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Extract from the 'Case of the Burnt Buttocks' expert-witness report.

TECHNOLOGY OVERVIEW

In conventional usage, an electrical 'cell' is a discrete physical entity which uses an internal chemical reaction to generate an electromotive force (EMF) measured in volts (V). In lay terms a 'cell' can be considered capable of generating a 'voltage' which when applied to an external circuit causes an electrical 'current' to flow. Current is measured in units known as amperes (A) although the ampere is rather a large unit for electronic circuits and it is common practice to subdivide it into a unit known as the 'milliampere' (mA), which is one-thousandth of an ampere. One possible definition of the science of electronics is the generation and control of the current flowing in various parts of a circuit or apparatus in order to perform or carry out some useful function.

All electrical cells work on a similar broad principle, which is the chemical reactions between a positive electrode and a negative electrode immersed in an electrically conducting fluid called the *electrolyte*. There are two main types of cell, usually referred to as *primary* and *secondary*. The type of cell intended for use in the Device is a primary cell. A primary cell is intended to be used to supply electrical energy until its internal chemical reaction is exhausted, but it cannot be successfully recharged from an external electrical source. A secondary cell is designed and intended to be so recharged and makes use of different internal chemical reactions which can be reversed, restoring the original EMF and capacity of the cell when it is fully charged. The secondary cell is therefore capable of being re-used through repeated charge-discharge cycles. Common examples of secondary cells are those used in vehicle batteries and the batteries used in mobile telephones.

All the internationally agreed standard characteristics of primary cells are set out in a document published by the International Electrotechnical Commission and known as IEC 60086. At the time of preparation of this report the current version of IEC 60086 was Edition 9 dated November 2000 and all references to it in what follows are to this. Part 1 of IEC 60086 (referred to as IEC 60086-1) refers to the general characteristics of primary cells. Part 5 (IEC 60086-5) refers to the safety of cells with aqueous electrolyte, such as manganese-alkaline cells. As with all IEC documents, IEC 60086 is a series of recommendations for international use.

There are many types of primary and secondary cells, but the majority of them have in common the fact that they generate EMFs of between 1·2 and 1·6V. The Cell used in the Device is an example of a very common type of primary cell which is known as an *alkaline manganese dioxide* or *manganese-alkaline* type. These are readily available almost everywhere in the world under several brand names and in a wide variety of sizes. It can be safely assumed that the physical size of a manganese-alkaline cell is a good approximation of its *capacity*, i.e. its ability to supply the required voltage and current to the equipment for a period of time. Capacity is conventionally expressed in ampere-hours or milliampere-hours. Larger cells have higher capacities than smaller cells using the same technology. A standardized letter system is applied to commonly used cells and batteries and indicates their physical size. For example, an 'AAA' cell has dimensions of 44·5mm in length and 10·5mm in diameter, irrespective of manufacturer. An 'AA' cell is 50·5mm in length and 14·5mm in diameter. The Cell used in the Device is a 'D' cell, whose dimensions are 61·5mm in length and 34·2mm in diameter. All manganese-alkaline cells have nominal working voltages of 1·5 although the actual voltage measured at the terminals of the cell is a function of how long it has been in storage, the ambient temperature and the amount of current drawn from it.

Since higher voltages than 1·5 are often required for the operation of electronic equipment, it is common practice for a number of cells to be combined to form a *battery*. The combination can either be carried out by the user physically and electrically connecting a number of separate cells together (as in the Device) or by the manufacturer combining a number of cells in a common enclosure. In both cases the consequence is that the voltages of the combined cells are added together to produce the required voltage. For example, the Device uses a combination of eight separate cells to form a battery whose voltage is (8 x 1·5) or 12V. Many other consumer-electronic products use a single 9V battery consisting of six 1·5V cells electrically connected together and combined in a single package. It is important to note the difference between a cell and a battery since the terms are often used interchangeably by non-specialists and a degree of confusion can result.

The brand of cell used in the Device is a 'Duracell' and eight D-size Duracells formed the 12V battery used in the Device. Duracell is one of the most common brands of manganese-alkaline cells and the brand name is applied to many different cells and batteries. As with all manganese-alkaline cells, the Duracell employs a combination of three main substances in its construction. The case of the cell is made from *zinc*, a common metal, which also forms the negative electrode. The positive electrode is manufactured from the chemical compound *manganese dioxide*. In between the case and the cathode is the electrolyte, which consists of the chemical compound *potassium hydroxide*. This latter is strongly alkaline in nature, hence the use of the word 'alkaline' in the name 'manganese-alkaline'. To improve its electrical conductivity, a small amount of *nickel* is added to the electrolyte. The EMF of a fresh (i.e. unused) Duracell is between 1·5 and 1·6V. It is characteristic of such cells that their EMF declines only slightly during use, and only drops markedly when the cell is almost exhausted. If a fresh or partly-used manganese-alkaline cell is stored and without being used (and hence is supplying no current), its EMF will remain substantially constant for a period of several years. This is reflected in the 'use by' date printed on each cell.

The essence of this case, from a technical point of view, is that allegedly one cell in the battery of eight in the Device was reverse-polarized and its electrolyte consequently leaked, causing injury to the Plaintiff. To deal with this issue, it is necessary to consider the Device in a little more detail. As discussed earlier, it uses a battery of eight 1·5V D-size cells which are connected together to produce an operating voltage of 12V. The nature of the connection is that the positive electrode of each cell is connected to the negative electrode of its neighbour so that the voltages produced by each cell add together. Such a connection is known as a *series* connection, and the cells are said to be connected 'in series.'

If one cell in a series-connected battery is reversed, its voltage would be subtracted from the overall voltage produced by the battery rather than added to it. In the case of the

Device, the voltage produced by the battery would therefore become not (1·5 x 8) = 12 but (1·5 x 7 – 1·5) = 9. The voltage appearing across the reverse-connected Cell when the Device was switched on would be 10·5 minus the voltage dropped in the Device when in operation. In the Consultant's tests and experiments, the reverse voltage was measured as between 1·8 and 2·5 volts.

It will be recalled that in order to perform some useful function, the voltage from a battery must be applied to an external circuit of some kind so that a current flows. A simple form of external circuit might consist of a lamp bulb and the associated wiring. The amount of current which will flow through the bulb is a function of two parameters. One is the voltage of the battery connected to it. The other is the electrical *resistance* in the circuit. Resistance is defined in terms of the voltage required to be connected across a particular device to cause a certain value of current to flow through the device, and is an intrinsic property of the material from which the device is made. Resistance is measured in units called *ohms*, and the relationship between voltage, current and resistance is simply that voltage (in volts) is equal to current (in amperes) multiplied by resistance (in ohms). This simple equation can be easily rearranged to show that current is equal to voltage divided by resistance and that resistance is equal to voltage divided by current.

Let us consider the example of a lamp bulb whose resistance is 24 ohms and to which we connect a 12V battery. What current will flow through the bulb? We know that current is defined as voltage divided by resistance. Hence the current will be 12/24 amperes, or 0·5 amperes. Note that if this is the value of current flowing through the bulb, it must by definition be the value of current which flows in the entire circuit; the battery, the wires which connect the battery to the bulb and the bulb itself.

We may now return to the Device. With fresh batteries correctly inserted and when switched to CD replay mode and replaying a CD with the sound volume at a medium setting, the Device when measured was found to draw about 0·76A of current (see below for a discussion of all measurements made on the Device and its battery). In consumer-electronic equipment such as the Device, the current demand rises with sound volume, within limits determined by the design of the equipment. There is also an essential minimum current which is independent of the sound volume. The Device is considerably more complex than a lamp bulb and it has many internal paths through which portions of this current will flow. However, for our purposes it does not matter exactly which elements of the Device are drawing current at a given moment. All we need to know is that the overall amount of current which is drawn from the battery in the Device by all its internal electronic elements and components adds up to about 0·76 amperes when it is switched to CD replay mode. The reason for stating the current requirement in CD replay mode is that it gives the highest figure. In radio and tape modes the current requirements is slightly less. The importance of establishing the highest likely figure for the current requirement will be seen later.

In the case of the lamp bulb, we noted that the current flowing through it also flowed through the rest of the circuit, including the battery. This is true for any electrical circuit, including that of the Device. It follows that when the Device is drawing an operating current of 0·76 amperes, this value of current is flowing through the battery, the wires connecting the battery to the Device's circuit elements, the Device's on/off switch and so on. It also follows that if one cell in the Device's battery were to be reversed, this value of current would flow through the cell in the opposite direction to the direction in which it would usually flow. Finally, it follows that when the Device was switched off, the current from the battery would be interrupted by the power switch and no reverse voltage could consequently be applied to the cell.

It should be noted, however, that the value of operating current quoted in the above example assumes a battery voltage of 12. If one cell in the battery is reversed, the voltage supplied to the Device becomes 9 rather than 12. We saw earlier that current is expressed as voltage divided by resistance, and it follows that if resistance is kept constant and the voltage across it is reduced, the current reduces too. Reverting to the example of the lamp bulb whose resistance was 24 ohms, if we apply 9 volts instead of 12 volts across it, the current through it reduces from (12/24) = 0·5 amperes to (9/24) = 0·375 amperes. As a technical aside, the Consultant is naturally well aware that neither lamp bulbs nor consumer electronic products such as the Device strictly obey Ohm's Law and that the argument above is simplified for illustrative purposes.

In the case of the Device, a similar reduction can be expected. Knowing that it draws 0·76 amperes from a 12V battery, we can calculate that its resistance is (12/0·76) ohms or 15·79 ohms. Knowing this, we can now predict the approximate value of current it will draw from a 9V battery by dividing 9 by 15·79. This gives a value of 0·57 amperes. When the Device was measured (see below), almost exactly this value of current was drawn when one cell in the battery was reversed. Here again, it is accepted that the Device's internal electronic circuitry is such that Ohm's Law would not normally be strictly obeyed by it and the close correspondence between measured and predicted values in this instance is fortuitous.

The issue in engineering terms is therefore whether a D-size Duracell with a reverse current of about 0·57 amperes flowing through it would be liable to leak its electrolyte in the manner asserted by the Plaintiff. However, before this can be considered fully, it is also necessary to consider the issue of the time for which the reverse voltage was applied and hence the time during which the reverse current would have flowed. The Defendant has stated that after having inserted the batteries, he used the radio "…for maybe a minute". Since no current can flow when the radio is switched off, it follows that any putative reverse current could only have flowed for the same period of time.

Hence the essence of the case can now be re-defined in terms of a single question. This is whether a D-size Duracell with a reverse current of about 0·57 amperes flowing through it for approximately one minute would be liable to leak its electrolyte in the manner asserted by the Plaintiff. Note that, as discussed above, the value of 0·57 amperes is a worst case if one cell has been reversed, and requires that the Device was switched to CD mode and replaying a CD at a medium sound volume while it was switched on. If it was switched to tape-replay or radio mode at the same sound volume, the current flowing in the cell would have been somewhat less. Given that the Defendant stated that he only tested the Device by playing the radio, it is likely that – as will be seen shortly – the calculated value of 0·57 amperes is too high. For the purposes of this analysis, however, it will continue to be used since it represents the worst possible case.