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RELIABILITY ANALYSIS OF LITHIUM CELLS

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Summary

Fault tree analysis has been used for many years in safety and reliability analyses of nuclear reactors and other large systems. This technique can also be useful in the design of high reliability lithium cells/batteries and in improving the reliability of existing designs.

The basic building blocks of a fault tree are discussed and an example, using the Li/SO_2 cell, is given.

Introduction

Lithium batteries are presently used in large quantities by the military and in increasing numbers in the OEM market (watches, calculators, cameras, memory backup, etc.). They have recently been introduced to the consumer market and will probably see growth in this area during the next several years.

A variety of lithium cells/batteries is presently in use. Many different chemistries in several configurations, using both hermetic and crimp sealed designs, are produced in a rapidly changing technology.

In this continually changing environment, reliability assessment is a difficult task, at best. A technique which may be helpful in the design of cells/batteries with increased reliability, and in improvement of the reliability of existing designs, is fault tree analysis.

Fault tree analysis

Fault tree analysis is a form of deductive or backward analysis, in that one starts with the final condition, *i.e.*, cell failure, and analyzes the system to determine the events that led to the final condition. It results in a graph-

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ical model which shows the logical interrelationships of various faults which lead to the event of interest. Fault tree analysis is simply a communication tool which helps direct analysis to pinpoint failures, and provides insight into system behavior.

A number of event symbols and logic gates are used in fault tree analysis; however, the use of only two events and two logic gates will suffice to define a fault tree which will give all the necessary information for reliability assessment. The two events are basic (initiating fault) and intermediate (caused by one or more prior events acting through logic gates). The two logic gates are or- (output event occurs if one or more input events occur first) and and- (output event occurs only if all input events occur first). The basic event is represented by a circle, the intermediate event by a rectangle, the or- gate by a shield and the and- gate by a shield with a flat bottom, Fig. 1. Use of the logic gates is illustrated in Fig. 2.

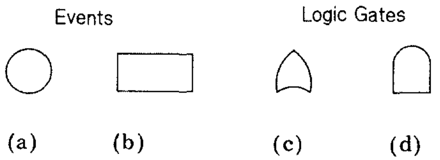


Fig. 1. Fault tree symbols. Events: (a) basic, (b) intermediate. Logic gates: (c) or- gate, (d) and- gate.

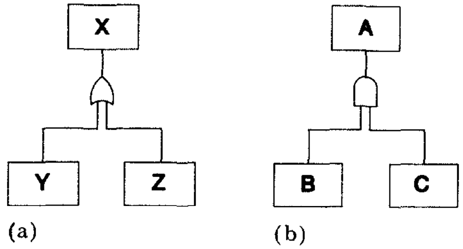


Fig. 2. Use of logic gates. (a) or- gate: event X will occur if either event Y or Z occurs first. (b) and- gate: event A will occur only if both events B and C occur first.

The Li/SO_2 battery fault tree

The Li/SO_2 cell will be used as an example in the construction of a battery fault tree. The top event or final condition will be cell failure. Four types of failure are defined: low capacity, leakage, poor rate capability, and catastrophic. Low capacity indicates an otherwise normal cell which runs for a shorter period of time than expected. Leakage, in the case of pressurized Li/SO_2 cells, will result in the loss of active cathode material and might also cause corrosion in electronic components in proximity to the cell. Low-rate capability arises in applications requiring a low rate for extended periods followed by a higher rate (*e.g.*, power a timer then turn on equipment). In many cases, the cell will not deliver full capacity at the higher rate. Catastrophic failure refers to the case of a normally discharging cell which suddenly drops below cut-off voltage with no prior sign of a problem. Figure 3 illustrates the above failure modes in fault tree format.

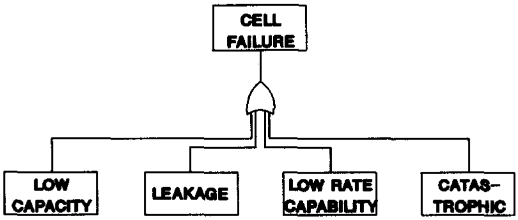


Fig. 3. Fault tree representation of Li/SO_2 cell failure modes.

Due to space limitations, only one branch of the battery fault tree will be developed. This will, however, demonstrate the principles involved in fault tree analysis and illustrate how this technique can be useful in reliability assessment. The leakage branch will be used as the example because it is the simplest of the four.

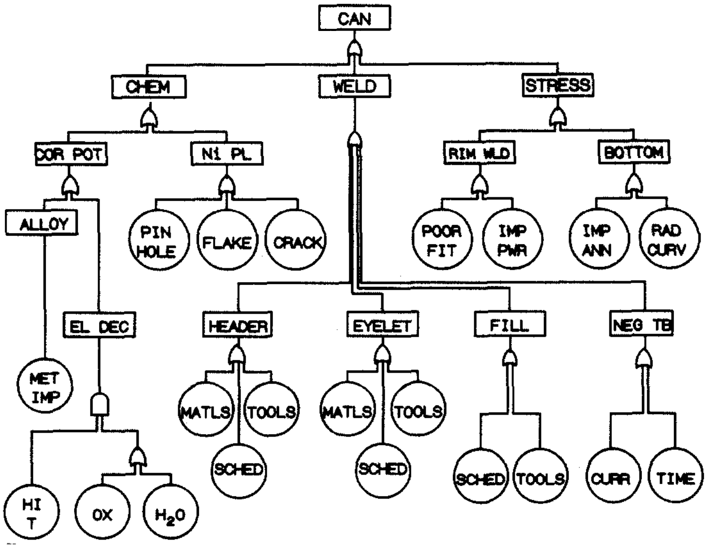
Leakage can occur from three areas of the cell: the can, the vent, or the glass-to-metal seal. Leakage through the can may be due to chemical corrosion, stress corrosion, or faulty welds. Chemical corrosion may occur as a result of decomposition of the electrolyte to form corrosive products, *e.g.*, bromine. Electrolyte decomposition often occurs when cells containing traces of water or oxygen are exposed to elevated temperatures for a period of time ranging from a few weeks to several months. Corrosion may also occur in Ni-plated steel cans if pinholes, cracks, or flaking exist in the plate. In these small openings a very large voltage gradient exists which may promote corrosion reactions that otherwise may not occur.

Stress corrosion of the can normally occurs in the region of the rim weld or at the bottom. Stress may be induced near the rim if the header does not fit properly and is forced into the can, or if the wrong power level is used during welding. Since the cans are drawn, the bottom is a region of high stress. If the can is not properly annealed, stress will remain in this area. Also, if the radius of curvature at the bottom is too small, excessive stress will result.

Improper welds may also lead to leakage paths. The header-to-can, eyelet-to-top, and fill port are often resistance or laser welded. If the materials are not compatible, the weld schedule is incorrect, or the equipment misaligned or worn, conditions may exist in the weld joint for corrosion to occur (particularly cracks or compositional heterogeneities), ultimately resulting in leakage. Another area of concern is the attachment of the anode tab to the can. This is normally a spot-weld, and if the current is set too high or the time too long, a pinhole may result in the can allowing the pressurized contents to escape.

All the above scenarios for leakage from the can may be represented by the fault tree shown in Fig. 4.

The safety vent in an Li/SO_2 cell is a weakened area that is stamped into the can bottom or side. As a result of this process, stress is introduced into this area of the can and may lead to stress corrosion if the can is not properly annealed. A fault tree representation of this process is given in Fig. 5.



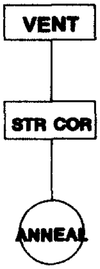


Fig. 4. Faults leading to leakage from can of Li/SO_2 cell, fault tree summary.

Fig. 5. Fault tree showing leakage from vent of an Li/SO_2 cell.

Leakage from the glass-to-metal seal may result from glass corrosion, cracking of the glass, or from a poor bond of the glass to the metal components. Corrosion will occur in many commercial sealing glasses that are not specially formulated to resist lithium attack. Corrosion may also occur in corrosion-resistant glasses if the composition is out of specification, due to high levels of impurities, evaporation of certain components during the fusing or sealing process, or to human error in blending the components. Also, if the proper temperature profile is not used in the sealing process, crystallization of certain compounds may occur in the glass. The crystalline phase and the immediate area surrounding it will most likely be out of spec. and be susceptible to corrosion.

The glass seal may crack during the sealing process, or during subsequent thermal cycling, if the header has an inherent stress designed into it, if materials are used for the body and pin which do not have the proper coefficient of thermal expansion, or if the centerpin is not properly aligned with the other components.

Poor bonding of the glass to the metal components may occur if the metal parts are not properly cleaned prior to sealing (*e.g.*, complete removal of oxide film). Sealing in the wrong type of atmosphere (*e.g.*, reducing *versus* oxidizing) may result in a nonhermetic bond between the glass and metal. Also, the proper thermal profile must be used in order to obtain a good bond between the various components of the glass-to-metal seal.

Figure 6 represents the glass-to-metal seal portion of the leakage branch of the Li/SO_2 fault tree.

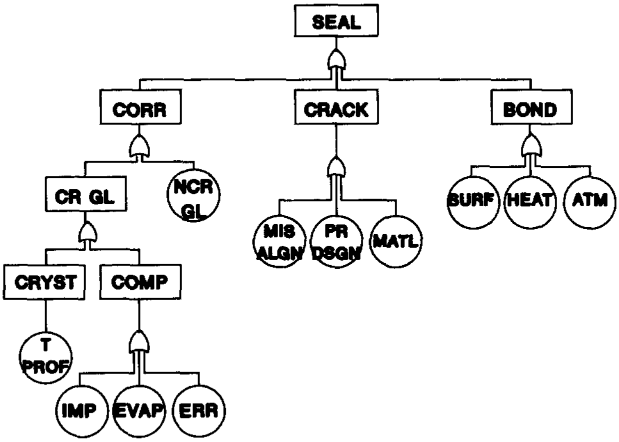


Fig. 6. Glass-to-metal seal leakage paths in fault tree format.

The three fault tree sections for the can, vent, and glass-to-metal seal described above are combined into the leakage branch of the Li/SO_2 fault tree in Fig. 7. This diagram shows all the possible faults that could lead to leakage in an Li/SO_2 cell, connected in a logical manner. If a leakage problem occurs in a cell, this chart could be extremely useful in quickly getting to the basic cause of the problem. In the process of designing a new cell, if one first looked at all the pitfalls that could result in a leaker, and took precautions to avoid them, a cell with increased reliability would result.

Similar branches may be constructed for the three other failure modes mentioned: low capacity, low-rate capability, and catastrophic. Combining those three branches with the leakage branch just developed will yield the complete Li/SO_2 cell fault tree.

Reliability

Reliability, relative to cells/batteries, can be defined in terms of four elements: probability, performance, time, and operating conditions. The probability indicates the number of cells/batteries one would expect to operate successfully out of the total number of cells/batteries placed into a particular application. Performance implies that the operating characteristics of the cell/battery (*i.e.*, current/voltage) must be defined prior to the start of a reliability assessment. The time a cell/battery is required to

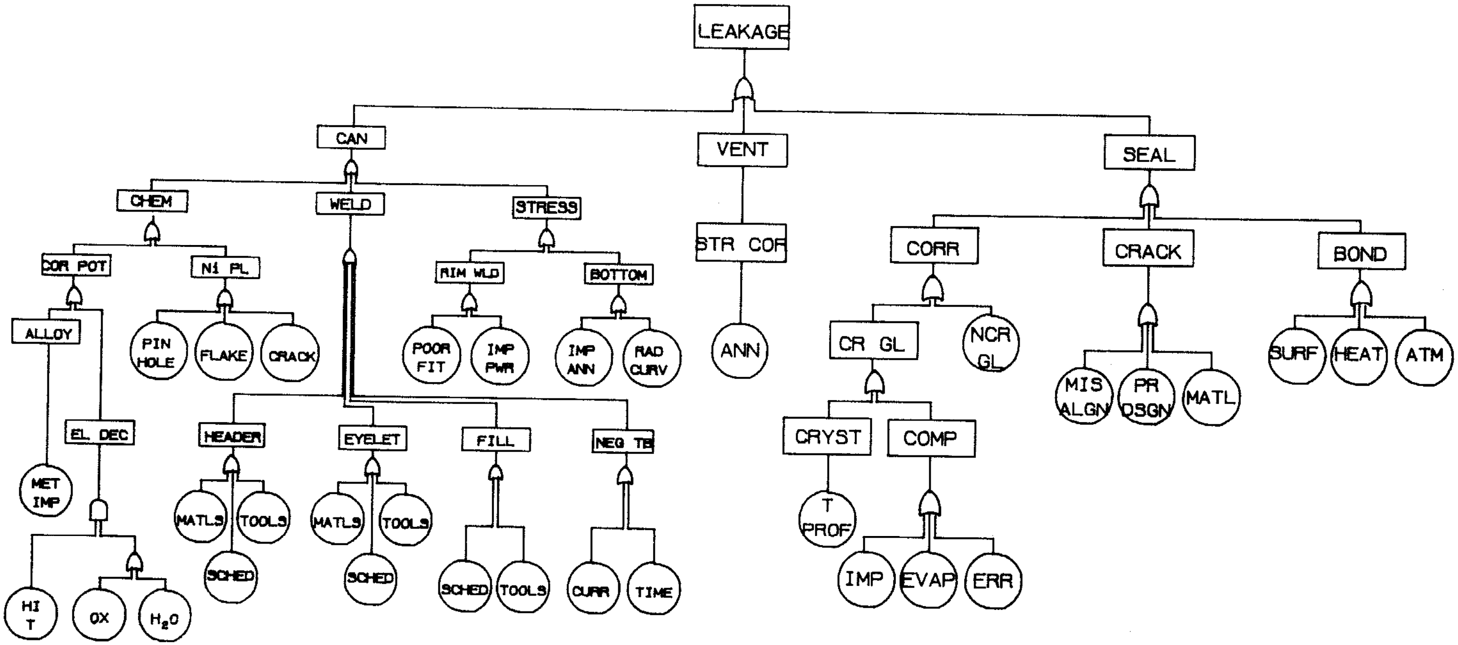


Fig. 7. Complete leakage branch of the fault tree for Li/SO_2 cells.

operate must be defined, since these devices will not operate indefinitely. Finally, the conditions under which the cell/battery must operate need to be stated, since environments such as temperature, shock, vibration, etc., all have an effect on performance. Thus, the reliability of a cell/battery in one application may be quite different from its reliability in a different application.

Estimating reliability

If the probability of each primary fault is known, or can be estimated, the probability of the top event in the fault tree can be calculated. However, even if the probabilities are not known, the most likely mode of failure can be identified by the fault tree.

The probability of an output event occurring through an or- gate can be approximated by the sum of the probabilities of the input events. Similarly, the probability of an output event occurring through an and- gate is equal to the product of the probabilities of the input events. Since the probability of a fault occurring is usually small, $\sim 10^{-3}$ or less, the more and- gates in a branch, the less likely that branch will be a major contributor to the top event. Thus, the top event is controlled primarily by the basic faults having the highest probability of occurring, and connected to the top event through or- gates only.

Using the leakage branch of the fault tree for Li/SO_2 cells as an example, and assuming that none of the probabilities of the primary faults occurring is known, we assign a probability of 10^{-3} to each. In the can portion of this branch there are 18 primary faults connected to the top event through or- gates only. Thus, we can assign a probability of 1.8×10^{-2} for leakage through the can. Similarly, a probability of 1.1×10^{-2} for leakage through the glass-to-metal seal and 1×10^{-3} for leakage through the vent may also be assigned. Therefore, we can conclude that the can and glass-to-metal seal are the areas requiring the most attention in the design of a cell with a low probability of leakage over a long period of time. However, if it can be determined that one primary fault has a much higher probability of occurring than the others, this fault will determine the highest probability path for leakage.

Conclusion

The fault tree is a shorthand technique for describing all of the possible failure modes that may occur in a cell or battery. A fault tree is a dynamic tool, and not necessarily fixed once constructed. As more information becomes available, additional faults or entire branches may be edited, added or deleted.

A properly constructed fault tree can aid in the post-mortem analysis of failed cells to determine the underlying cause of failure. If can also be useful in the design and fabrication of high reliability cells and batteries, since critical areas are highlighted in a well-thought-out and constructed fault tree.

The most likely mode of failure can be identified through fault tree analysis, even if the probabilities of the underlying faults are not known.