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Reliability and performance of primary lithium batteries for ultrasonic gas meters

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Abstract

BG Technology is evaluating primary batteries for battery powered electronic domestic gas meters. Two meter designs have been developed to date and are in production with over 1 million already installed. Only commercially available batteries have been considered for the application, and the meters have been designed to accommodate either one R20 or two R14 sized cells. This paper looks at the meter/battery specification and its implications for battery design, the available technologies and their basic characteristics, methods of evaluating performance and reliability together with a test programme. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Lithium primary batteries; Applications/electronic equipment; Reliability

1. Introduction

BG Technology is evaluating primary batteries for battery powered electronic domestic gas meters. Two meter designs have been developed to date and are in production with over 1 million already installed. Only commercially available batteries have been considered for the application, and the meters have been designed to accommodate either one R20 or two R14 size cells. The main advantages of the electronic gas meter are that in addition to increased accuracy, the electronic designs add significant functionality in terms of fraud detection, temperature compensation, and providing the facility for remote meter reading. However, the meter is designed to operate as a completely self-contained equipment, so the electrical power supply is an integral component without which the meter will not register gas consumption. Thus, the battery is a key component of the meter design, and its performance and reliability are critical to the overall meter success.

The safety hazard assessments were the first tasks to be undertaken, and the results have been reported [1]. This paper summarises present progress in the identification and evaluation of the electrical performance of candidate cells.

The main objectives for this initial phase of the study are to:

(a) Specify the meter power requirements.
(b) Identify candidate battery technologies and manufacturing sources.
(c) Specify the main design criteria and performance characteristics.
(d) Define the test strategy for evaluating the electrical performances of the battery options.
(e) Design and commission a battery performance test rig.
(f) Carry out initial laboratory evaluations.
(g) Analyse the implications of the test results.

2. Meter power requirements and the battery power specification

2.1. The power requirements of the ultrasonic meter

Two versions of the ultrasonic meter have been developed to date, which have key differences in their power requirements, Meter Type A presenting a main drain of approximately 90 μA and a low voltage threshold or cut-off point of 2.5 V, and Meter Type B having significantly greater values of 200 μA and approximately 3.2 V, respectively. The two meters employ different power management systems and hence, present different load characteristics.

Meter Type A presents a sharply changing load, with phases of high current demand when ultrasonic transducers are firing. These phases represent about 50% of the power

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Table 1
General specification for the ultrasonic meter batteries

Parameter	Meter A	Meter B
Required capacity (A h)	9	12.5
Minimum voltage (V)	2.5	3.2
Peak pulse current (mA)	−5	−8
Background current (μA)	~10	−20
Mean current (μA)	~90	~150
Preferred service life (y)	11	9
Physical size (I.E.C.)	One, R20 or two, R14	One, R20
Cell orientation	Horizontal	Vertical

consumption. One data read through the optical head causes a drain of about 12 mA for about 150 ms.

Meter Type B exhibits a different load characteristic, in that a capacitor charging circuit smooths the current drawn from the battery. A high current drain occurs during the initial stages of the measurement period, followed by a lower drain when the microprocessor is active.

2.2. General specification for the meter battery

The key battery requirements for the two meters are as follows:

(a) Service life greater than 11 years.
(b) Operating voltage at least 2.5 V (Meter Type A); at least 3.2 V (Meter Type B).
(c) Operating temperature range −20°C to +60°C.
(d) One R20 size or two parallel-connected R14 sized cells.
(e) Non-rechargeable, i.e., primary type

Values for the main current and voltage operating parameters for the two designs are given in Table 1. The required service life is over 11 years, although a 15 to 20 year ‘sealed-for-life’ design would be ideal. As can be seen, the two meters have significantly different voltage and power characteristics, and transitions through the two low voltage thresholds are used in this study to define the end-of-life cut-off points in calibrating the effective capacity of test cells.

3. Lithium battery options

Over the past 30 years, technological progress (particularly in the space and military fields) has increased the demand for lightweight, compact electrical power sources. Progress made in battery developments, particularly in resolving safety and reliability problems of mass produced lithium technologies, has made such systems viable for use in long-term residential applications such as utility metering.

A battery system having a high specific energy depends on large differences in the electronegativities of the anode and cathode reactants—lithium possesses the lowest electronegativity of all existing metals and it is the anode material which gives up its electrons most easily to form positive ions [2].

The theoretical specific energy density can be expressed on a volume W_v basis through the relationship:

$$W_v = -\Delta G/\Sigma_v$$

where ΔG is the Gibbs free energy for the reaction and Σ_v is the sum of the volume of reactants (based on the number of moles of each reactant involved in the overall process). The thermodynamic reversible cell potential E is related to the Gibbs free energy change ΔG by the equation:

$$E = -\Delta G/nF$$

where n is the number of electrons involved in the reaction, and F is the Faraday constant. Gabano [2] lists the theoretical energy densities and reversible cell potential (E) of a range of lithium battery systems—but for the two meters only couples having $E > 2.5$ V or 3.2 V are of interest. Lithium primary cells possess several advantages over conventional batteries that makes them ideal for use in the present meter application, namely:

(a) High voltage.
(b) High energy density.
(c) Operation over a wide temperature range.
(d) Good power density.
(e) Flat discharge characteristic (constant voltage and impedance during most of the discharge).
(f) Excellent shelf life.

In practice, commercial considerations (normally the cost of refining the cathode material and safety) limit the option available for use in mass produced lithium battery technologies. In addition, the volumetric limitation (maximum equivalent battery size of one R20 size of cell), and the high voltage requirements restrict the practical range of primary battery options to lithium thionyl chloride ($LiSOCl_2$), lithium polycarbon monofluoride ($Li/(CF)_x$, and lithium manganese dioxide (Li/MnO_2).

4. Experimental

4.1. Experimental aims

The main aim of this phase of the test programme was to obtain voltage/time discharge curves for the range of batteries under review. The aims were to:

(a) Establish a reference database of battery performance in terms of individual battery designs and for the different electrochemical technologies.
(b) Quantify the repeatability of the cells under identical operating conditions and hence, investigate the quality of the battery manufacturing process.

4.2. Laboratory test programme

The initial aims of the battery tests in the laboratory are to determine the maximum achievable capacity under constant resistive load, and to determine the effect on voltage of a temperature cycling regime which is representative of the range of UK diurnal and seasonal atmospheric fluctuations. Test cells of selected battery types are discharged in batches of 10 under five temperature regimes; a temperature cycle (−20°C to +40°C, 72 h cycle period), −20, 0, room temperature and +40°C, under different loads (100, 200, and 560 Ω), to determine available capacity (A h), and the voltage/temperature relationship. Voltages are logged at 60 s intervals to give good time resolution during transient events.

Battery failure in this application occurs when the voltage falls below the respective ‘low voltage thresholds’ of 3.2 V (Meter Type B) and 2.5 V (Meter Type A) under the meter load. Ideally, battery selection should be based on measurements of performance and reliability to these criteria.

4.3. The performance test rig

A purpose-designed battery performance test rig and data acquisition (DAQ) and control software system has been built and is operating satisfactorily. The DAQ, control and processing tasks are carried out by two dedicated PCs, which are connected via Ethemet cards to form a Local Area Network (LAN), to enable transfer of data between the two. The first PC controls and executes the DAQ tasks, and the second one performs the data processing and analysis. The DAQ, control and processing tasks are controlled by a suite of three purpose-designed software modules (Data Acquisition and Control, Data Processing and Test Configuration Database), that was written to a BG Technology specification. These all ran under Microsoft Windows, allowing multi-tasking, and full compatibility with other utilities which perform concurrently scheduled tasks.

Temperature control of the test batteries is by means of two environmental cabinets (−20 to 40°C, and −20°C), a freezer (0°C) and an oven (40°C). The environmental chamber temperature is measured by means of a platinum resistance thermometer (PRT) which senses temperature in the geometric centre of the test chamber and the others by using a K-type thermocouple.

The test battery and thermocouple voltages are measured by means of a purpose designed 1024 channel multiplexer (Anville Instruments) which incorporates a 16 bit analogue to digital voltage converter giving a resolution of 150 μV on the voltage measurement. The multiplexer is connected to the data acquisition and control PC via an RS232 interface. The system is programmed to log voltage from each of the 1024 channels at 60 s intervals.

The raw data is transferred at 24 h intervals to the second PC. Preliminary processing of the raw data generated during battery discharge tests is executed by an Analysis Programme which runs continuously under Microsoft Windows, and which performs scheduled data processing and system housekeeping tasks.

The resistance of the connections and wiring was measured to ensure that no extraneous voltage effects were present.

4.4. Selection of batteries

At an early stage, two manufacturers of $Li/SOCl_2$ cells, cells A and B, and one $Li/(CF)_x$ manufacturer, expressed keen interest in the application, appeared to offer mature designs of good manufacturing quality. On the basis of acceptable safety performance, cells from these manufacturers were utilised in production meters.

5. Results and discussion

5.1. The effect of battery temperature on discharge performance

To evaluate the battery service life against the actual meter load would require at least 11 years, which is obviously impractical, although long-term discharge tests are in progress. It is normal in these circumstances to utilise accelerated regimes and extrapolate/interpolate the data and calculate the service life at the actual lower discharge rate of the application.

Account has to be taken of increased efficiencies at lower rates of discharge and also of self-discharge losses over the extended real-time period.

To date, the analysis of results, which is in progress, has focused on the two types of $Li/SOCl_2$ cell, and one $Li/(CF)_x$ which are the main power sources used so far in the ultrasonic gas meters that are now in production.

The discharge capacities of the test batteries are measured when the voltage falls to 2.5 V; as for this study, battery failure has been defined as the point at which the voltage falls below 2.5 V.

In these discharge tests, the batteries are normally discharged to 0 V, to ensure that the all electrochemical reactivity has ceased, and to characterise fully the ‘end-of-life’ behaviour.

The discharge curves for cells at room temperature under a resistive load of 100 Ω are shown in Fig. 1. In general, the discharge curves for the test cells are very repeatable, and follow similar voltage/temperature trends. However, some tests indicate that a few cells failed prematurely. The premature failures are characterised by the onset of a large voltage drop. In certain cases, the cells recover (without any known external influence) to operate

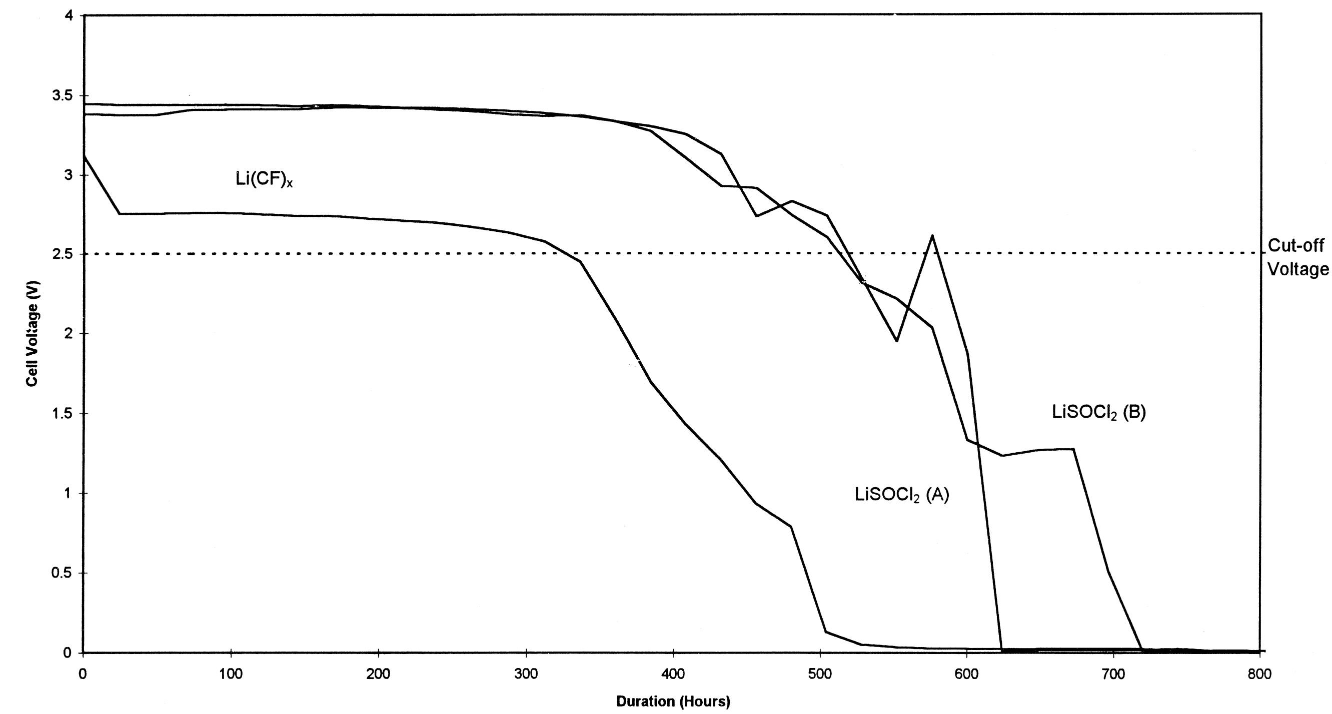

Fig. 1. Room temperature performance of lithium cells when discharged into 100 Ω to 0 V.

in a more or less predictable manner. Unlike the spiky voltage profiles observed for the Li/$SOCI_2$ cells, the discharge profile for Li/$(CF)_x$ is smooth and no recovery occurs.

From the current test results, the lithium thionyl chloride operates well over a relatively wide range of temperatures. The voltage stays above 2.5 V for over 80% of the entire life of a cell under a 100 Ω load. The cells discharged at −20°C under 100 Ω failed at approximately 300 h and delivered an average of 11 A h before end-of-life. The relative performances of all cells decreased as the temperature is decreased.

Chemical reactions, in general, tend to occur more rapidly as the temperature is increased, and more slowly as it is decreased. The conductivity of an electrolyte varies similarly with temperature. Therefore, batteries tend to perform better at higher temperatures, and worse at lower temperatures. Of course, there are limits to the temperature range in which batteries can be used, owing to such factors as boiling or freezing of electrolyte, stability of the battery components, etc.

Table 2
Capacities (A h) of test batteries when discharged at room temperature into 100 Ω, to an end voltage of 2.5 V

	Available capacity (A h)		
	Li/$(CF)_x$	Li/$SOCl_2$, (type A)	Li/$SOCI_2$ (type B)
Minimun	8.26	13.76	18.13
Maximum	9.65	16.54	18.96
Mean	9.02	15.02	18.78
Standard deviation	0.59	2.23	0.26

5.2. The effect of battery temperature on available capacity

Table 2 shows the comparison of cell capacity at room temperature under a 100 Ω load. The capacity parameters given in Table 2 show that the Li/$SOCl_2$ cells, types A and B achieve a mean capacity of 15.02 and 18.78 A h, with standard deviations of 2.23 and 0.26 A h, respectively.

From the test results, the lithium/thionyl chloride cells types A and B, when discharged at −20°C, deliver approximately 60% of their room temperature capacity. Cell discharged at 40°C deliver approximately 90% of their room temperature capacity. At room temperature, cells A and B deliver a maximum capacity of 16.5 A h and 18.9 A h, respectively. All the above capacities were calculated to 2.5 V cut-off.

6. Summary

Tests have been carried out on two types of Li/$SOCl_2$, and one Li/$(CF)_x$ cell under various temperature and constant resistive load conditions to determine the capacity in each. The results were analysed to an end-point voltage of 2.5 V. The distributions of performance parameters as a function of constant resistive load, state of discharge, and temperature, have been established. The analysed results have provided a unique data set of voltage/temperature relationships and capacity.

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