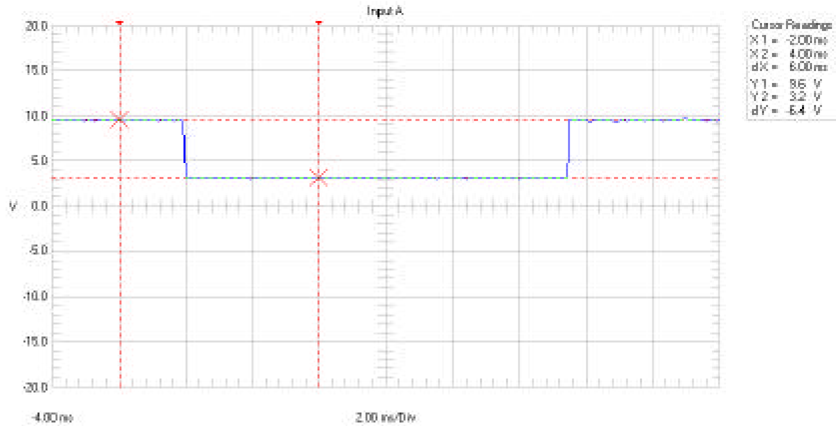
Battery Sample No.	*Installed in Smoke Alarm*	*Battery Type*	*No Load Battery Voltage*	*Stand-by Battery Voltage**	*LED Load Battery Voltage**	*Low Battery Chirp**
01-440-8328-01	yes	Lithium	9.64	9.60	9.60	no
01-440-8328-02	yes	Lithium	9.62	9.60	9.60	no
01-440-8328-03	yes	Lithium	9.7	9.80	9.60	no
01-440-8328-04	no	Alkaline	9.42	9.40	9.40	no
01-440-8328-05	yes	Alkaline	9.47	9.60	9.60	no
01-440-8328-06	no	Alkaline	9.29	9.40	9.40	no
01-440-8328-07	yes	Alkaline	9.52	9.60	9.60	no
01-440-8328-08	no	Alkaline	9.56	9.60	9.60	no
01-440-8328-09	yes	Alkaline	9.57	9.80	9.60	no
01-440-8328-10	no	Alkaline	9.34	9.20	9.00	no
01-440-8328-11	yes	Alkaline	9.34	9.20	9.20	no
01-440-8328-12	no	Alkaline	9.52	9.40	9.40	no
01-440-8328-13	yes	Alkaline	9.53	9.60	9.40	no
01-440-8327-19	no	Lithium	9.6	9.60	9.80	no
01-440-8327-20	no	Lithium	9.6	10.00	9.80	no

*Measurements using smoke alarm sample 00-800-2400-06

<u>**Alkaline Batteries**</u>

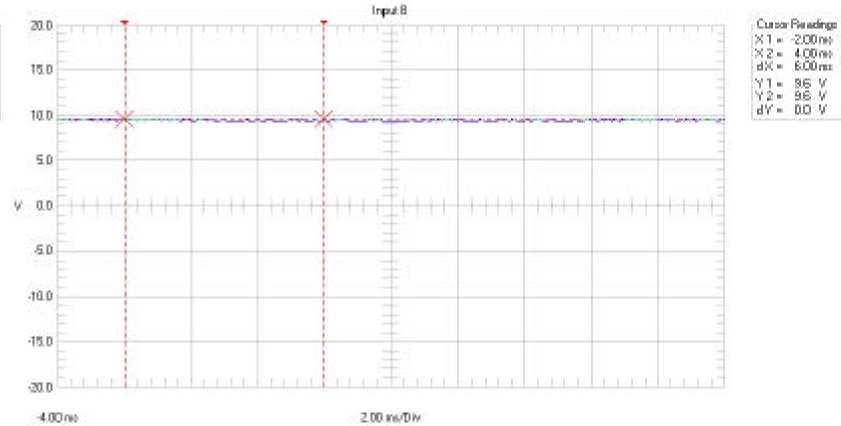
Figures 7a and 7b show the voltage waveforms for sample 8328-05 at the beginning of testing. Figure 7b shows a stand-by and LED test load voltage of 9.6 volts. After 7 months of testing, the alkaline batteries had an average standby and LED test load voltage of 8.8 volts; sample 8328-05 is shown in Figure 8b. The waveforms for each of the batteries still appeared "normal" and no low battery chirping was emitted. A "normal" battery waveform has no sudden drop in voltage when the LED test load is applied, e.g. greater than 1 volt. Figures 8a and 8b show that the waveforms after 7 months of testing are similar to the original waveforms except for a slight overall decline in voltage, as expected. The LED test period still had the same duration – approximately 11 milliseconds – at the beginning of testing and 7 months later.

Figure 9 graphs the stand-by and LED test load voltages for the alkaline batteries up to May 2002. Table 2 lists the measured stand-by and LED test load voltages for the alkaline batteries.



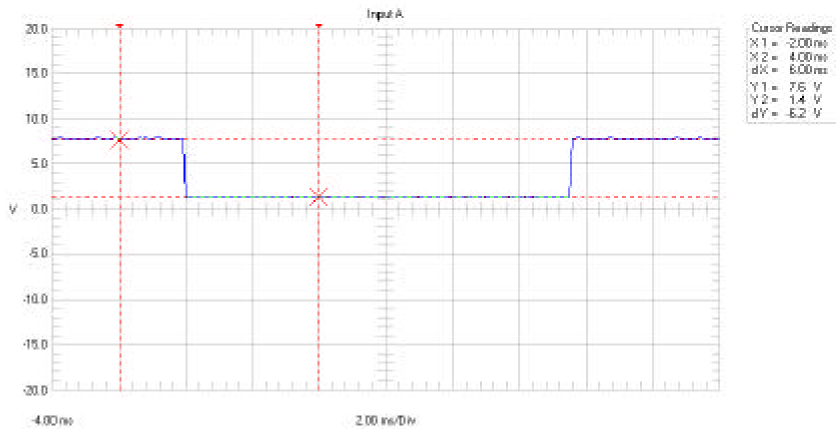
sample 8328-05

Figure 7a. LED Load Waveform at the Beginning of Testing



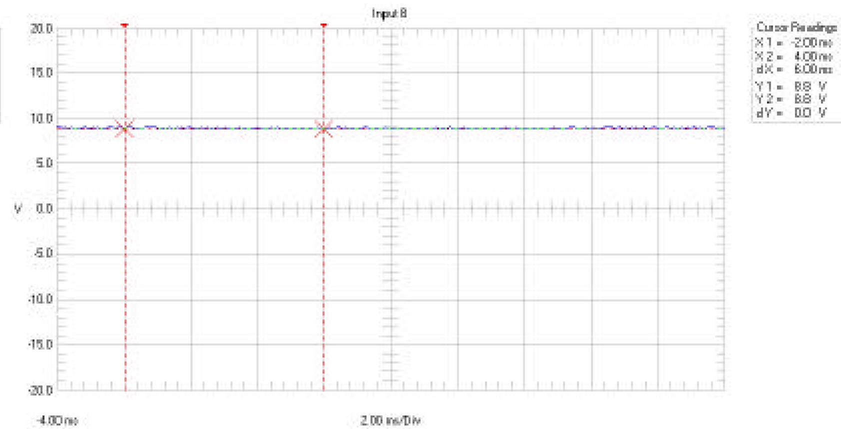
sample 8328-05

Figure 7b. Battery Voltage Waveform during the LED Test Load at the Beginning of Testing



sample 8328-05

Figure 8a. LED Load Waveform after 7 Months of Testing



sample 8328-05

Figure 8b. Battery Voltage Waveform during the LED Test Load after 7 Months of Testing.

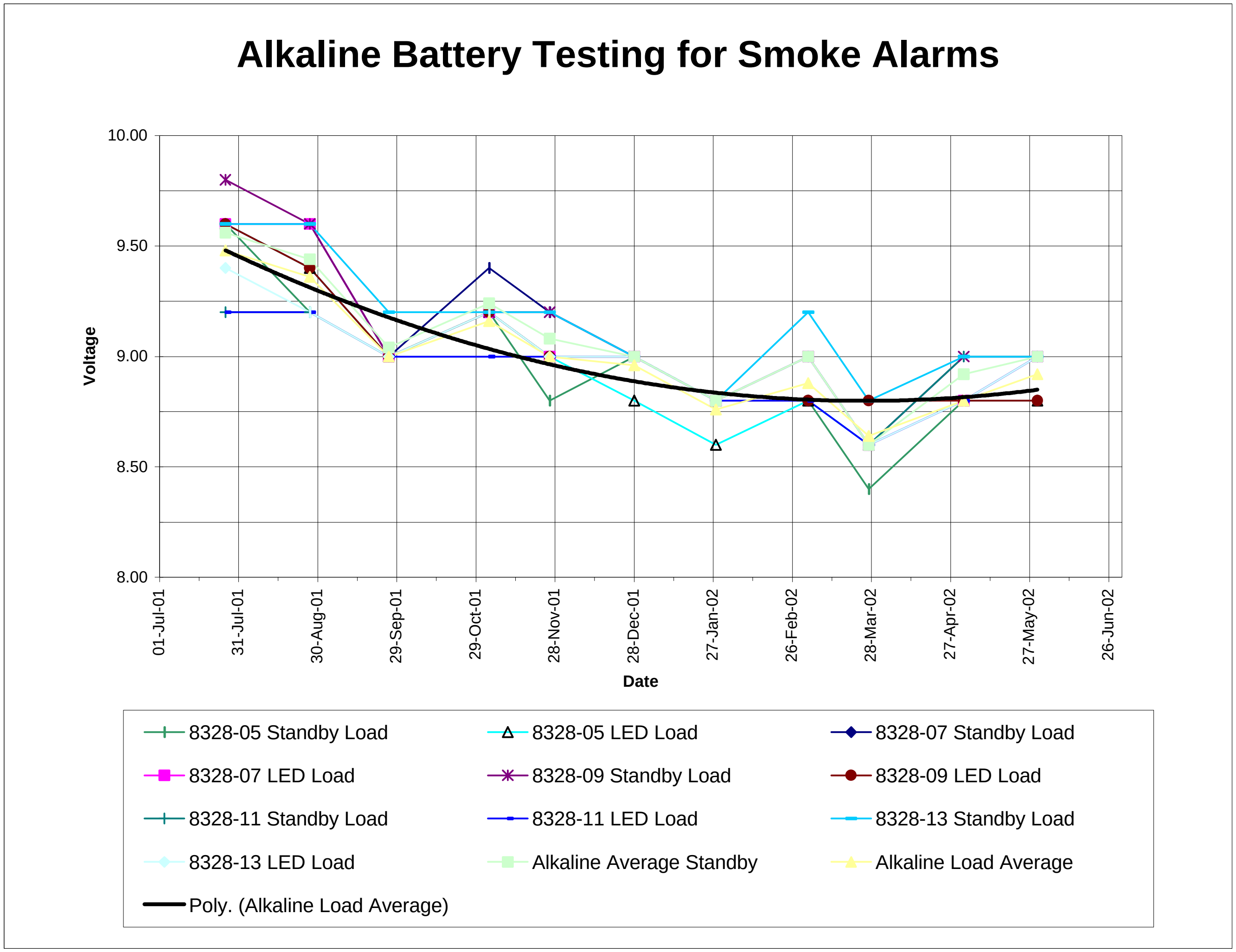


Figure 9. Battery Responses for the Alkaline Batteries

Table 2. Stand-By and LED Test Load Voltages for the Alkaline Batteries

Date	***Battery Sample 8328-05 Standby Load Voltage****	***Battery Sample 8328-05 LED Load Voltage****	***Battery Sample 8328-07 Standby Load Voltage****	***Battery Sample 8328-07 LED Load Voltage****	***Battery Sample 8328-09 Standby Load Voltage****	***Battery Sample 8328-09 LED Load Voltage****
26-Jul-01	9.60	9.60	9.60	9.60	9.80	9.60
27-Aug-01	9.20	9.40	9.60	9.60	9.60	9.40
26-Sep-01	9.00	9.00	9.00	9.00	9.00	9.00
03-Nov-01	9.20	9.20	9.40	9.20	9.20	9.20
26-Nov-01	8.80	9.00	9.20	9.00	9.20	9.00
28-Dec-01	9.00	8.80	9.00	9.00	9.00	9.00
28-Jan-02	8.80	8.60	8.80	8.80	8.80	8.80
4-Mar-02	8.80	8.80	9.00	9.00	9.00	8.80
27-Mar-02	8.40	8.60	8.60	8.60	8.60	8.80
2-May-02	8.80	8.80	8.80	8.80	9.00	8.80
30-May-02	9.00	8.80	9.00	9.00	9.00	8.80

Date	***Battery Sample 8328-11 Standby Load Voltage****	***Battery Sample 8328-11 LED Load Voltage****	***Battery Sample 8328-13 Standby Load Voltage****	***Battery Sample 8328-13 LED Load Voltage****	***Alkaline Batteries Average Standby Load Voltage***	***Alkaline Batteries Average LED Load Voltage***
26-Jul-01	9.20	9.20	9.60	9.40	9.56	9.48
27-Aug-01	9.20	9.20	9.60	9.20	9.44	9.36
26-Sep-01	9.00	9.00	9.20	9.00	9.04	9.00
03-Nov-01	9.20	9.00	9.20	9.20	9.24	9.16
26-Nov-01	9.00	9.00	9.20	9.00	9.08	9.00
28-Dec-01	9.00	9.00	9.00	9.00	9.00	8.96
28-Jan-02	8.80	8.80	8.80	8.80	8.80	8.76
04-Mar-02	9.00	8.80	9.20	9.00	9.00	8.88
27-Mar-02	8.60	8.60	8.80	8.60	8.60	8.64
2-May-02	9.00	8.80	9.00	8.80	8.92	8.80
30-May-02	9.00	9.00	9.00	9.00	9.00	8.92

*Measurements using smoke alarm sample 00-800-2400-06

Lithium Batteries

After 7 months of testing, one of the three lithium batteries began causing a low battery chirping when installed in the test smoke alarm. The low battery chirping was discovered on the morning of January 14, 2002. Since January 14 was a Monday, the actual low battery chirping could have occurred as early as the evening of Friday, January 11, 2002.

Figures 10a and 10b show the waveforms for sample 8328-03 at the beginning of testing. Figure 10b shows stand-by and LED test load voltages of 9.8 and 9.6 volts, respectively. After 7 months of testing, lithium battery sample 8328-03 had stand-by and LED test load voltages of 7.40 and 7.20 volts, respectively. Figures 11a and 11b show the same waveforms after 7 months of testing. The LED test period still has the same duration of approximately 11 milliseconds at the beginning of testing and after 7 months.

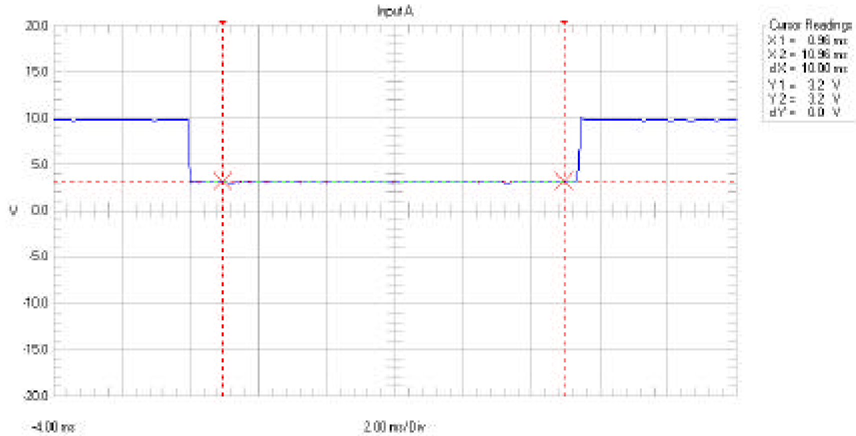
Figures 12a and 12b graph the stand-by and LED test load voltages for the lithium batteries through May 2002. Figure 12b does not include sample 8328-03. The calculated averages in both figures do not include sample 8328-03 after December 28, 2001. Table 3 lists the measured stand-by and LED test load voltages. Sample battery 8328-03 was removed from the smoke alarm and subsequently stored with no load.

Table 3. Stand-By and LED Test Load Voltages for the Lithium Batteries

Date	***Battery Sample 8328-01 Standby Load Voltage****	***Battery Sample 8328-01 LED Load Voltage****	***Battery Sample 8328-02 Standby Load Voltage****	***Battery Sample 8328-02 LED Load Voltage****	***Battery Sample 8328-03 Standby Load Voltage****	***Battery Sample 8328-03 LED Load Voltage****	***Lithium Batteries Average Standby Load Voltage***	***Lithium Batteries Average LED Load Voltage***
26-Jul-01	9.60	9.60	9.60	9.60	9.80	9.60	9.67	9.60
27-Aug-01	9.40	9.40	9.40	9.40	9.40	9.40	9.40	9.40
26-Sep-01	9.20	9.20	9.20	9.00	9.00	9.00	9.13	9.07
03-Nov-01	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20
26-Nov-01	9.20	9.20	9.20	9.20	9.20	9.20	9.20	9.20
28-Dec-01	9.20	9.20	9.20	9.20	9.00	9.00	9.13	9.13
14-Jan-02	9.20	9.20	9.20	9.20	7.40	7.20	9.20†	9.20†
28-Jan-02	9.00	9.00	9.00	9.00	5.80	4.60	9.00†	9.00†
04-Mar-02	9.20	9.20	8.60	8.60	5.80	4.80	8.90†	8.90†
27-Mar-02	9.20	9.00	9.00	9.00	5.80	3.60	9.10†	9.00†
2-May-02	9.20	9.20	9.20	9.00	6.40	3.40	9.20†	9.10†
30-May-02	9.40	9.40	9.40	9.20	6.60	3.40	9.40†	9.30†

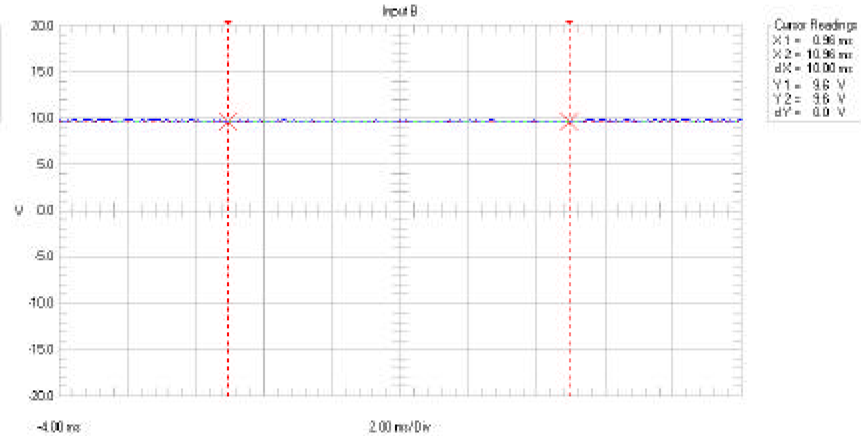
*Measurements using smoke alarm sample 00-800-2400-06

† Does not include sample 8328-03



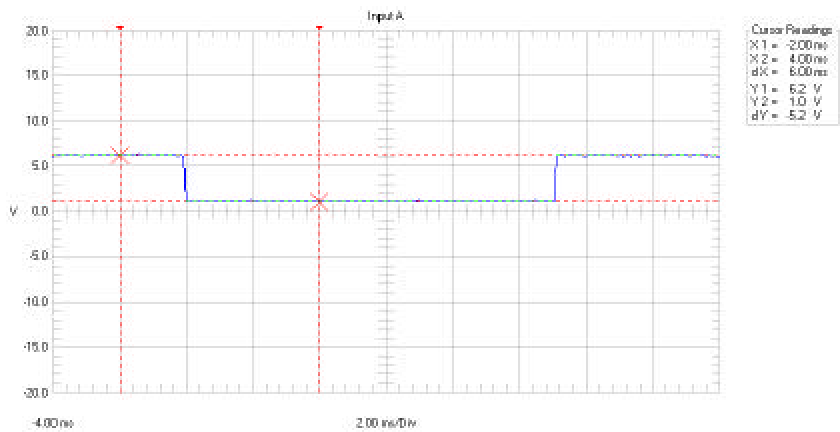
sample 8328-03

Figure 10a. LED Load Waveform at the Beginning of Testing



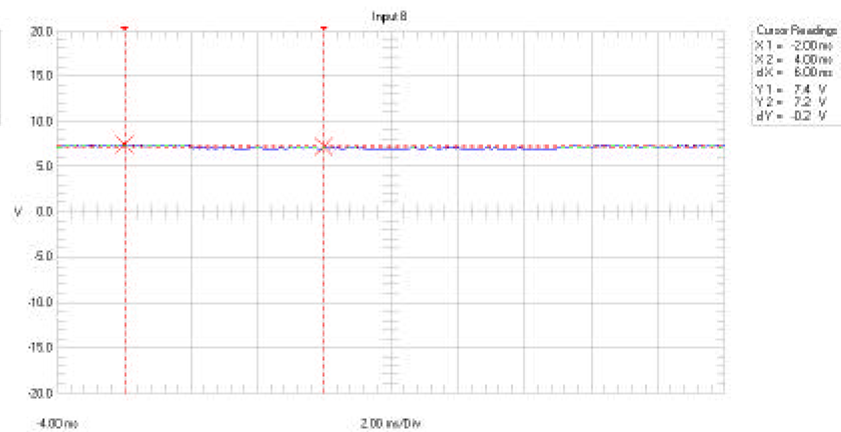
sample 8328-03

Figure 10b. Battery Voltage Waveform during the LED Test Load at the Beginning of Testing



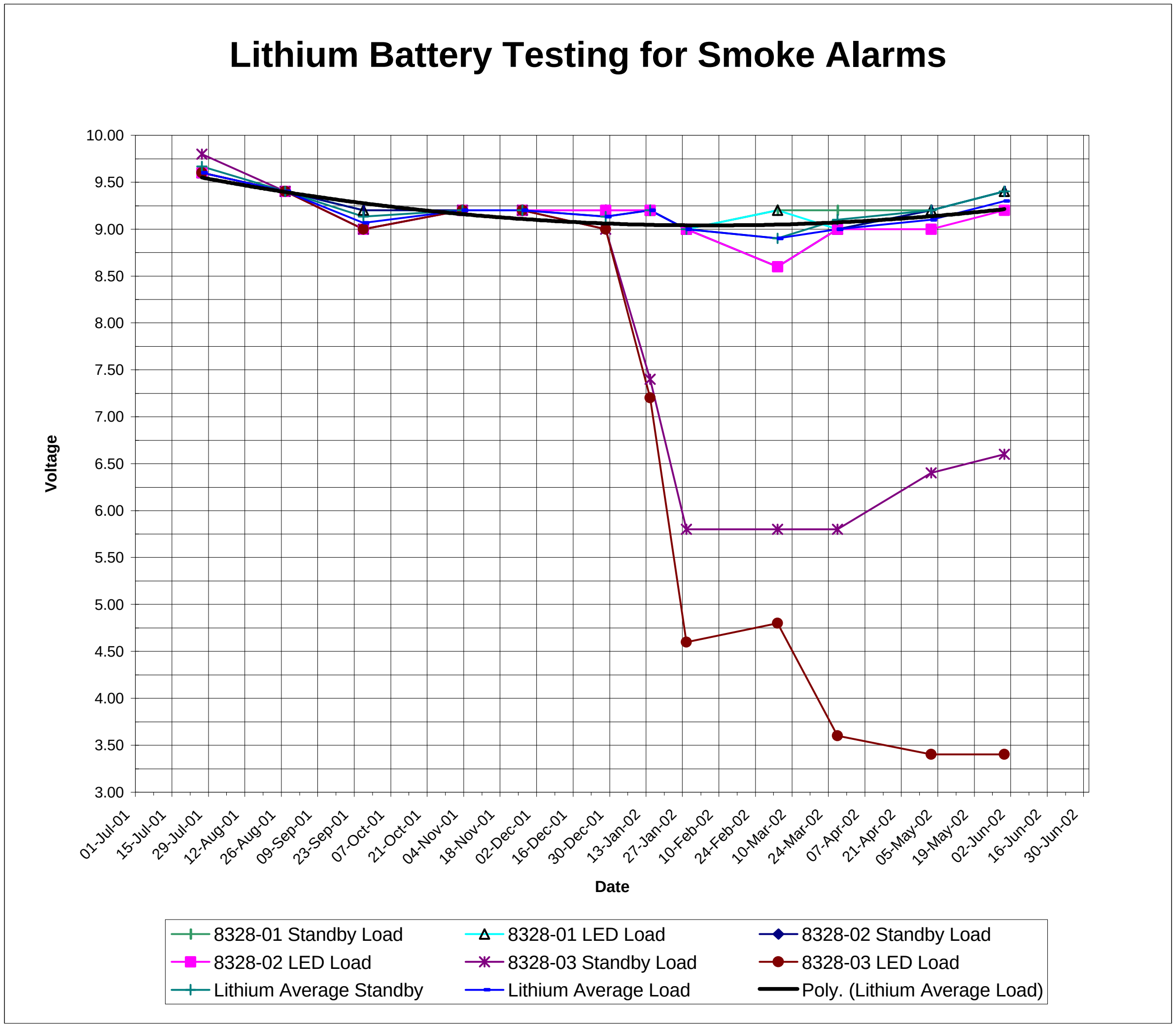
sample 8328-03

Figure 11a. LED Load Waveform after 7 Months of Testing



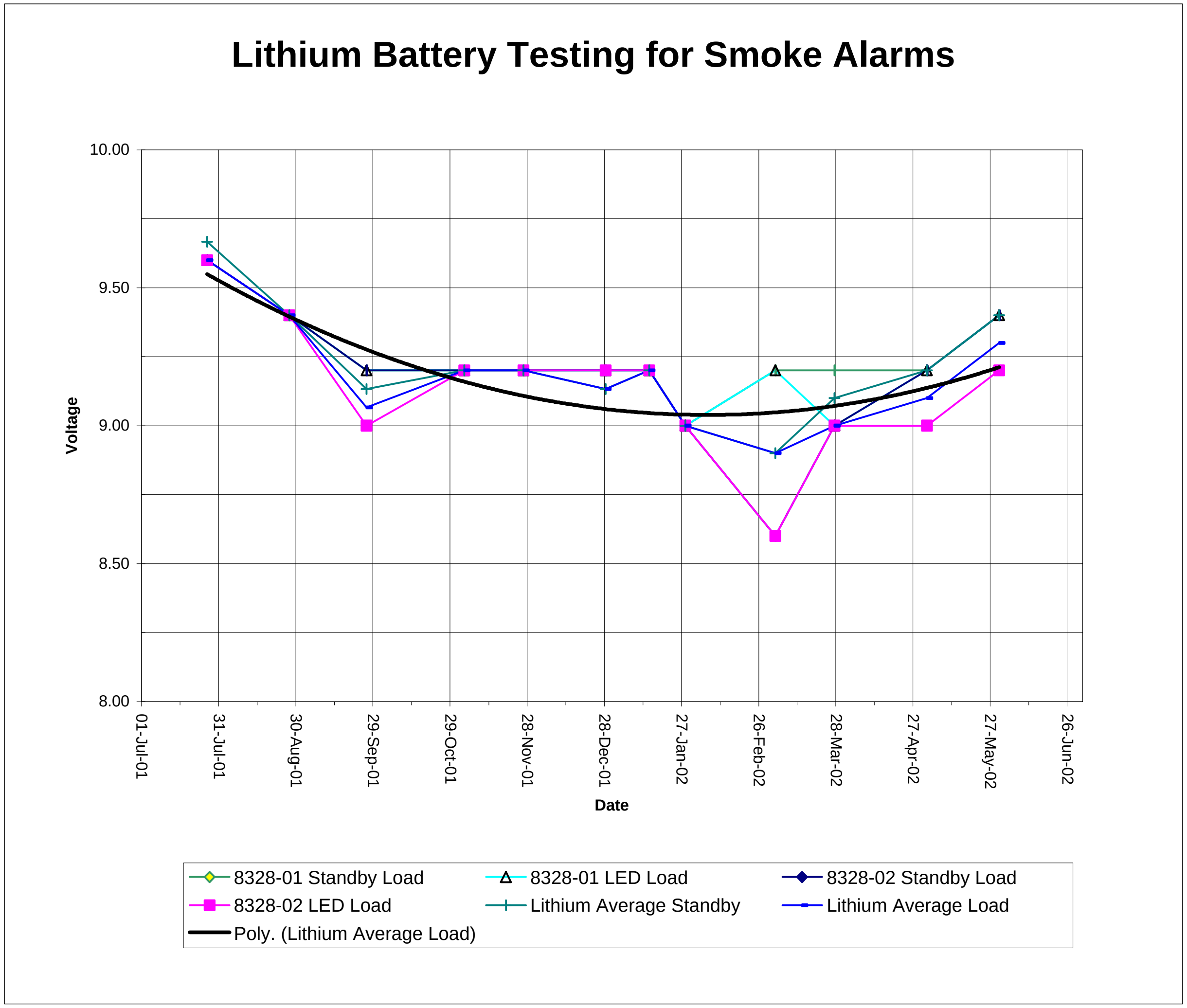
sample 8328-03

Figure 11b. Battery Voltage Waveform during the LED Test Load after 7 Months of Testing



The Averages do not include sample 8328-03 after December 28, 2001

Figure 12a. Battery Response for the Lithium Batteries



The Averages do not include sample 8328-03 after December 28, 2001

Figure 12b. Battery Response for the Lithium Batteries without Sample 8328-03

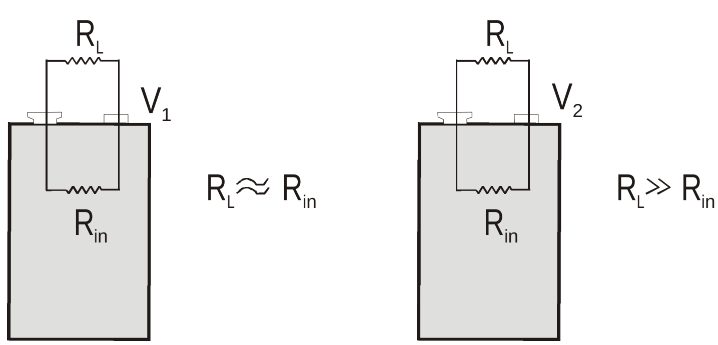
DISCUSSION

The voltage waveforms for the lithium batteries that caused premature low-battery chirping during Phase I testing were different from that of the failed battery observed during Phase II testing. In Phase I, battery data showed standby and no-load voltages significantly above the low-battery threshold, and large voltage drops when the LED test load was applied. In comparison, in Phase II testing, sample 8328-03 exhibited a sudden drop in the standby and no-load voltages to about 7.4 volts (below the low-battery threshold). The failed battery in Phase II was likely caused by one of the three cells shorting.

The cause of failure for the batteries tested in Phase I is believed to be abnormally high internal resistance within the battery. A battery's internal resistance R_{in} is defined as the opposition or resistance to the flow of an electric current within a cell or battery[5]. The internal resistance consists of two parts -- the sum of the ionic and electronic resistances of the cell components. The battery's internal resistance can be expressed by

$$R_{in} = \frac{(V_1 - V_2)\, R_L}{V_2} \qquad (1)$$

where R_{in} *= internal resistance, W*
V_1 *= initial "standby" voltage, stabilized closed-circuit voltage,* R_L *is small*
V_2 *= closed-circuit "LED test load" voltage with application load,* R_L *is large*
R_L *= application load, W*



[5] Linden, D., *Handbook of Batteries*, McGraw-Hill Inc., 1995

The internal resistance of a “good” lithium battery (sample 8327-19) was estimated. The battery was installed into the test smoke alarm to measure the current during the LED test load. The current was 14 mA at 9.2 volts. Assuming that R_L is much larger than R_{in} and using Ohm’s Law,

$$V = I\,R_L \qquad (2)$$

where V = *voltage, V*
I = *current, A*
R_L = *resistance load*

The resistance load R_L is calculated to be 657 Ω. This is the resistive load that will be used in equation (1).

Using equation (1), the internal resistance R_{in} for a “good” battery is 14 Ω.

The voltage and current from sample 2400-08, which emitted a premature low battery chirp, was measured; and the internal resistance was calculated using equation (1). Figures 13a and 13b show the battery voltage and current in sample 2400-08 before and during application of the LED test load, respectively. Figure 13a shows a standby voltage of 9.8 volts and an LED test load voltage of 7.6 volts. Figure 13b shows the current was 12.7 mA* during the LED test load.

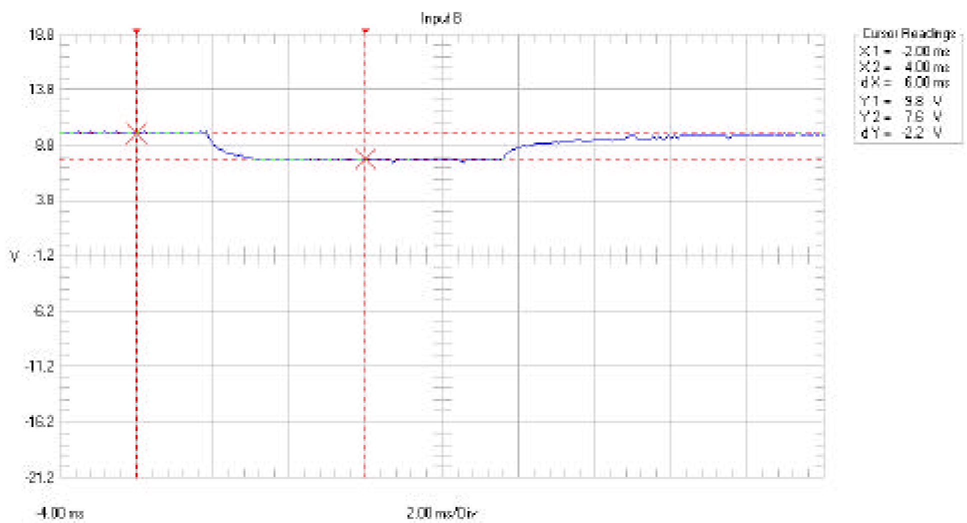


Figure 13a. The Battery Voltage Before and During the LED Load (sample 2400-08)

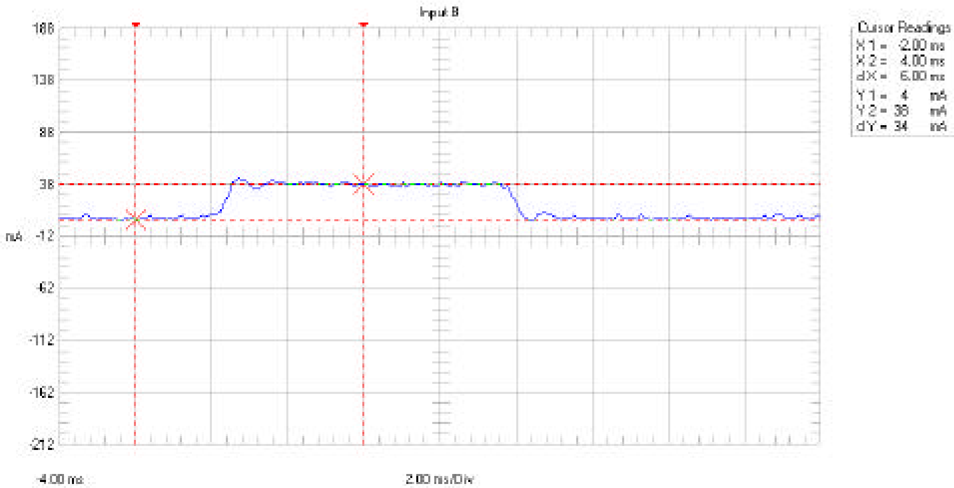


Figure 13b. The Battery Current Before and During the LED Load (sample 2400-08)
*The figure represents 300% of the actual current measured

Applying equation (1) to sample 2400-08,

$$R_{in} = \frac{(V_1 - V_2)\,R_L}{V_2} \qquad (1)$$

where R_{in} = *internal resistance, W*
$V_1 = 9.8\ V$
$V_2 = 7.6\ V$
$R_L = 657\ W$

R_{in} is 190 Ω. Subtracting the initial resistive load of 14 Ω, the increase in the battery's internal resistance is 176 Ω.

An external resistor was placed in series with a "good" battery to simulate a "bad" battery with an internal high resistance. The battery waveforms from a good battery with an external resistor would be compared to a bad battery with possibly an internal high resistance.

Using a "good" battery, an external resistance of 176 Ω was placed in series with a resistive load R_L (smoke alarm) and compared to the graphs for sample 2400-08. The setup included placing a variable resistor between the battery and the smoke alarm as shown in Figure 14.

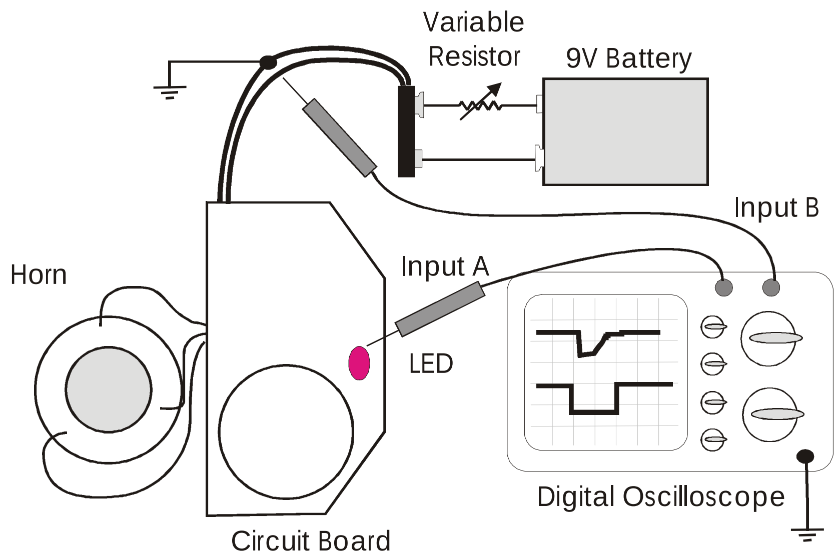


Figure 14. Setup with a Variable Resistor between the Battery and Smoke Alarm

As mentioned, a “good” battery (sample 8327-19) with no indication of premature low battery warning was used in the setup. The variable resistor was set at 176 Ω. Figures 15a and 15b show the current and voltage with LED test load, respectively.

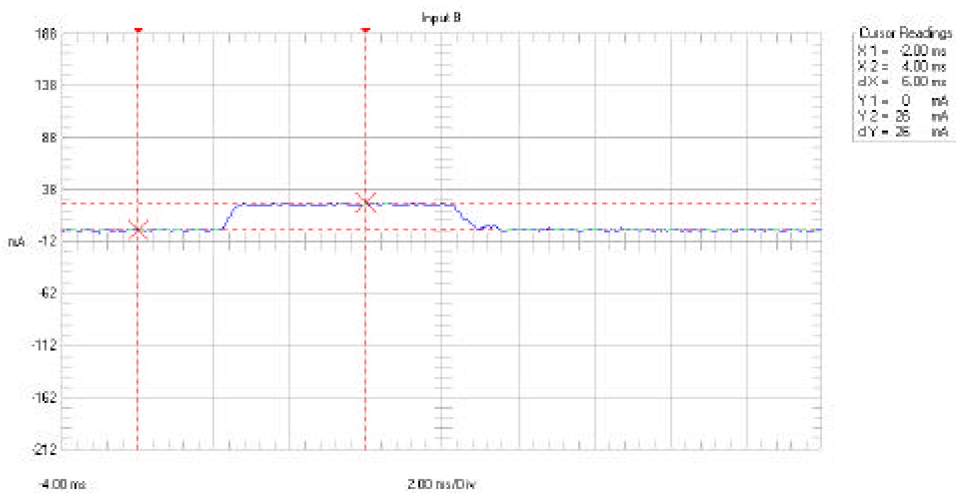


Figure 15a. The Current Before and During the LED Test Load
with a 176 Ω Resistor.*

* The figure represents 300% of the actual current measured

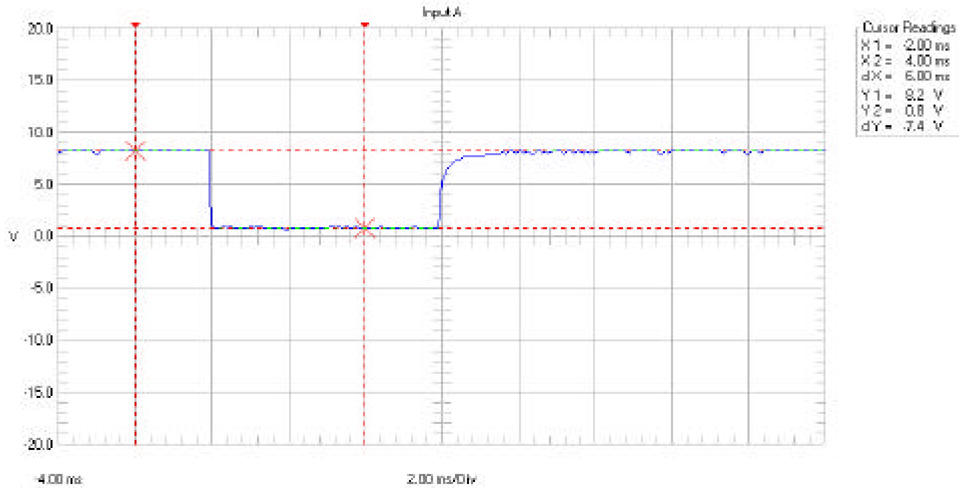


Figure 15b. The LED Voltage Before and During the LED Test Load with a 176 Ω Resistor.

The current waveforms shown in Figure 15a (applied external resistance) and Figure 13a were similar during the LED test load. The pulse length for the good battery and the external resistive load was shorter than that seen in sample 2400-08 (6.4 ms compared to 7.6 ms for the sample 2400-08). The discrepancy may be caused by not applying the exact external resistance or because applying an external resistance is not an exact representation of internal resistance.

The same procedure was performed for sample 8327-21. This sample had a calculated internal resistance R_{in} of 381 Ω. Subtracting the initial internal resistance of 14Ω, the increase in internal resistance was 367 Ω. The variable resistor was set at 367 Ω. Figures 16a and 16b compare the voltage waveforms for sample 8327-21 and the good battery (sample 8327-19) with an additional 366 Ω, respectively.

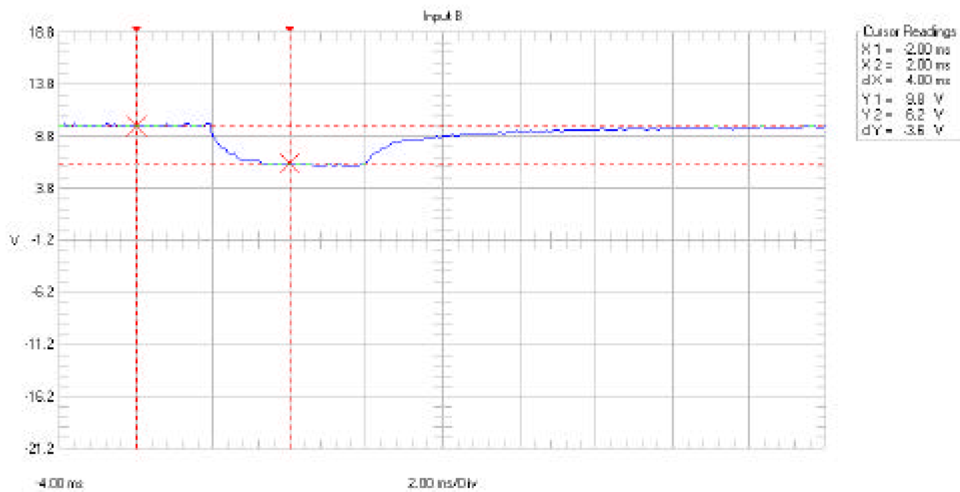


Figure 16a. Battery Voltage for Sample 8327-21

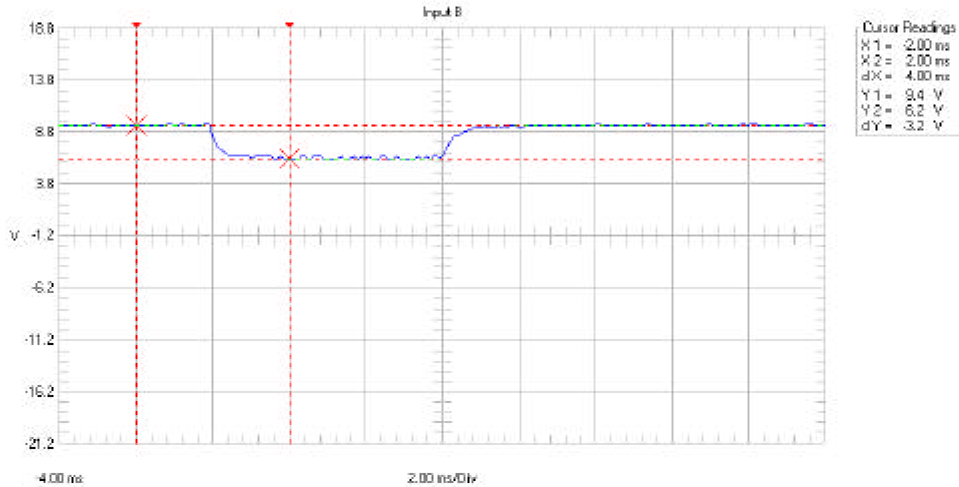


Figure 16b. Battery Voltage (sample 8327-19) with 366 Ω Resistor.

The voltage waveforms shown in Figures 16a and 16b are similar. As before, the pulse length was shorter by 2 ms for the battery with the external resistive load. The difference in LED pulse width for a premature low battery and a "good" battery with an applied resistive load becomes greater as the delta voltage (standby V_1 and LED test load V_2) in the battery increases.

Some of the batteries that were initially tested in July 2001 that had no indication of low battery chirping began causing a low battery chirping when tested again. The batteries would cause a low chirp when reinstalled in the test smoke alarm. Figures 17a and 17b show the battery voltage measurements of sample 8326-04 in July 2001 and May 2002, respectively. The initial test in July 2001 showed the battery had standby V_1 and LED test load V_2 voltages of 9.6 and 8.6, respectively. The V_2 voltage was 1 volt above the 7.6 V low battery threshold. When tested in May 2002, V_2 had dropped to 7.8 volts. The battery had been in storage and under no load since initial testing in July 2001.

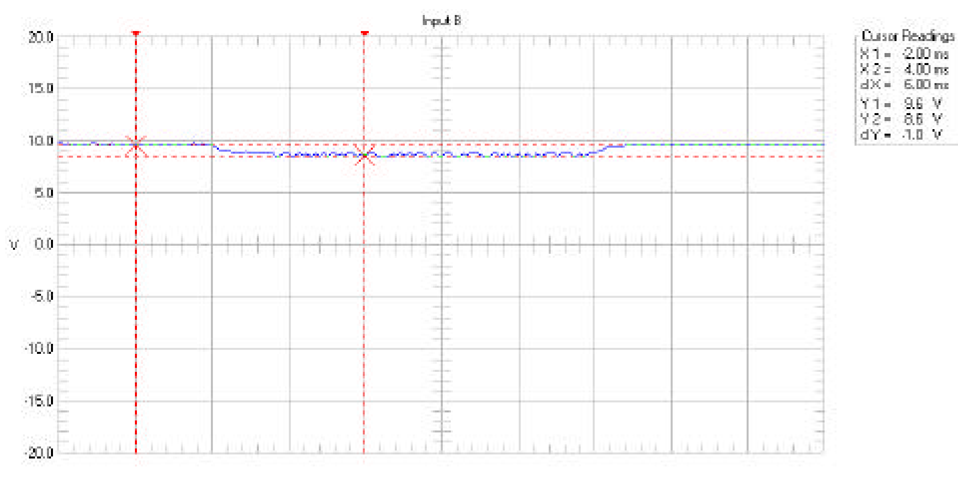


Figure 17a. No Low Battery Chirping, Sample 8326-04 tested on July 23, 2001

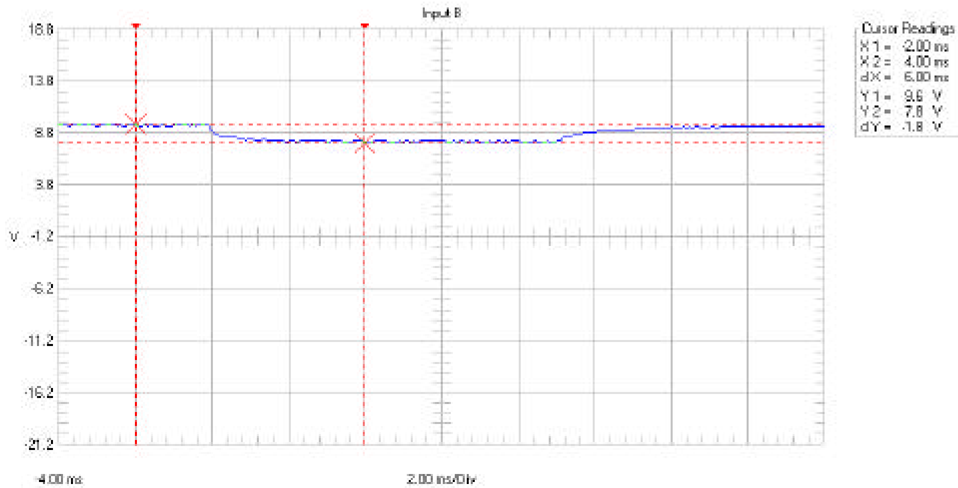


Figure 17b. Low Battery Chirping, Sample 8326-04 tested on May 07, 2002

The data for the 16 batteries that were initially tested and had no indication of low battery chirping were reviewed. Six of the 16 batteries displayed characteristics that indicated that the batteries would degrade to the point where they would begin to cause premature low battery chirping; e.g. the initial voltage V_2 was close to the smoke alarm low battery threshold (7.6 V), and the delta voltage between V_1 and V_2 is greater than 1 volt.

One of the possible causes for the increasing internal resistance in a short amount of time is the increasing contact resistance such as corrosion between internal contacts. As shown in Figure 1, the three cells are connected in series through contact pins and pads. The contact pads are located on the cells and the contact pins are located on the top cover, along with the external positive and negative terminals.

Sample 5500-03 was opened to determine if corrosion between the contact pins and pads on the cells had occurred. Before opening, the battery voltage and LED test load voltage waveforms were recorded as shown in Figure 18a and 18b. Since the delta voltage between V_1 and V_2 was 4.6 volts, the expected amount of corrosion should be significant.

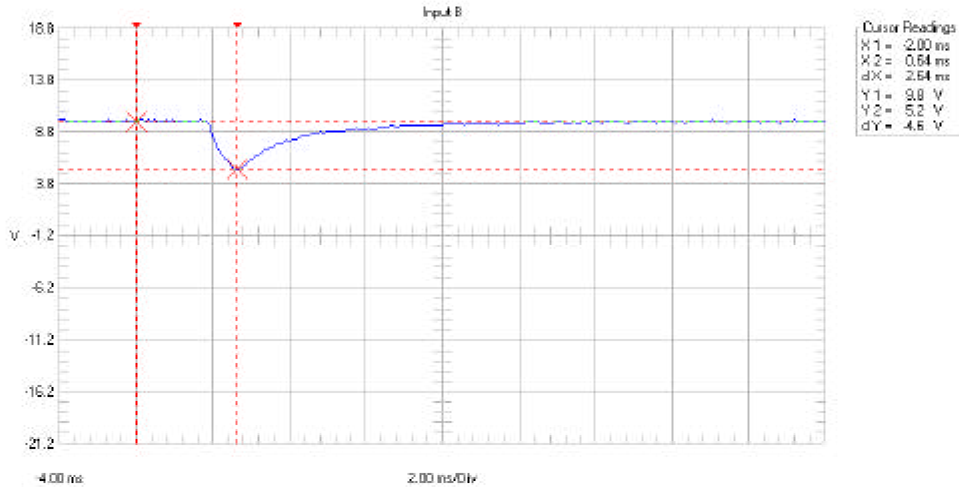


Figure 18a. The Battery Voltage during the LED Test Load for Sample 5500-03

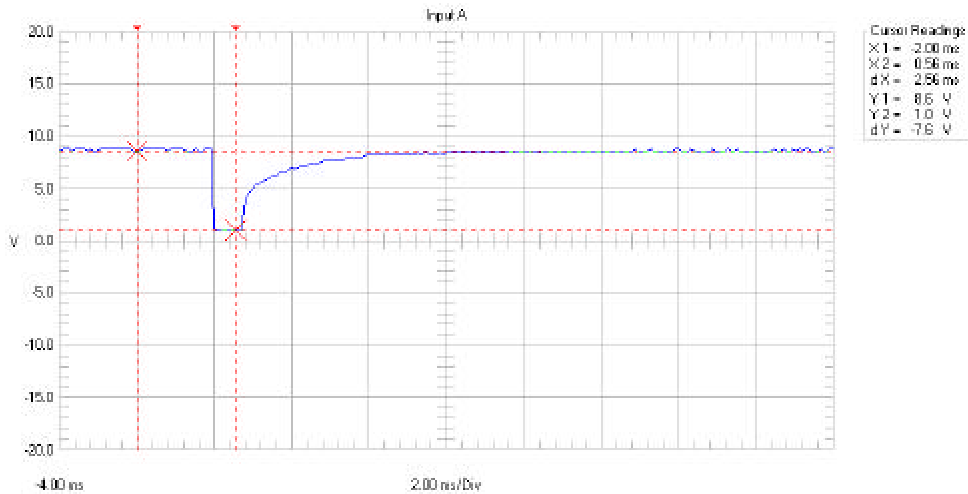


Figure 18b. The LED Test Load Pulse Width for Sample 5500-03

The top of the battery was removed to reveal the cells' contact pads and the contact pins (see Figure 19a and 19b). There were noticeable amounts of white deposits on three of the six contact pins (Figure 19b).

Figure 20 shows a close-up of the contact pins with and without the white deposits. Each cell consists of a positive (mesh) and negative (solid) contact pad. It was also noticed that only the solid contact pads on each cell had a thin film of white deposits. Figure 21 shows a close-up of one of the three solid contact pads with the thin film of white deposits.

A small amount of the white residue was dissolved in concentrated HCl/HNO3 mixture. A very small part of the residue was dissolved. The remainder of the residue floated on the acid solution. A qualitative analysis of acid solution was done by an Inductively Coupled Plasma (ICP) spectrometer. Lithium, iron, nickel and silver metals were used as elemental scanning for the ICP spectrometer. The only metal detected in the acid solution was lithium.

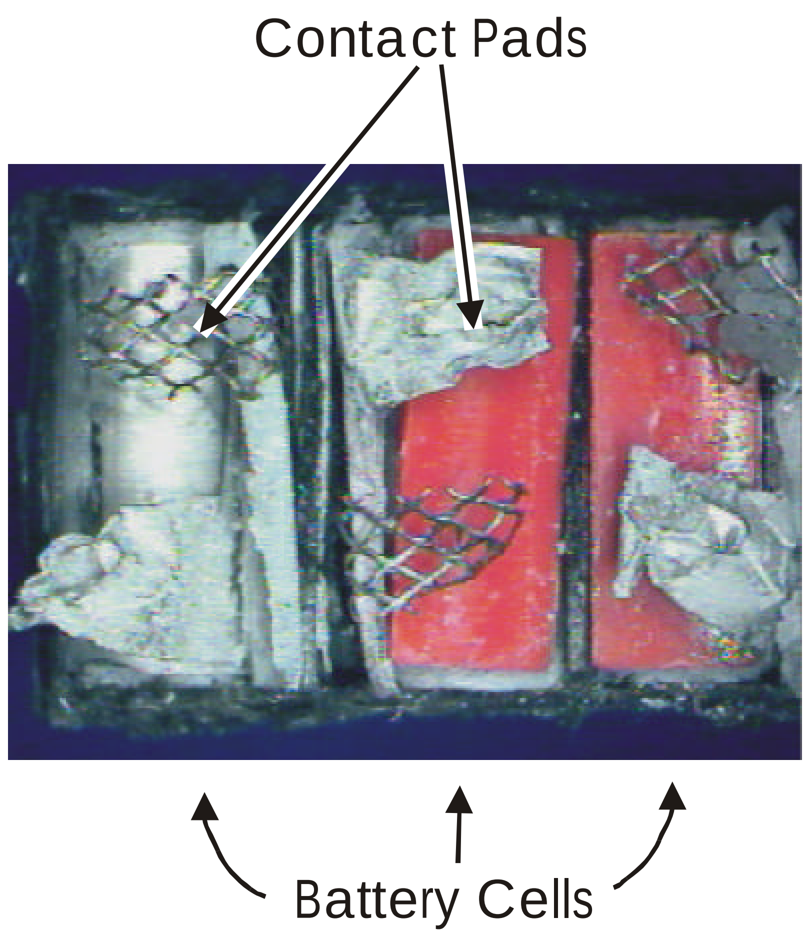


Figure 19a. Battery Cells and Contact Pads

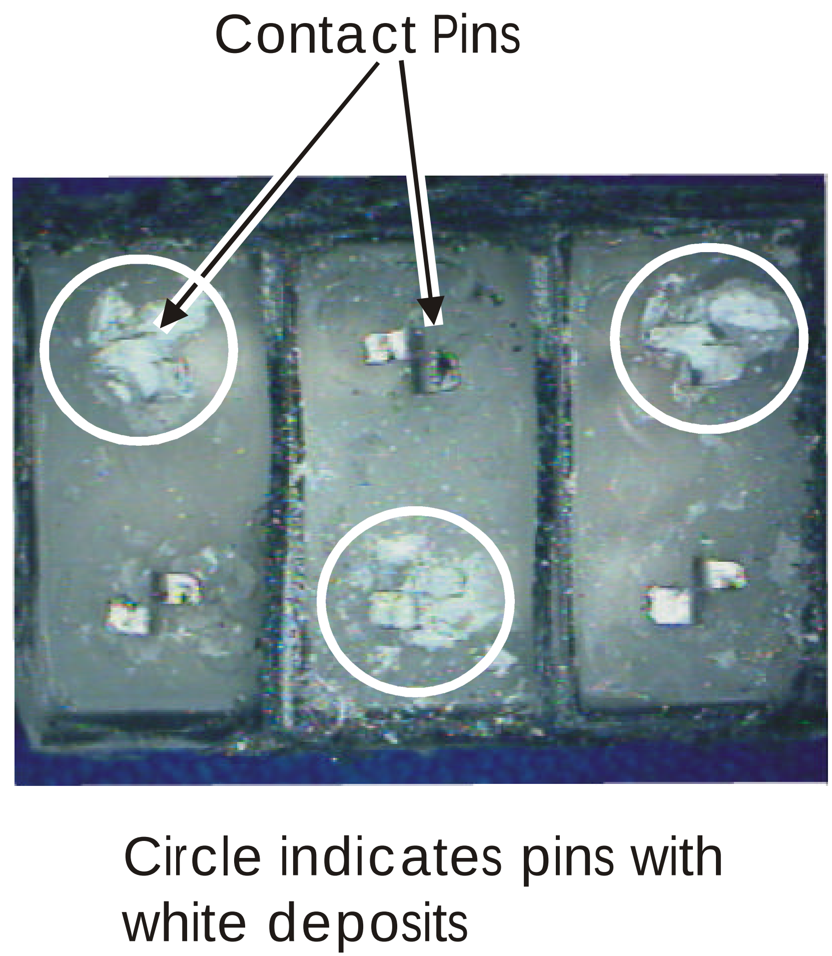
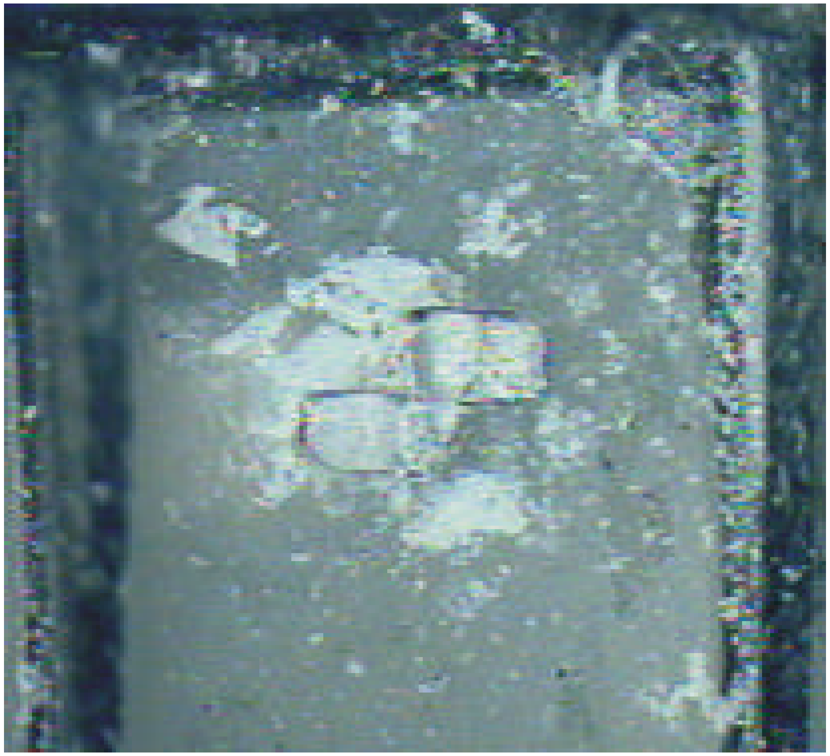


Figure 19b. Contact Pins

Figure 19a and 19b. The Battery cells and Contact Pins for Sample 5500-03

Pin with
White Deposits



Pin without
White Deposits

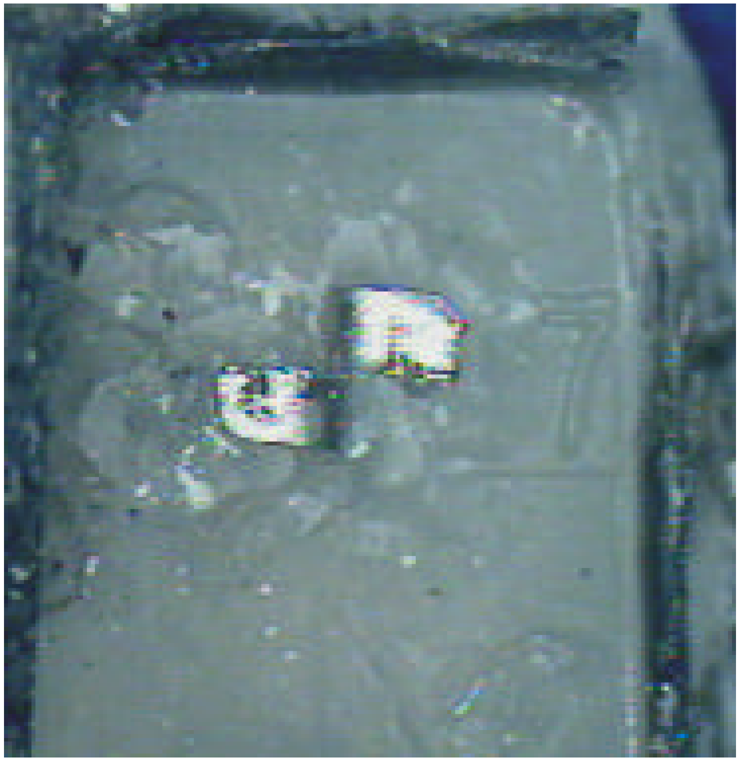


Figure 20. Contact Pins with and without White Deposits

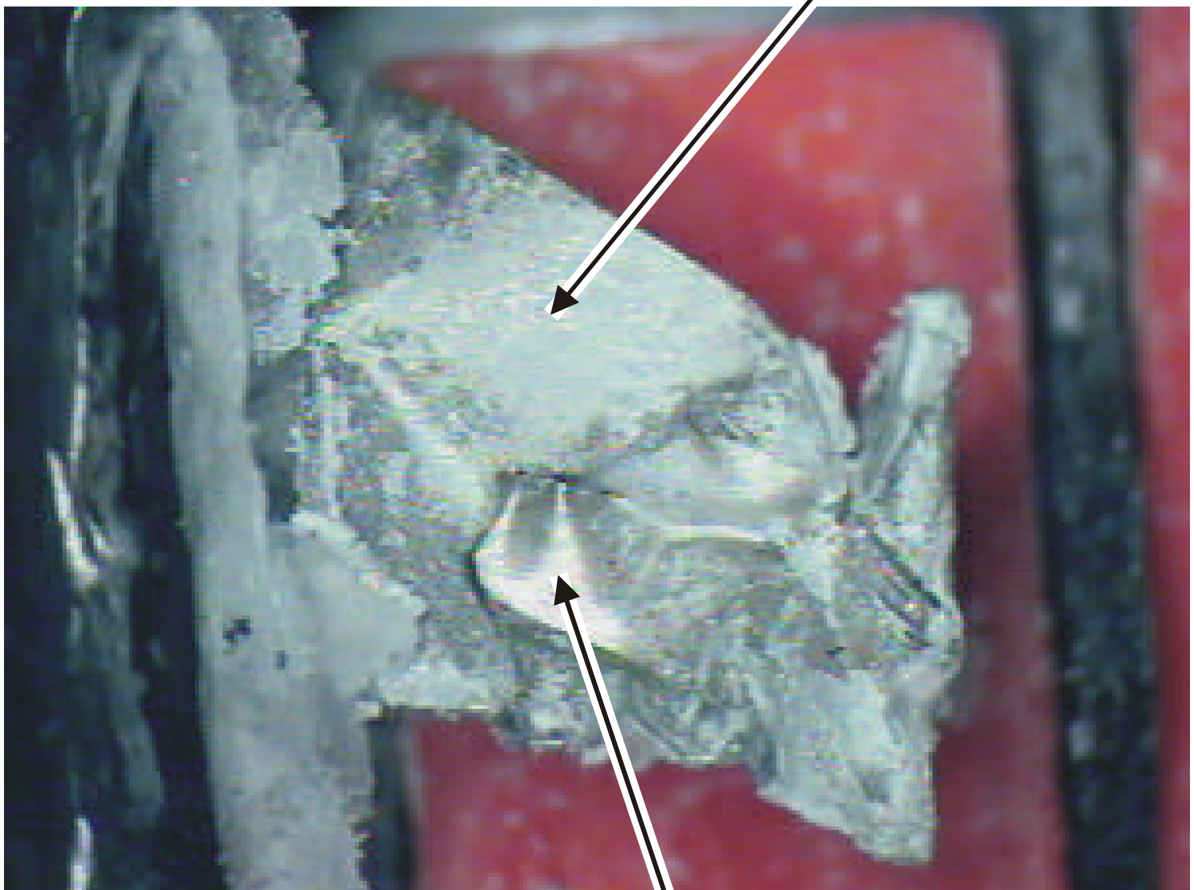


Figure 21. Contact Pad with Thin Film of White Deposit

CONCLUSION

The CPSC staff received from the CDC a number of lithium batteries and 10-year smoke alarms that exhibited premature low-battery signals. Most of the smoke alarms had failed within the first year of use. A technical evaluation was undertaken to determine the cause of the premature low-battery signal. Testing and analysis indicate that failure is associated with the batteries. In summary, CPSC staff noted the following:

- 67 lithium batteries were received and tested. In initial tests,
  - 47 caused a low-battery signal when installed in a test smoke alarm
  - 16 did not cause a low-battery signal when installed in a test smoke alarm
  - Six of the 16 began to cause a low-battery signal when re-tested 9 months later.
- The no-load, open-circuit voltage of a "bad" battery appeared normal; a "bad" battery was only detected under load.
- The cause of premature chirping in the smoke alarms appeared to be related to a higher than expected increase in internal resistance in the batteries.
- For bad batteries, internal resistance appeared to increase over time, even under no-load conditions.
- For batteries exhibiting an increased internal resistance, there were deposits of a white material on the anode contact pads and contact pins of the cells in the batteries.
- The smoke alarm hardware did not appear to be the cause of the premature low-battery signals.
- For the new batteries that were tested, there were no failures that exhibited similar failure mechanisms. One failure appeared to be associated with a shorted cell, as evidenced by the lower open-circuit voltage.