A CAPACITY RATING SYSTEM FOR CARDIAC PACEMAKER BATTERIES

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Summary

This paper considers the special problems of making accurate capacity projections for cardiac pacemaker batteries. It describes a systematic approach for making accurate capacity projections in a reasonable time. A necessary set of definitions is developed and illustrated by examples based on Li/I_2 battery chemistry.

Introduction

The purpose of any electrical power source or battery is to provide electrical current within certain voltage limits in order to operate some device. Once a battery with adequate current and voltage capability is selected, one generally needs to know how long it will last in the given application. The answer to this question lies in the battery's electrochemical size or capacity. Capacity is defined as the quantity of charge the battery is capable of delivering under a given set of conditions. Though the physical unit of charge is the coulomb, the charge delivered by a battery is usually expressed in units of ampere-hours (A h) or milliampere-hours (mA h), as these units can be readily related to the battery's primary function, *i.e.*, supplying current over some interval of time.

No matter how capacity is expressed, it is apparent there should be a single number that characterizes a battery's electrochemical size for any specific application. In many battery applications this is not a problem because the battery capacity can be measured under conditions which are exactly like those of the application. However, the problem to be considered in the present paper is the determination of this number for long operating times. For example, primary batteries for pacemakers take 5 - 10 years to complete discharge whereas practical considerations demand numerical values in a much shorter period of time.

Obviously, the physical size of a battery is not a reliable indicator of its electrochemical size since the internal chemistry and the efficiency of the design can vary immensely from one battery type or model to another. Recent reviews of data by Owens and Fester [1] and Hermann and Luksha [2] focus on the diversity of commercially available long-lived power sources. Parsonnet [3] has also reviewed currently available batteries for cardiac pacemakers. In reading this literature one becomes aware of the need for capacity numbers that are true or at least comparable indicators of anticipated performance for each type and model. One reason for this need is that capacity values serve as guides for the selection of a power source and are also used to project the operating time of the device.

As charge is drawn from a battery, its voltage eventually decreases to a level where it will no longer drive sufficient current to the device it powers. The battery is then considered depleted and the charge delivered up to that time is referred to as the capacity for that particular application. A depleted battery is generally not incapable of delivering current, but merely incapable of delivering the amount of current needed at the operating voltage of the device it powers. Thus, the current and voltage requirements of the device, as well as the battery design, determine where in the battery's life depletion will occur.

Ideally, the capacity of a battery in a given application can be determined by discharging a statistically significant number of batteries under application conditions and measuring the total amount of charge delivered by each one prior to depletion. Since such real-time testing is not practical for very long-lived batteries and it is not practical to test batteries at all possible discharge conditions, it becomes a challenge to develop a method to project accurate capacity values for new battery designs as early as possible in the development cycle using a limited amount of data. The projection must be accurate, especially in the case of the cardiac pacemaker, where the battery is a key component that limits the maximum operating time [4].

A single cell lithium–iodine battery will be used to illustrate this discussion. We will consider calculations based on battery chemistry, electrical discharge testing by several techniques, and mathematical modeling. Some of the testing techniques have been described by Owens and Untereker [6] and the reader is referred to that paper for a detailed description of the methods. The model cell is a lithium–iodine battery having parallel electrodes 7 cm^2 in area. It is comprised of: (1) anode current collector, (2) lithium anode, (3) layer of lithium iodide solid electrolyte, (4) cathode composed of iodine and poly-2-vinyl-pyridine (P2VP), and (5) cathode current collector. The two current collectors of corrosion resistant metal serve as electrical contacts to the anode and cathode. The P2VP in the cathode serves to increase cathode conductance through the formation of several chemical species [7]. A lithium iodide layer forms as the product of the battery discharge reaction, i.e., $Li + 1/2 I_2 \rightarrow LiI$. It serves as a separator, but one which increases in thickness as the battery is discharged.

Rate and time dependent processes

A variety of processes can take place within a battery during its operation. Those of primary interest are reactions which produce new compounds from the original reactants. Other, potentially important, processes include changes of state, morphology, or distribution of reactants and products, the internal conduction of current and the formation of concentration gradients. All of these processes acting together determine the capacity of a battery under any given set of conditions.

In every battery some processes proceed at a rate proportional to the rate at which the battery delivers charge to the load, *i.e.*, the current drain. In the lithium−iodine battery, for instance, the rates of the two electrode reactions, $Li \rightarrow Li^+ + e^-$ and $I_2 + 2e^- \rightarrow 2I^-$, are directly proportional to the current, and thus the rate of accumulation of discharge product is also proportional to the current. Polarization or internal voltage loss associated with current flow through the battery is also proportional to current. All these processes are classified as rate dependent. A battery in which all processes were only rate dependent would be relatively easy to model and would exhibit an infinite shelf life at zero drain.

Unfortunately, in every battery some processes go forward even when the drain is zero. It is these time-dependent processes that shorten the useful life of the battery. Time-dependent reactions which utilize some of the active battery materials are referred to as self-discharge reactions. Loss of reactants to the self-discharge process is directly equivalent to a loss of capacity. Self-discharge reactions may also decrease useful capacity by increasing internal resistance beyond that which would result from the discharge process alone, or by corrosively attacking parts of the battery structure. In general, time-dependent processes are more difficult to characterize and quantify than rate-dependent processes. To make matters more complicated, many processes, such as self-discharge in the lithium−iodine system, depend upon both rate and time in some complex fashion. The practical importance of any time-dependent process depends not only upon its rate but upon the sum of the expected storage life and service life of the battery. Thus, it becomes necessary to measure very low rate self-discharge processes if one is accurately to estimate the losses in a battery expected to have a decade of service life. Methods to determine self-discharge rates have been designed around the techniques of analytical chemistry, electrical discharge testing and microcalorimetry. Some specifics of these will be discussed later.

Capacity evolution

The process for determining the capacity of a long-lived battery is a progression of logical steps along an appropriate time frame. This sequence of events generates a series of capacity numbers which converge to the real application capacity. A typical time-table is given in Table 1. The

TABLE 1

Times involved for capacity determination

Capacity type	Typical elapsed time
Formal capacity	Hours (if chemistry known)
Operational capacity	One to two years
Projected capacity	Several months after operational capacities

development process proceeds through three levels which we classify by origin and characterize by listing the time required for completion. We will first consider the major characteristics of each capacity type and then consider some specific examples within each type.

The *formal capacity* values are theoretical capacities calculated by applying the formalisms of chemistry to the active materials initially placed in the battery. A formal capacity can be determined without ever constructing a battery. Since the applicable formalisms of stoichiometry and thermodynamics do not deal with rates, and usually focus only on the current yielding reaction, formal capacities do not consider real operating conditions. They represent the theoretical upper limit of battery capacity. However, formal capacities are unambiguous and represent a convenient starting point for developing capacity *vs* size relationships, though they are of limited use for comparing batteries.

The second grouping, *operational capacities,* are numbers derived directly from battery discharge data and represent demonstrated performance. Since discharge experiments can be performed with an infinite number of variations, it is necessary to specify exactly the conditions under which any operational capacity was obtained. For many battery types the operational capacity can be quickly measured in real time under conditions closely approximating the application conditions, thus providing an accurate application capacity value. The remaining problem for these batteries may be to determine how shelf life and storage conditions affect the capacity value. The solution of this problem completes the capacity rating process for such batteries.

Projected capacities, comprising the third grouping of capacity ratings, are required for batteries which cannot be readily depleted in real time. All projected capacities are derived from some data combined with a model of the battery and represent an extrapolation from known performance to future performance. The model may be as simple as the assumption that there is a 1:1 correspondence between a capacity measured at high discharge rate and the capacity available at the lower application rate. The projection may also be based on a technique using numerical or graphical extrapolation from a data base of operational capacities. A complex set of equations based on an understanding of the physics and chemistry of the battery may also be the model.

The accuracy of a projection depends primarily on the precision and accuracy of the data, and the completeness of the model. A description of these three quantities is necessary in order completely to qualify any projected capacity value. Several broad categories of projections are discussed in the next Section.

Now, Table 1 can be viewed as a simple flow diagram representing the steps leading to an accurate assessment of capacity for a long-lived battery. Each step represents an increase in the state of knowledge of the battery performance. If the details, as described below, have been well handled, the capacity eventually realized in field applications will emerge as the value projected by this system.

We have assumed throughout that the reliability of our battery system is high, meaning that the capacity limiting process or processes are always the same in supposedly identical batteries. But capacity might at some point be limited by the loss of reliability, *i.e.*, intervention of some unforeseen failure mode. Such a possibility seems remote for the solid-state, lithium–iodine system with its established performance record, but reliability can be a performance limiting factor with new battery designs. Thus, in the development cycle, several iterations through this capacity rating system may take place while manufacturing and design engineers maximize battery reliability.

Definitions

The terms formal, operational, and projected capacity are not common usage, but do serve to organize our understanding of the capacity rating process. In this Section we define, discuss, and illustrate the specifics of an adequate approach to developing capacity ratings.

Stoichiometric capacity
Two formal capacity ratings are useful in discussing lithium–iodine batteries. The stoichiometric capacity of a battery is the quantity of charge it contains calculated from the weight of reactant incorporated into the battery. Faraday's Laws are used to calculate the capacity. The stoichiometric battery capacity is equal to the stoichiometric capacity of the limiting electrode. The chemistry must be known well enough that the stoichiometric equivalence can be obtained from the chemical equations for the discharge reaction. The stoichiometric capacity is the theoretical upper limit of battery capacity. It is generally not a deliverable capacity because not all of the reactant is normally available for electrochemical reaction. Since stoichiometric capacity ratings do not address the issue of deliverability, there is no need to specify application conditions with this rating.

A stoichiometric capacity can be calculated for each of the battery electrodes. If the two values are not equal, the battery is said to be limited by the electrode with the smaller value. Presently lithium–iodine cardiac

pacemaker batteries are designed to be cathode limited. As an example, consider the stoichiometric capacity of a cathode limited battery containing 2.37 g of I_2. Since the lithium–iodine reaction produces 0.211 A h per gram of I_2, the stoichiometric capacity is 0.500 A h.

Maximum available capacity

A second formal capacity is the maximum available capacity. This is the amount of deliverable charge a battery contains at time zero. It is the amount left after the stoichiometric capacity has been adjusted for any initial loss of reactant availability predictable from knowledge of the battery chemistry. This value is the practical upper limit of capacity available at time zero. The maximum available capacity does not have application conditions attached to it. Although it denotes a deliverable charge, not all of the charge may be deliverable at a useful voltage.

Brennen and Untereker [7] have discussed calculation of the maximum available capacity in the lithium–iodine system. Two processes which take place during preparation of the I_2/P2VP cathode bind iodine in such a form that it is not available for electrochemical discharge. The first process is the formation of a one-to-one mole ratio charge transfer adduct between iodine and the polymeric pyridine. This process seems to be essential to good battery performance, but removes a mole of iodine from the available I_2 supply for every mole of pyridine nitrogen in the cathode.

Additional iodine is lost to the iodination of the α-carbon on the P2VP, a reaction which takes place during the preparation of the cathode depolarizer. The results of analyses show that this reaction and the adduct formation account for the loss of about 1.5 moles of I_2 for each mole of pyridine nitrogen in the cathode. The cathode in our example was prepared with a 6.2:1 mole ratio of iodine to polymer. Down to a 1.5:1 mole ratio of I_2 to P2VP, the maximum available capacity is 0.37 A h or 74% of the stoichiometric capacity.

Formal capacities can be obtained quickly and are guidelines in the design process, but capacity losses associated with self-discharge and with the irreversible transport phenomena of current flow and diffusion must be determined experimentally. The operational capacities defined below encompass these effects and form a data base from which application capacities can be projected.

Rated capacity

The term rated capacity is defined as the capacity of a battery discharged at a specified set of conditions. These include the temperature, the discharge mode (constant current or constant load), the discharge rate, and the cutoff voltage. Rated capacities are usually measured under fixed conditions. If these approximate the application conditions, the capacity obtained is the *rated application capacity*.

Rated capacity values are a function of current for two reasons. First, the internal voltage loss or polarization at any given depth of discharge in-

creases monotonically with the current. This results in a systematic loss of capacity with increasing discharge current. As an example, the rated capacity of our typical battery to a 2-volt cutoff at 37 °C is 0.27 A h when it is discharged at a constant current density of 3.6 μA/cm^2. When the current density is doubled, the loss due to polarization increases and the rated capacity becomes 0.25 A h. When the drain is increased by a further factor of 2.5, the effects of increased polarization cause the capacity to fall to 0.22 A h.

Secondly, the effect of self-discharge on capacity is just the opposite of the polarization effect. This is a consequence of the fact that a longer time is required to discharge the battery at low drain rates, which allows the self-discharge processes a longer time to consume reactants and thus reduce capacity.

Accelerated application capacity

The accelerated application capacity is the capacity delivered when a battery is discharged at a rate or sequence of rates higher than the application rate, but is returned to the application rate for determination of the cutoff point. The underlying intent in using this technique is to discharge the battery as rapidly as possible to save time, and then to determine the point of depletion under polarization conditions almost identical with those at application drain. Two techniques are commonly used to determine accelerated application capacity. In the first, current is decreased stepwise one or more times during a test. The final step reduces the current to application drain while the battery attains the cutoff voltage. An alternative involves periodically returning the battery to application drain during a high rate discharge test. The battery is left on application drain just long enough to ascertain its steady-state voltage before it is returned to the high discharge rate. A series of points obtained this way defines a discharge curve from which an accelerated application capacity can be obtained.

Use of accelerated rates does decrease the amount of time required to deplete a battery but it also decreases the time available for self-discharge and parasitic reactions to consume battery reactants. Hence, an accelerated application capacity will generally be larger than the true application capacity. The size of the difference will be a function of the self-discharge rate of the battery and the details of the discharge scheme.

When our illustrative battery is discharged initially at 18 μA/cm^2 and then returned to 1 μA/cm^2 to determine the depletion point, the capacity is found to be 0.36 A h. The capacity for the same cell discharged at 1 μA/cm^2 from beginning of life is 0.34 A h. The difference between these two values is the increased self-discharge loss in the longer term test.

While high rate operational capacities can approximate application capacities for the lithium–iodine system, more accurate approximations can usually be obtained from the projection schemes discussed below.

Projected application capacity from accelerated testing
    A projected application capacity from accelerated testing can be obtained from high rate discharge data. A series of rated capacities from identical batteries discharged at various rates reflects a systematic dependence on discharge rate for reasons discussed above. Such data may be extrapolated graphically or numerically to the application rate. A capacity projected this way can be quite accurate since self-discharge and polarization effects are included in the data and, hence, in the extrapolation.

Projected capacity on pacemaker circuit
    The projected capacity on pacemaker circuit is a specialized definition. It is a value projected from a computer simulation of the entire pacemaker system. The major system components to be modeled are the patient load, the electronic circuitry and the battery. The result of this modeling is an estimation of the amount of charge actually drawn from the battery prior to depletion in a real pacing situation. The battery model derived from accelerated testing can be used in this projection. However, the load drawn by a pacemaker is more complex than the simple load conditions used to derive data for the accelerated test model, and so the projected capacity on pacemaker circuit will generally be different from the projected capacity from accelerated testing. A detailed discussion of this type of modeling for a constant energy output pacemaker was given by Gerrard *et al.* at the 1977 NBS Pacemaker Workshop [8].

Projected application capacity from other designs
    The capacity for a new battery design can often be calculated from the capacity of a similar, but well characterized, battery by applying adjustment factors indicative of the geometric and chemical differences between the two battery designs. The accuracy of the projection may depend upon factors which are not fully understood, so it is generally highest when the two designs are very similar. This method is usually used when no other method is available or when the effect of a design change is obvious. Whenever this technique is used, the level of confidence in the source capacity should be indicated, along with any underlying assumptions.

Projected application capacity from physical models
    Capacities can be estimated from physicochemical models derived from a detailed study of the individual processes within a battery. Modeling of these processes, *i.e.*, self-discharge and polarization, requires an extensive effort, but can lead to an understanding which allows one quickly and accurately to project the capacity of any new design. Self-discharge has been characterized for some lithium—iodine batteries using the technique of microcalorimetry [9]. Studies have also been made of the relationship between cathode composition and resistance, the chief cause of polarization in these systems [10]. A recent paper has discussed the modeling of lithium—iodine batteries from discharge and self-discharge (microcalorimetric) data
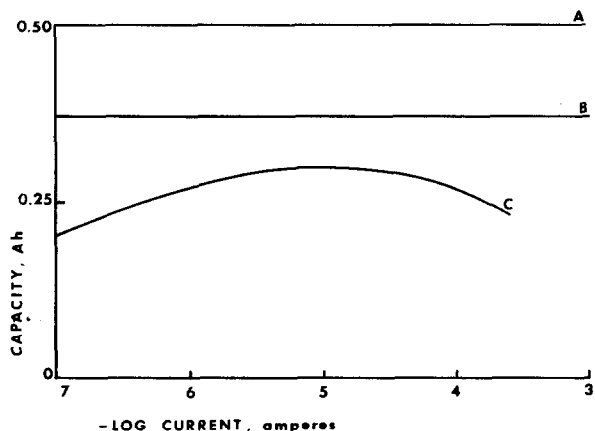
Fig. 1. Battery capacity as a function of current drain. (A) stoichiometric capacity based on Li + $1/2I_2$ = LiI; (B) maximum available capacity based on known I_2 losses to P2VP; (C) projected capacity from a model incorporating discharge and self-discharge data.

[11]. The model treats self-discharge as a reactant consuming current in parallel with the load current. Application of the model to our illustrative battery yielded the curve of Fig. 1 which plots deliverable capacity to a 2-volt cutoff as a function of constant current drain. The curve shows a broad peak in the region of 1 $\mu A/cm^2$. To the left of the peak self-discharge predominates as the capacity limiting process. To the right of the peak polarization is the chief capacity limiting process. Both the location of this peak and its shape can be shifted by changes in battery chemistry and battery design. As understanding of the lithium–iodine system improves, more complete and accurate physicochemical models will appear.

Conclusion

Development of accurate capacity ratings for the long-lived cardiac pacemaker batteries of today begins with calculations based upon battery composition and size, proceeds through the collection of accelerated data, and concludes with a projection based upon the data and some model of the battery. Thus, in a high reliability system such as lithium–iodine, accurate capacity values are generated long before batteries become depleted under application conditions.

Table 2 summarizes, in chronological order, the sequence of capacity values for the prototype Li/I_2 battery.

At various stages of a battery's development only some of the values listed in Table 2 may be known. These values cover a wide range, hence it is important to realize that the different values may all be correct, but yet not all yield the ultimately desired information relating to how long the battery will perform in the application.

TABLE 2

Capacity type	Value at 37 °C (A h)
Stoichiometric	0.50
Maximum available (to 1.5:1 mole ratio)	0.37
Rated at 18 $\mu A/cm^2$	0.22*
Accelerated application 18 → 1 $\mu A/cm^2$	0.36*
Rated at 7.1 $\mu A/cm^2$	0.25*
Rated at 3.6 $\mu A/cm^2$	0.27*
Graphically projected for 1 $\mu A/cm^2$	0.34*

*2.0 volt cutoff.

Meaningful definitions are available accurately to describe the various capacity ratings generated. While the various capacity ratings for the same battery are not identical, they are all equally valid as long as the conditions associated with each measurement or derivation are completely specified.

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