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FAULT TREE SAFETY ANALYSIS OF A LARGE $Li/SOCl_2$ SPACECRAFT BATTERY

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Summary

The use of Fault Tree Analysis allows designers to identify the relative importance of events and their probabilities in leading to a catastrophic failure of a spacecraft battery. Such an analysis is demonstrated for the case of a 576 cell $Li/SOCl_2$ battery, showing how the probability of catastrophic failure can be reduced to one in one million.

1. Introduction

A current spacecraft hardware program at the Johns Hopkins Applied Physics Laboratory requires an 1100 A h, 250 lb. battery. This requirement can only be satisfied by a lithium-chemistry battery. Several lithium-chemistry systems were investigated with several manufacturers. A lithium–thionyl chloride ($Li/SOCl_2$) F-size cell was selected.

To assess the safety hazard associated with a battery composed of eight modules, each containing 72 F-sized cells, a fault tree analysis was required by the program. Previous experience with lithium-chemistry batteries in the ALDOT (Air Launched Deep Ocean Transponder) and SARSAT ground transmitter (Search And Rescue Satellite) programs enabled us to carry out such an analysis efficiently.

This current report presents the results of the safety fault tree analysis on the eight module, 576 F cell $Li/SOCl_2$ battery on the spacecraft, and in the integration and test environment on the ground prior to launch.

2. Electrochemical requirements

The battery requirement of the satellite is for a total capacity of 1100 A h at a nominal 30 V at 21 °C and for a battery weight of less than 250 lb. Figures 1 - 3 show the electrical and mechanical configuration of the battery. This translates to a specific energy density of at least 132 W h lb^{-1}. A previous vendor survey for a battery requiring only 750 A h resulted in proposals

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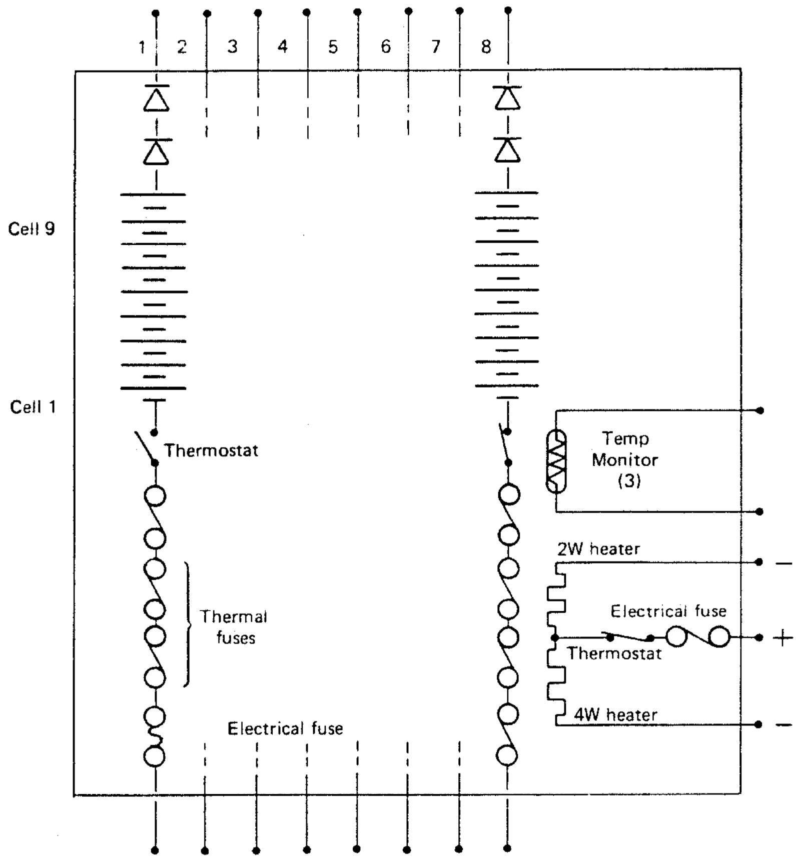

Fig. 1. Module circuit configuration.

which would have utilized $Li/SOCl_2$, Li/SO_2, Li/CF_x and Zn/AgO cells, but with only $Li/SOCl_2$ complying with the energy density requirement. When the battery capacity requirement was subsequently increased from 750 to 1100 A h, the cells considered were the $Li/SOCl_2$ and the Li/SO_2Cl_2. Lithium–sulfuryl chloride was quickly abandoned, however, because it is not as well developed as $Li/SOCl_2$. Thus the electrochemical cells chosen in this program were the F-sized $Li/SOCl_2$ cells.

3. Quality assurance considerations

In the fault tree analysis discussed later in this paper, it is shown that manufacturing defects such as internal mechanical shorts between anode and cathode or low cell capacities due to improper fill or failure of hermeticity, and current leakage due to lithium diffusion through the ceramic insulator, can lead to a decrease in the reliability and safety of the battery. It was

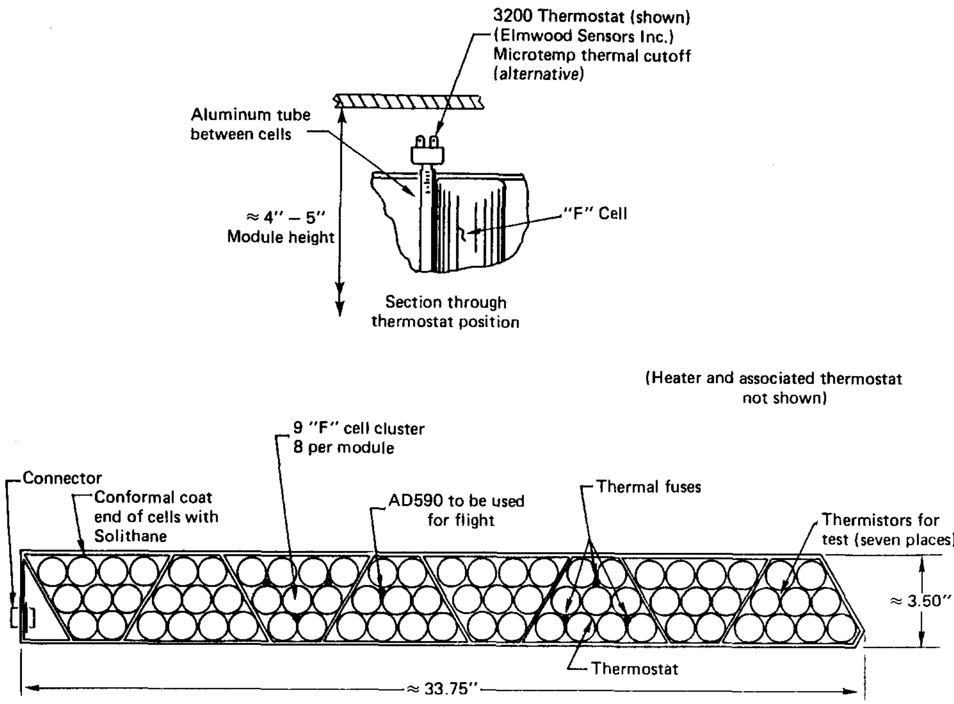

Fig. 2. Module configuration.

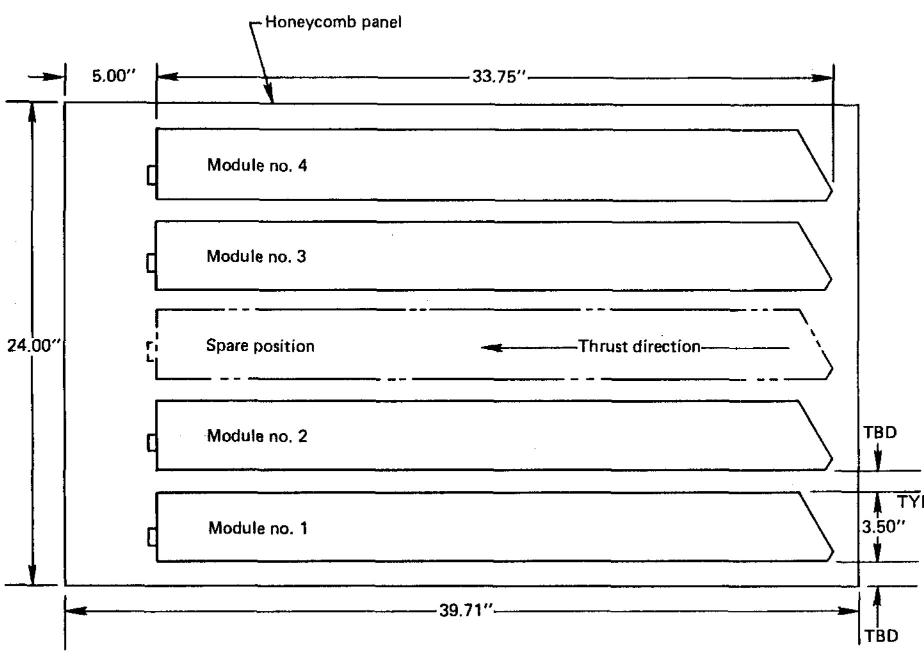

Fig. 3. Battery module panel layout.

therefore decided that a rigorous quality assurance procedure must be implemented with the cell manufacturer, with proper controls for acceptance and qualification of cell lots. We have chosen to incorporate the quality assurance documents from NASA [1, 2], the U.S. Army [3], and Navy [4], and negotiated with the cell vendor in order to come up with specific quality assurance procedures for the procurement of the battery, the flow-charts of which are shown in Figs. 4 - 6. Even though these QA procedures are tailored to this program and this vendor, APL will be procuring lithium battery systems with similar specifications in the future.

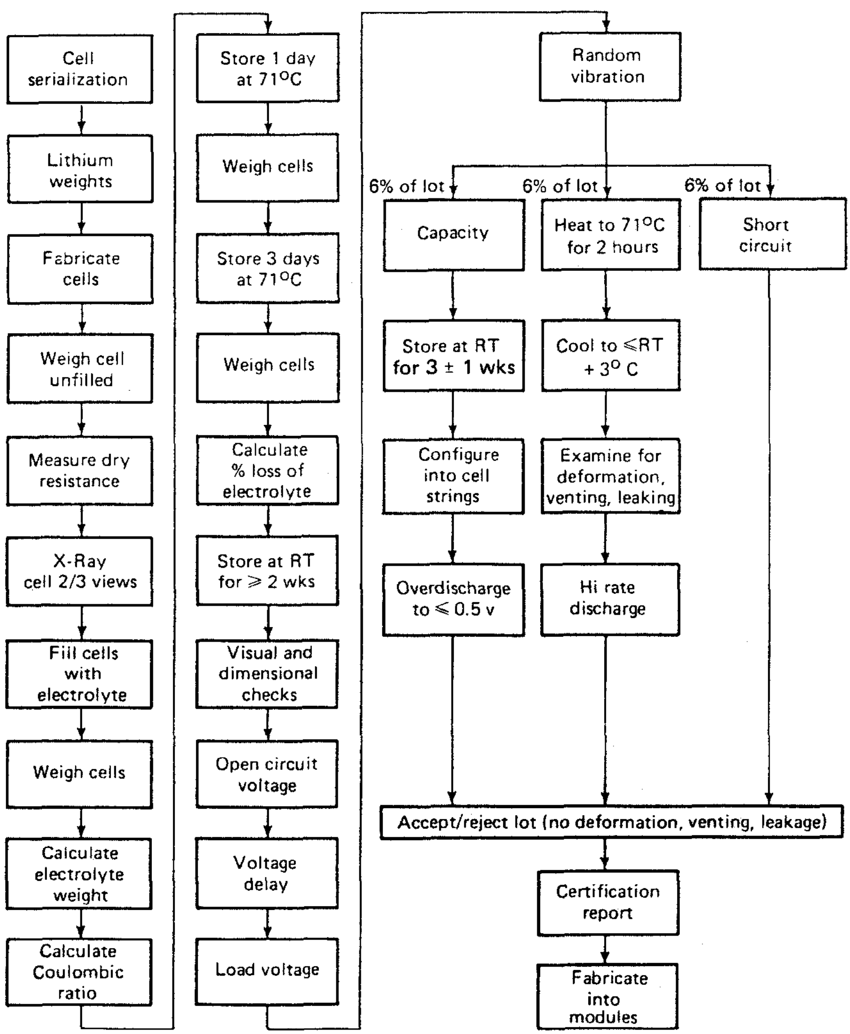

Fig. 4. Cell fabrication and test flow.

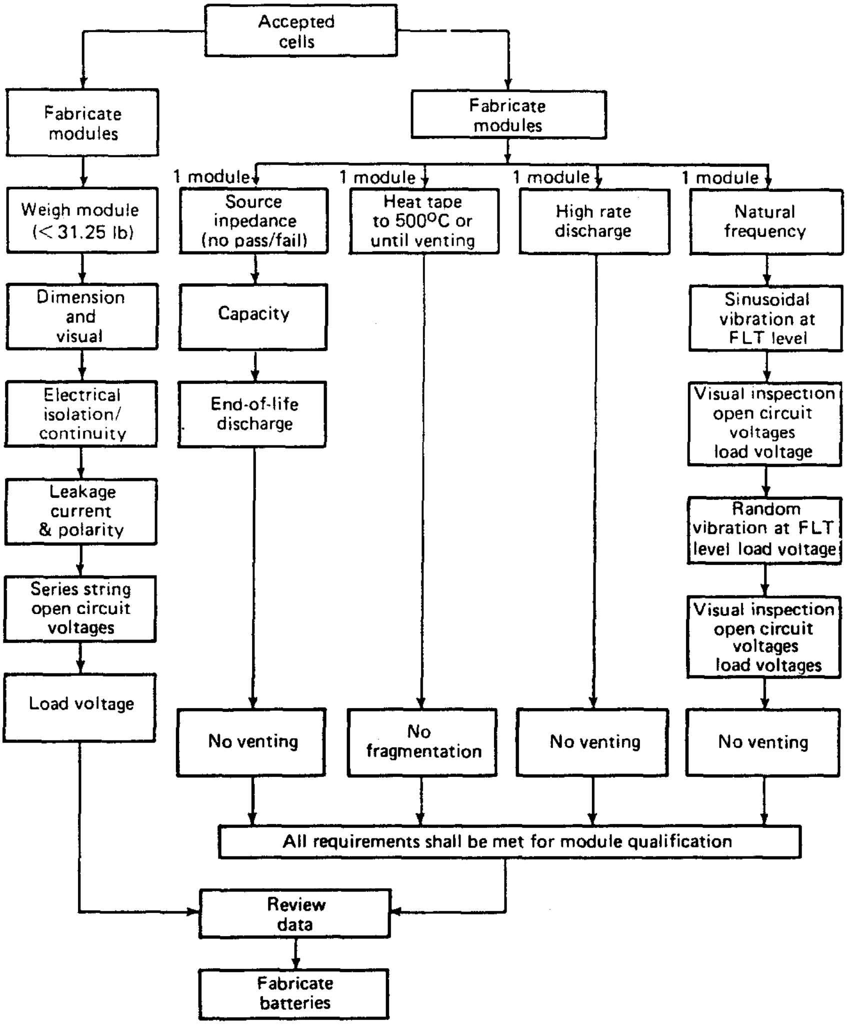

Fig. 5. Module fabrication and test flow.

4. Safety considerations

Because of the high reliability and safety requirements of the program, the cells, as well as the electrical components used in the assembly of the battery, are high reliability space or military parts. For example, the thermal fuses are 100% X-rayed and lot tested for thermal performance. There are three thermal fuses per string so that every cell in the battery is adjacent to a thermal fuse. Two blocking diodes are used in series in order to preclude charging of a cell string in the event of a single diode failure. The cells, modules, and battery are subjected to random vibration and thermal environ-

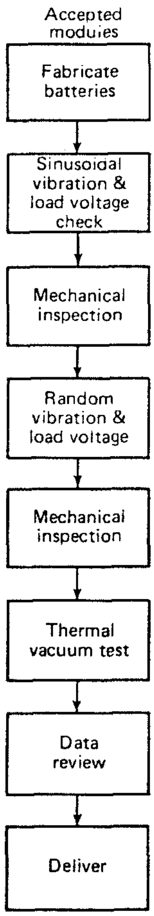

Fig. 6. Battery fabrication and test flow.

ments in order to screen out workmanship defects such as weak solder or welding interconnections. Considerable attention is paid to ensure that the cells used in each string and module are manufactured uniformly with respect to processes and materials. Finally, the sample cells and batteries will be subjected to overdischarge, high-rate discharge, short-circuit, heat-tape, capacity, vibration, and thermal vacuum testing before the flight and spare batteries will be accepted for shipment to APL.

5. Development of fault tree analysis

The safety fault tree for the battery module is shown in Figs. 7 and 8. It has been developed applying the principles of safety fault tree analysis published in the *IEEE Transactions on Reliability* [5], the *Journal of the System Safety Society* [6], and the *Reliability Design Handbook* [7].

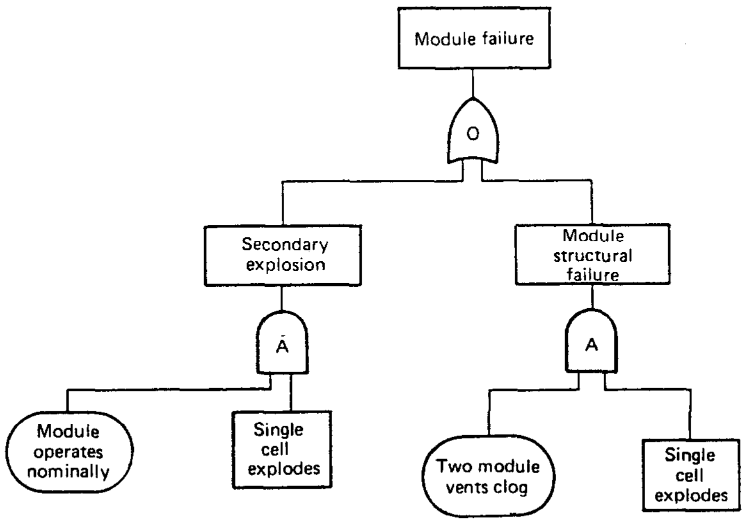

Fig. 7. Battery module safety fault tree for spacecraft.

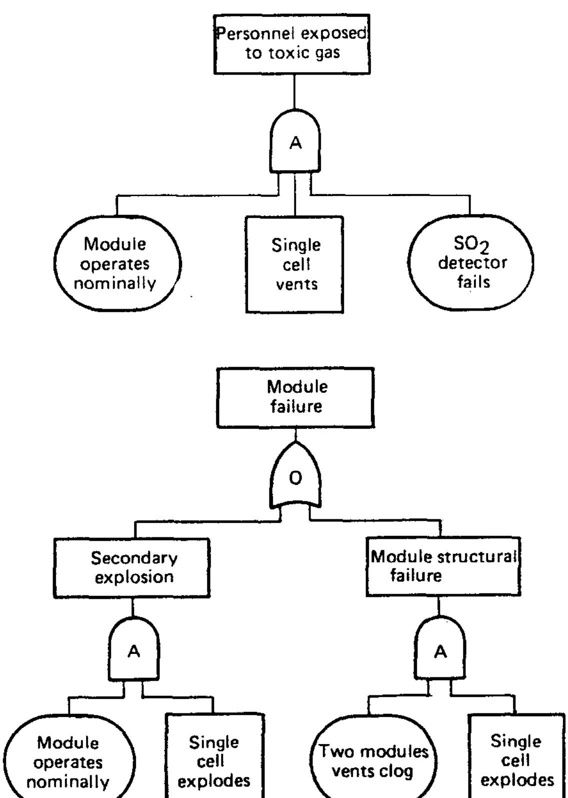

Fig. 8. Battery module safety fault tree for ground integration.

In the fault tree the Top Event whose occurrence is potentially catastrophic leading to mission failure is the explosion or structural fragmentation of a battery module initiated by the explosion of one or more cells in the battery pack. A single cell explosion may lead to the Top Event if the module container fails to operate as designed and relieve the overpressure condition; thus, a primary explosion may cause the Top Event. In addition, a single cell explosion may cause the Top Event to occur by creating overpressure and overtemperature conditions inside the battery pack which damage or make other neighboring batteries unstable, leading to a second, sympathetic explosion of such speed (less than 100 ms) and force that venting cannot occur sufficiently quickly, even with the module vents functioning as designed (see Figs. 7 and 8).

Basic events which either initiate the Top Event or enable it to occur are shown as ovals in the fault tree diagrams. AND gates in the tree are marked with A; OR gates with O. Intermediate and Top Events are shown as rectangles. Due to the size of the fault tree, it has been split into two Figures with the intermediate event, single cell explodes, common to each main branch in Figs. 7 and 8, and shown in detail in Fig. 9. Figures 7 and 8 show that a single cell exploding *and* the failure of the module vents *or* a single cell exploding and the module operating nominally but with a sympathetic secondary explosion occurring, can lead to the Top Event. The assumption that has been made in the analysis is that if a single cell explodes, a secondary explosion, of greater magnitude due to a multiple battery explosion, will follow with some non-zero probability — here very conservatively taken as a probability equal to 1.

The basic events causing a single cell to explode are shown in Fig. 9. Note that we have assumed that it is much more likely for a single cell to explode in the primary explosion scenario than for several to explode simultaneously. We would expect that a two or three cell primary explosion would occur with a frequency approximately equal to the square or cube, respectively, of the single cell primary explosion probability. This low probability, multiple battery primary explosion is to be distinguished from a multiple battery sympathetic secondary explosion, which seems to be of a fairly high probability once the unstable conditions created by the primary explosion of a single cell are in existence.

Figure 9 is the part of the fault tree showing the possible causes of a single cell explosion. The branch of the tree under battery charging leads directly to an overpressure condition so quickly that the individual cell vent cannot prevent explosion from occurring. This charging condition can occur if a cell in a given string of cells, which is parallel with other strings of cells in the module, has low capacity relative to the other cells in the string *and* if the two diodes protecting the string either both fail shorted or have been installed backwards in any combination of these two fault conditions.

In order to make more understandable the various conditions necessary for the singlè cell explosion to occur, we list the ten minimum cut sets (Table 1) for all critical system states leading to the event "Single Cell

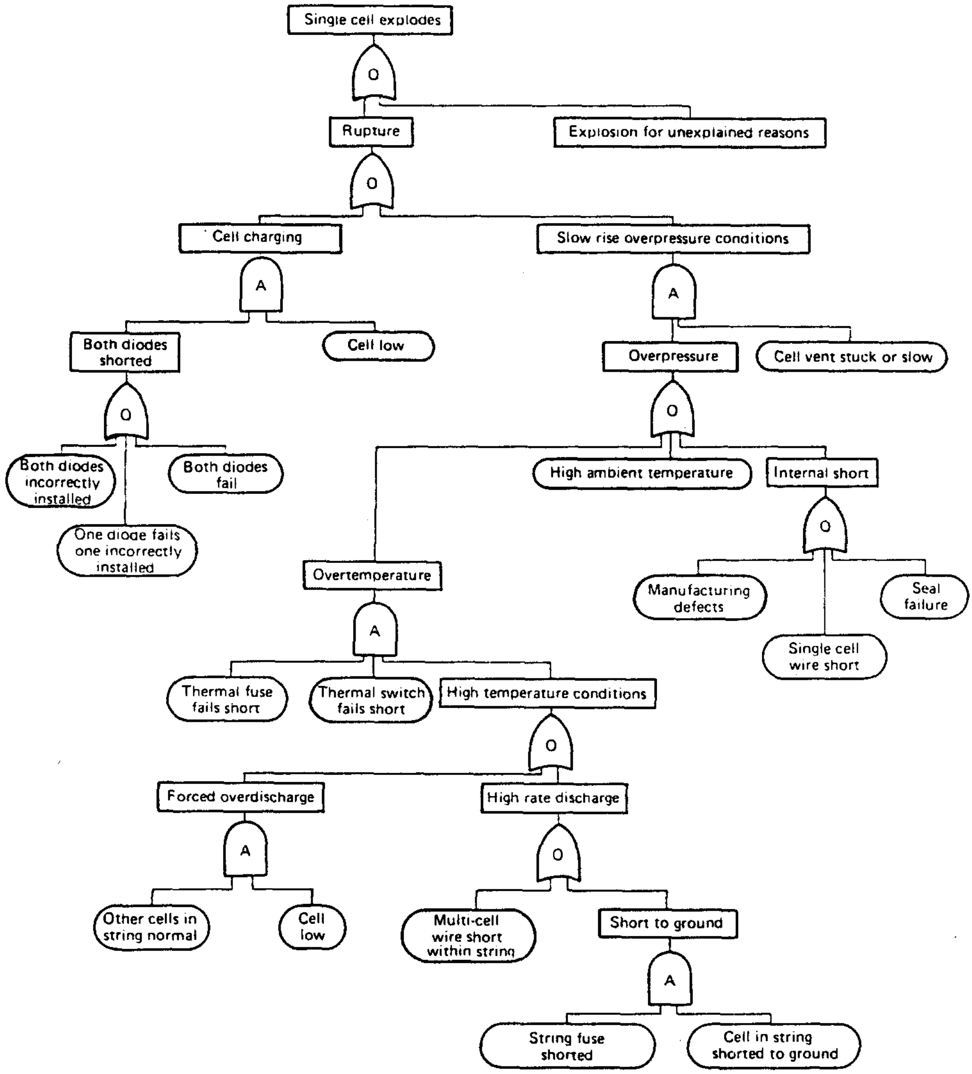

Fig. 9. $LiSOCl_2$ single cell safety fault tree.

Explodes" in Fig. 9. The first set will be for the battery charging condition explained above.

The ten sets of basic events have been determined from a literature search and from discussion with experts involved in the manufacture and use of lithium batteries for both military and commercial applications. In order to determine the relative importance of the various branches in the fault tree, estimates must be made of the probability of occurrence of all basic events, which are then propagated through the fault tree by addition at OR gates and multiplication at AND gates. These estimates and the rationale for their use are the subject of the next section.

TABLE 1

Minimum cut sets for critical system states for the event "Single Cell Explodes"

A.	*Cell charging*
	1. Cell low *and* diodes installed backwards
or	2. Cell low *and* diodes fail shorted
	3. Cell low *and* one diode fails *and* the other is installed backwards.
B.	*Overtemperature*
	1. High ambient temperature *and* cell vent stuck or slow
C.	*Internal short (leading to overtemperature)*
	1. Seal failure leading to shorting condition *and* cell vent stuck or slow
or	2. Single cell shorted by external wire or conductive debris *and* cell vent stuck or slow
or	3. Manufacturing defects creating internal short *and* cell vent stuck or slow
D.	*High rate discharge (leading to overtemperature)*
	1. Multi-cell short due to external wire or debris *and* thermal fuse shorted *and* thermal switch shorted *and* cell vent stuck or slow
or	2. One or more cells shorted to ground *and* fuse shorted *and* thermal fuse shorted *and* thermal switch shorted *and* cell vent stuck or slow
E.	*Forced overdischarge (the rate may not be very high)*
	1. Cell within string with low capacity *and* other cells in string with normal capacity *and* thermal fuse shorted *and* thermal switch shorted *and* cell vent stuck or slow

After the original fault tree to estimate the module failure in the spacecraft had been developed, we also estimated the safety hazard incurred if modules were stored for one month on the ground during integration (Fig. 8). The presence of an SO_2 detector lowers the risk of undetected cell or module venting and the consequent release of toxic gases in the vicinity of integration personnel to about one chance in 10 000.

6. Probabilities of fault tree basic events

The probabilities of the fault tree basic events for a single spacecraft mission are shown in Table 2, together with comments about the rationale behind the use of the numbers. Table 3 shows the probability of an individual battery having a capacity which is 25% discharged.

It is readily seen that some of these basic event probabilities are time dependent and that some (usually related to conditions existing at the time of manufacture or to human factors) are independent of time. When the probability of module failure in storage is estimated, all time dependent basic event probabilities are multiplied by the number of hours in a month (720) rather than the 168 h value assumed for the duration of the spacecraft mission.

The probability of failure for the diodes, gas sensors, relief valves (vents) and fuses are calculated with models and data from *MIL Handbook 217D* for the electronic parts [8] and the *Nonelectronic Parts Reliability*

TABLE 2

Basic event probabilities for single module

Basic event	Probability of failure	Comment	Fault tree number
1. 1N5614 diode fails short	2.73×10^{-10} h^{-1}	*MIL Handbook 217D* [8] number × 168 h flight time squared for two diodes per voltage string	2.10×10^{-15}
2. Diode installed incorrectly	10^{-4} per diode	*Aerojet General Human Error* [10] *Rates Table*; square of probability for single diode	10^{-8}
3. Fuse or thermal fuse fails short	3.89×10^{-7}	Non-electronic parts [9] reliability data × 168 h flight time × one fuse	6.54×10^{-5}
4. Battery cell shorted to ground	10^{-4} per cell	Experience with welded wire board shorts × 72 cells	7.2×10^{-3}
5. Battery cells shorted together	10^{-4} per cell	Experience with welded wire boards × 288 possible pairs to short together	2.88×10^{-2}
6. Single cell internal manufacturing defects	7×10^{-5}	Non-electronic parts [9] reliability data × 72 cells	5.04×10^{-3}
7. Single cell short due to conductive fragments	10^{-4} per cell	Experience with welded wire boards × 72 cells	7.2×10^{-3}
8. Internal short due to seal failure	1.83×10^{-6} h^{-1}	Sandia data [11] on new cell seal × 168 h flight times × 72 cells	2.21×10^{-2}
9. High ambient temperature	1×10^{-6}	Temperature greater than 100 °C highly unlikely in spacecraft or storage	1×10^{-6}
10. Individual cell vent stuck or slow	1×10^{-5}	Non-electronic parts data [9] on relief valve	1×10^{-5}
11. Explosion for unexplained reasons	1×10^{-6}	An estimate	1×10^{-6}
12. Module vents clog	5×10^{-6} h^{-1}	Non-electronic parts data [9] on failure of mechanical couplings or springs × 168 h flight time squared for two vents	7.06×10^{-7}
13. SO_2 sensor on ground malfunctions	3.5×10^{-6}	Non-electronic parts [9] data on sensors in general × 720 h per month on ground	2.52×10^{-3} $month^{-1}$
14. Thermal switch fails to open	10^{-4} h^{-1}	Non-electronic parts [9] data on thermal switches × 168 h flight time	1.68×10^{-2}

TABLE 3

Probability of low cell capacity (25% discharged)

Coefficient of variation ($\sigma/\bar{x}$)	Standardized normal variate (Z)	Probability of 25% discharge	Fault tree number	
			Cell charging	Forced over-discharge
0.09	2.78	2.7×10^{-3}	0.194	0.151

(1) Calculate: $Z = \dfrac{\text{Mean-lower limit}}{\text{Standard deviation}} = \dfrac{\bar{X} - \text{LL}}{\sigma}$

$$= \frac{1 - \text{LL}/\bar{X}}{\sigma/\bar{X}} = \frac{1 - 0.75}{\sigma/\bar{X}} = \frac{0.25}{\sigma/\bar{X}}$$

(2) Probability found assuming a normal distribution
(3) 72 cells in voltage strings for battery charging branch
(4) 56 cells in position for forced overdischarge branch of fault tree
(5) Probability of other cells in string having nominal capacity (for forced overdischarge)

Prob $= p^8 = (1 - q)^8 = 0.979$

where q is the probability of a single cell being 25% discharged

Data [9], both compiled by the Reliability Analysis Center of the Rome Air Development Center at Griffiss Air Force Base, New York. Base failure rates are taken from life test data and are usually given at a 60% confidence level from testing involving 10^5 component hours or more. These base failure rates are subsequently derated for several factors among which are:

(a) the environment in which the part will be used; *e.g.*, airborne, uninhabited transport;

(b) the quality level of the part, *e.g.*, commercial or military, and the level of screening that has been applied in part selection;

(c) in some cases, the current rating of the device;

(d) the application of the device, *e.g.*, analog circuit with less than 500 mA operating current;

(e) a stress factor usually calculated as a ratio of the applied voltage or power to the rated voltage or power of the device;

(f) in some cases a construction factor, *e.g.*, hermetically sealed or metallurgically bonded.

These numbers are generally given as failures per million hours of operation which is easily transformed into a rate of failures per hour for a single unit.

When the mode of failure is also significant, data on the distribution of failure modes have also been used. In assessing mission reliability, whether a part fails electrically open or short may make no difference since a subsystem will often fail to function in either case. However, in assessing safety hazards it is often the case that only one failure mode presents a threat. In the case of the battery module, diodes and fuses must fail in a shorted condition for the various branches of the fault tree to be able to initiate a catastrophe. For example, 90% of the time fuses fail short or perform as if short because they are slow to open or exceed the designed current rating.

As shown in Table 2 the values used for probability of failure are multiplied by the number of hours, assumed to be 168 for the spacecraft mission, when they are time-dependent and also multiplied by the number of parts when more than one can be independently susceptible to failure at the same time. For the storage case, a separate table was not created but the numbers inserted into the fault tree (see Fig. 9) have been multiplied by 720 h, representing one month of storage/integration time. Figures 10 - 13 show the numbers used in the respective spacecraft and storage fault trees for basic events from Table 2 and for intermediate and top events as calculated by either multiplying (AND gates) or adding (OR gates) as one proceeds up the branches of the fault tree from the bottom.

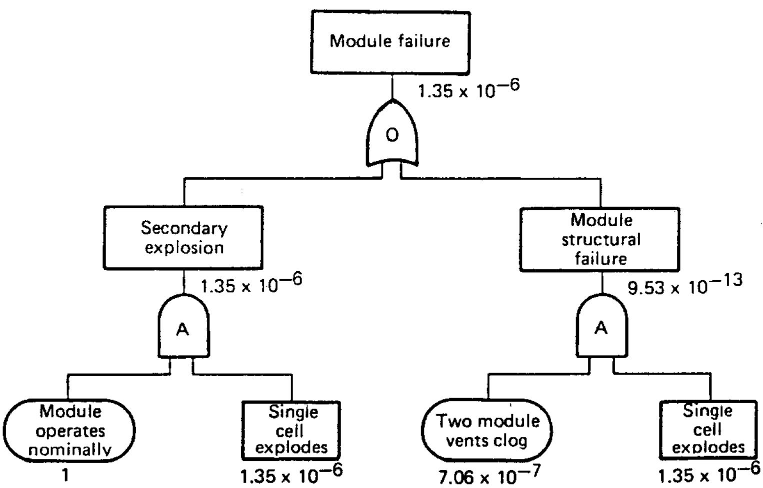

Fig. 10. Battery module safety fault tree for spacecraft.

Several more comments about the basic event probabilities are listed in Table 2. Mechanical basic-event probabilities were assigned from data on devices which were similar in function and operation. The number on the individual cell vent being stuck or slow comes from data on pressure relief valves but is not considered to be time dependent because of the method of manufacture.

Probabilities for shorting to occur come from the authors' experience with the fabrication of welded wire boards for space hardware and soldered test boards for large designed-reliability test programs.

Human factors probabilities are the most variable and the "softest" numbers in the fault trees. The values presented have used the *Aerojet*

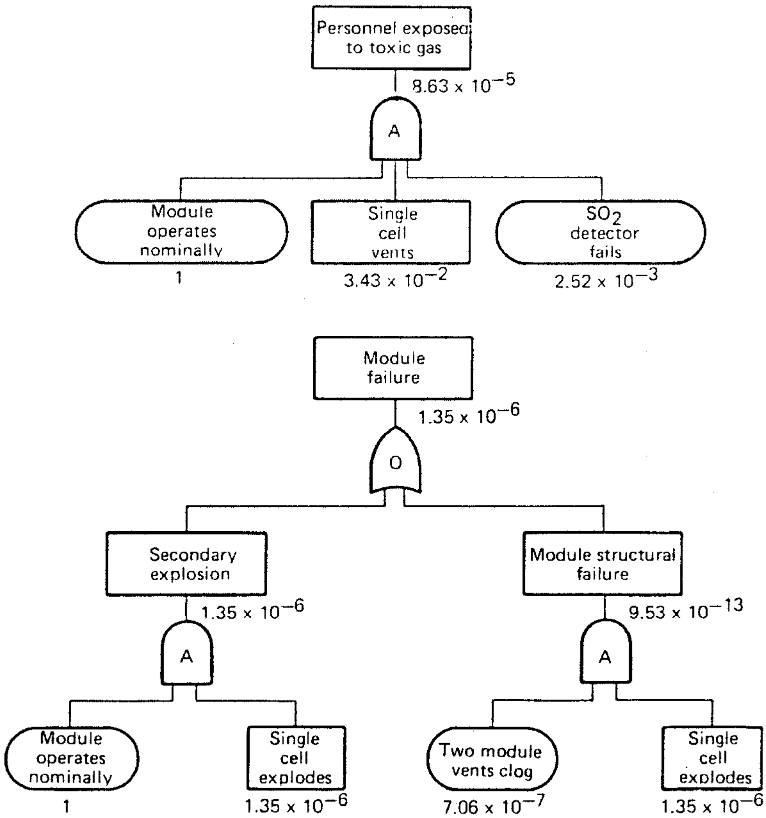

Fig. 11. Battery module safety fault trees for ground integration.

General Human Error Rates Table [6] for various common tasks as well as advice from a safety expert at the Naval Safety Center in Norfolk, Virginia [12].

Table 3 shows the probability of having an individual cell of low capacity (A h) given the coefficient of variation (the ratio of the standard deviation to the mean of the capacity for a set of samples) of the cells as-manufactured. Selection of the value 0.09 is the result of discussions with the manufacturer. We defined "battery low" as being a 25% discharged condition, even though testing has most often concentrated on 50% discharged cells. Thus, if the coefficient of variation of the lithium–thionyl chloride cells is 0.09, a 25% discharge state is 2.78 standard deviations from the mean with a probability of occurrence of 2.7×10^{-3}. This latter number comes from any table of probabilities for standardized normal variates, assuming a normal distribution for cell capacities.

The probability of an individual cell being 25% discharged (CELL LOW in the fault trees) is then multiplied by the number of cells in the module battery pack. Thus, "Fault Tree Numbers" presented in Table 3 are entered

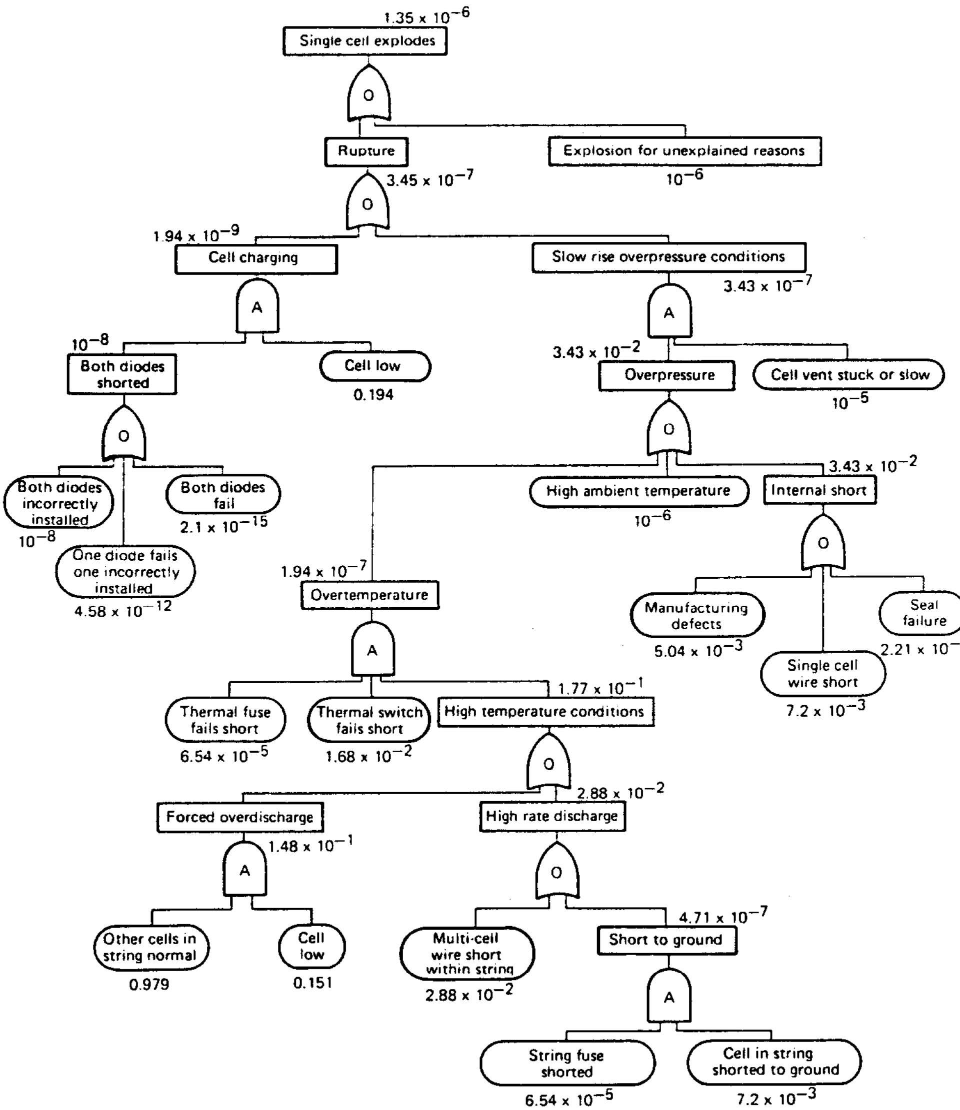

Fig. 12. $LiSOCl_2$ single cell safety fault tree for spacecraft.

as CELL LOW in calculating the frequency of occurrence of the Top Event of the fault tree. In addition, (see Cell Charging branch) the probability for one diode being incorrectly installed is 10^{-4}; for two to be simultaneously incorrectly installed is 10^{-8}. Actually, if one diode were inserted backwards, the second one might also have a high probability of being inserted in a like manner; however, a polarity check has been specified in the fabrication process. The probability of this polarity check failing has been judged to be

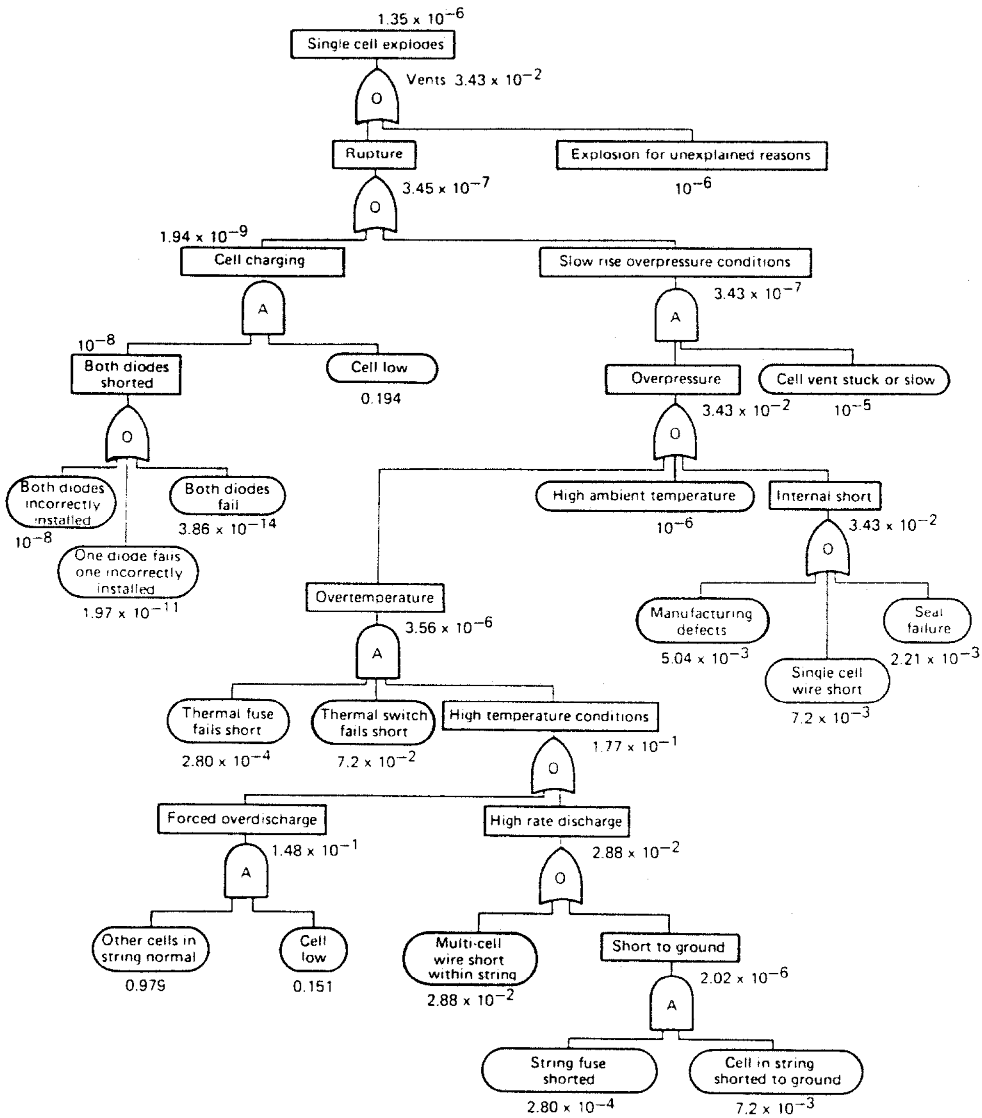

Fig. 13. $LiSOCl_2$ single cell safety fault tree for storage of 1 month.

the same order of magnitude as installing a diode backwards. This sustains the 10^{-8} value.

Some logic implicit in the fault trees will now be explained. Once we have determined the probability for any one of 72 independent cells having low capacity or being shorted to ground or being internally shorted, we must be careful not to overestimate the probability of protective devices such as diodes, fuses or cell vents failing at the same time to enable the cell failure to cause cell explosion. That is, any of 72 cells can have low capacity or be internally shorted, which is why the single cell probabilities are multiplied by 72 in some cases in Table 1. However, once a single battery cell has low capacity or is internally shorted, it is only the vent for that cell or the diodes for that cell's string or the fuse associated with that cell that can simultaneously fail, enabling single-cell explosion to occur. The failure of other vents, diodes, fuses, etc., not associated with the cell in question would not enable the top event of single cell explosion to occur. Therefore, the probabilities of failure for protective devices such as diodes, fuses, cell vents, etc., are not multiplied by the total number of such components in the battery module (see Table 2).

Table 3 also contains a column showing values for the Forced Overdischarge branch of the fault trees. For these phenomena cells at the end of strings are not included because voltage reversal cannot occur unless both cell terminals are connected to neighboring cells in a series circuit. Only the seven interior cells in the voltage strings — a total of 56 cells — can experience this failure mode. Together with a single cell having low capacity, the remaining cells in the same string must have nominal capacities. The probability for nominal cell capacity in this case is $p^8 = (1 - q)^8$ where q is the probability of one interior cell having low capacity.

In Table 2, the probability of failure from an"internal short due to cell seal failure" is given as 1.83×10^{-6} h^{-1}, which, when multiplied by the 168 h flight time in the spacecraft and 72 cells in the battery pack, yields 2.21×10^{-2} for the spacecraft fault tree (see Fig. 12). For the storage fault tree (see Fig. 13), however, we do *not* multiply by the 720 hours in a month. The shorting due to seal failure is a self-limiting process in that as a crack in the seal becomes larger with time, there is less capacity in the cell to supply the greater current that can now flow. The "seal failure internal short" is a very slow physical mechanism and consideration of both individual cell capacity and the level of current necessary for heating lead us to conclude that such an internal short must take place over a period of roughly 100 - 200 h to generate heat fast enough to create an OVERTEMPERATURE condition. For the Storage Fault Tree the "seal failure" basic event probability has also been multiplied by 168 instead of 720 h.

7. Use of the fault tree

Two points must be emphasized at the outset of this discussion: (a) we have assumed that failure of the battery module initiated by the explosion of a single cell is equivalent to damage to the spacecraft; (b) the main usefulness of the fault trees and the purpose for which they are most valuable is in determining the relative importance of the various branches of the fault tree and the sensitivity of the Top Event occurrence frequency to significant changes in any of the basic event probabilities. The fault tree will show which factors are most important to be improved or closely controlled in order to make the Top Event frequency as low as possible within the limits of practicality.

The "hardness" or absolute accuracy in many of the probabilities presented in Figs. 10 - 13 can be argued at some length. Thus, instead of taking a given Top Event probability as a fixed value it is better to state that if we relax stringent limits on quality control and don't do a good job in the battery module design, our Top Event hazard probability may be as great as 10^{-2} for the mission; while, conversely, if we do the best possible job of quality control on components and cells and do a good job on the module design, our Top Event hazard probability may be as low as 10^{-6} per module, essentially that for explosion for unexplained reasons.

Likewise, the probability of an undetected "single cell venting" (Fig. 11) during one month's storage/integration is reduced from 3.43×10^{-2} to 8.63×10^{-5} per module by the use of an on-site SO_2 detector during integration. The probability of a single cell venting is calculated from Fig. 13 with the basic event "cell vent stuck or slow" probability set equal to one (the cell vents as designed; no explosion occurs, but gases are released from the battery module).

8. Conclusions

The analysis has shown that with the right combination of blocking diodes, electrical fuses, thermal fuses, thermal switches, cell balance, cell vents, and battery module vents, the probability of a single cell or a 72-cell module exploding can be reduced to 10^{-6}, essentially the probability due to explosion for unexplained reasons. This one chance in a million value for the module is quite conservative since we have assumed (see Fig. 10) that if a single cell explodes, then one or more additional cells will also explode in a sympathetic secondary reaction, even though the module vents operate normally. This certainty of an uncontrollable secondary explosion seems to us to be the only reasonable assumption based on the present absence of data for battery modules in the present design and for $Li/SOCl_2$ cells.

For one month of integration and test of the spacecraft on the ground the probability of module failure is 10^{-6} (Fig. 11) as stated above. Of equal importance we have considered the possibility of a cell venting (the cell vent operates correctly in Fig. 13 and the 10^{-5} probability of the cell vent being stuck or slow is replaced by 0.999 99) and releasing toxic gases that may injure personnel. The probability of a cell venting has been calculated as 3.43×10^{-2} in Fig. 13. We can reduce the probability of personnel exposure by the use of a sulfur dioxide monitor in line with the module vent manifold. An audible alarm will be triggered whenever the concentration of SO_2 exceeds 1 p.p.m. in the manifold. The left side of Fig. 11 shows that this reduces the probability of an undetected toxic gas release to 8.63×10^{-5} per battery module or about 7×10^{-4} for the complete spacecraft battery.

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