ACCELERATED TEST DESIGN

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I have been working on the same accelerated test program that Dr. Landers has. We have come up with some variations on the predicted equations, and I agree on a number of things with Dr. Landers, and disagree on several things. And those I would like to highlight in this talk. It refers to the type of variation of functional changes that occur with the various parameters.

I agree wholeheartedly with Dr. Landers that we have learned a lot about accelerated testing in this program. Because of the lengthy nature of the test and the analysis itself, a lot of things haven't come out yet about how to test out a new accelerated test. But, I think we should move towards this.

Simply, the motivation for accelerated testing is very high. The expectations may also be too high, or overambitious, but that shouldn't deter us from really trying to do accelerated testing. You can't do good development work on batteries if you have to wait four or five years before you can make a change to see if it is going to be an improvement. And the same for very long-term, real-life tests or programs.

Is it going to help if the battery is going to last seven or eight years? So, the Crane accelerated test program possibly was overly ambitious from the beginning in terms of expectations, that we thought we could learn a lot very quickly. But, still I think we have come out of it with an idea of how to do accelerated testing so that we could do it within, say, a year. And that these expectations are more real and more useful.

When I sat down to figure out for myself what lessons I had learned from the program, they came out somewhat like this.

(Figure 5-21)

(These are some things which I had reflected on and which I had learned from the program.)

General observations about accelerated testing.

Lesson 1. Do not make the accelerated test too complicated. Some practical problems that we ran into with this particular test — and, of course, this was an initial large accelerated test program, so what we are really going to say about it is Monday morning quarterbacking, or hindsight. We really had to go through the process in order to learn these things. But I think it is good to reflect on what we have learned.

Too big a test increases the risk of error. As you automate a program you have unknown unknowns that creep in. The automation itself tends to postpone some decisionmaking if something

goes wrong and you are not able to analyze the result on a real-time basis. As you increase the number of packs, you are increasing exponentially the problems of keeping all of that data in good order and being able to react to changes that are going on during the test period.

So, just the size of the program is going to present a problem.

Too many factors complicate the analysis. As I think Dr. Landers pointed out, say that three design parameters may have overly complicated our analysis of the accelerated parameters, the first five parameters. And if they had been left out, the analysis itself would have been simpler.

Lesson 2. Do not make the accelerated test too short.

Dr. Landers mentioned this, and I agree with it, that overstressing the cells may generate a mode of failure that is not "natural." For example, the hydrogen failures were not natural in the sense that you had had a very great degradation of cell components, electrodes and so on. And that is what I think we want to look at, the degradation of the electrodes and the materials within the cell, rather than a sort of short-high-rate zap of the cell that makes it fail according to some rather arbitrary principles; arbitrary meaning is failure at 250 psi or 200 psi when we are trying to figure out a pressure failure.

Lesson 3. Stay ahead of the data. This we found was a real difficulty with large volumes of data that is being taken in a sort of automatic fashion, put on magnetic data tape, and stored for long periods of time.

We found, for example in our post-test analysis that we didn't need every cycle, and voltages every 30 seconds or so on every cycle. So we went through a routine of trying to figure out what is it that we really wanted from the data, and came up editing these 200-odd tapes, magnetic data tapes which contained a lot of data. I figured out once, if all the data was on cards, it would have stretched from Washington to Crane if you put the boxes of cards end to end.

This becomes almost unmanageable at a point.

So, from the beginning, how do you try to determine what data you are going to take? That is what I mean by preplanning the end use of it.

We came down, for example, in selecting the data from these 200 tapes and condensing it down to four tapes (three or four tapes), and what those four tapes contained are the whole life-time of one pack every 30 or 40 cycles. In other words, at cycle 1, 30, 60, 90 and so on, we would pull out fairly complete voltage data on those cycles.

We also compressed the number of samplings at the beginning of life and compressed the number of samplings at the end of life, because we felt during these long periods of the test, the data were not going to be that useful in the sense that the cells were in a sort of equilibrium state and there were not great changes going on there.

Obviously, in terms of recording, you cannot predict the failure at the end of life, you really cannot predict that from the very beginning. But you can predict how you should take the data at the beginning of life when the cells are reaching an equilibrium. And that your sampling procedure itself can cut down the headaches of amassing great quantities of data and not knowing what to do with it afterwards. Edit and clean up the data as you go.

We ran into problems when we adopted the philosophy that we are going to take a lot of data and later we are going to go back and sift through and throw out the stuff we don't want and so on. This is a problem.

If you are not watching carefully when you begin to take data and something is going on within the test itself that may not be recording properly on the mag tape, we have large sections of blank data simply because the retrieval procedure itself was faulty at that point. So you have to stay on top of the actual collection of data.

Lesson 4. Schedule activities properly. I have divided pretest, test, and post-test. We had some problems with concentrating a lot of our efforts at the wrong time. The pretest should be basically working out all your hardware problems, and early testing the system so that you don't have failures in the middle of the test with, say, data acquisition.

Most of your effort should go into making sure that once the test goes on line, the management of the data from that point on is going to be fairly straightforward.

In the test phase, concentrate on the data acquisition and not on the analysis of the data. We tended to take fairly spotty data, the test cells had not been on test very long, and working equations and grand regressions over a very small data base.

Now, part of this is needed to tool up your analysis so that by the time all the data does come in, you will have the tools ready, which is the post-test. Concentrate on the data analysis after the cells have failed, or most of the cells have failed.

This will tend — you don't run out of steam too fast. I think we had a tendency because a lot of the analysis effort went on too early, that we were sort of over that hump before we really had enough data to do the proper analysis.

Lesson 5. Do not overestimate complexity of batteries and frustrate your efforts. This is not in jest. When you take a large test program — and particularly using large statistical analysis techniques that are developed in other accelerated testing of other types of components — you may have some problems. For example, testing transistors; accelerated testing other components may fit a particular model easily because you can generate reliable distributions and so on, which pretty much map the failure mechanisms that are going on within the component.

But batteries tend to have more "inherent" variables either through manufacturer's design variability, that predictability of the battery itself is not that clean. Therefore, we really need to look for the first order effects and not concentrate too much on finetuning it.

I remember a quote in Dave Pickett's Laboratory back at Wright Patterson of Edison which said when it comes to accumulators, man's inherent capacity for lying comes out. In other words, the nature of the beast itself is tough to deal with, so don't oversensitize your analysis and possibly miss your main effects.

Lesson 6. Choose your stress factors carefully.

(Figure 5-22)

I would like to discuss the better parameters used for accelerating testing and why. Pretty much the same conclusions would be reached as those of Dr. Landers'. I have done it in a slightly different way.

These are the test parameters as seen in the star point, center point test cells. I have tried to see what the effect would look like if you select out each parameter, holding everything else constant. I have presented this in the past in other workshops, so I have done mostly a summary here.

Depth-of-discharge temperature and so on down to volume of KOH as shown.

Then I have shown a range in the star point test.

If you are looking at DOD, this would mean 20, 60 and 100 percent would be the three variables, and everything else would be the same. So for the star point we would be looking at three packs, 20, 60 and 100 everything else the same. I found the variation over that range is around 13,000 cycles. The cycle life exponentially increases toward lower stress.

I guess the way I look at it is the DOD is not a function of 100 minus DOD over DOD as Dr. Landers has found. What I have used in my model is that it is exponentially changing and that the function is E to the DOD, the power of DOD. I found that its usefulness as an accelerator and a predictor is very good because when the cycle life is plotted or logged against DOD, it comes out fairly linear.

What might be happening here is that Dr. Landers' function and this function are probably mapping each other's fairly closely. That is 100 minus X over X is in that range to E to the X. I don't know how you expand E to the X. You might find a series which comes closer to Dr. Landers' function as a close approximation.

So probably in the range that we are dealing with, our functions are fairly consistent with each other. But I think when we get to lower DOD, that's where we get quite a bit of difference.

When I start extrapolating down to very low depths of discharge, I am not getting 100- or 300,000 cycles, I am getting much less. So I think we might be mapping our functions in this region, but when we go below that region our functions are really diverging.

Temperature I put is a good accelerator and a predictor. Not very good, but good.

The variation in the range that we considered here is about 5000. It is approximately linear. It is not actually linear, but within that range it is close enough to consider it linear.

So when I do my regression equation, I put it in as a linear function. Below 20 degrees it does become possibly very nonlinear, but it is close enough to use it at least in a regression equation.

The recharge rate is approximately linear, at least in the range that we are dealing with. Here I am disagreeing with Dr. Landers also.

The effect of the variation is not as great as the other two, and I would say it is a fair predictor.

When I put up the regression equation and I build in a linear recharge rate, I will show you that it comes out as fair, but not as good as the other two.

Charge and discharge rate, I agree with Dr. Landers, is problematic. They can accelerate, depending on various combinations of charge and discharge rate. They can accelerate deterioration, but they are not very good to use as predicting because you are not really sure what effects are going on there.

Dr. Landers showed, for example, that 4C, 2C actually prolongs life, which is sort of against your intuitive feel, perhaps. So it is not very good as a predicting tool.

Precharge — and here it is parabolic in nature with the high point at mid-range. It may not actually follow a parabola, but it is sort of a haystack type thing. That is, the low-charge rate and the high-charge rate show the lower-cycle life and midrange shows the higher-cycle range.

This becomes a problem in using it in the regression model because as you go towards what you conceive of as lower stress, that is lower charge rate, lower discharge rate, cycle life is actually going down. Whereas when you are going to lower temperature, cycle life is going up.

So you are interacting two variables. One is going up while the other is going down, and it is hard to control that. They are sort of nulling each other out.

Precharge and KOH and volume KOH, these are the cell design parameters. And their effect is not large.

These two were parabolic in nature which meant that the range that we were taking had this as one extreme and that as the other, and midpoint was the highest cycle life.

Here again it is problematic to use it as a prediction model, or in the prediction model. If you are going to use parameters for prediction, they ought to all be increasing in the same direction as your lowering stress.

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That may not be true if you are trying to use accelerated testing for a new cell design. Suppose you want to test out and see if the percentage of electrolyte for a particular test should be low, high, or in the middle. In that case you would definitely want to box the range. In other words, you would want to try to get the most stress at each end, but not to be used in prediction, but to be used mainly for teardown analysis after it is over to look at what the effects of the accelerating were.

The volume of KOH turned out to be the lowest variation. It was approximately linear in effect, but its effect was too negligible. In other words, that range just was not large enough to make a difference.

(Figure 5-23)

Now here are the predictions that I have based on my nonlinear regression equation and this took the Crane data, so it includes pretty much all of and maybe more of the data than Dr. Landers had in his equation. I'm not sure. This took almost all the packs.

This is the equation itself. Cycles to failure. Here is a linear recharge term, and here is a linear temperature term, and here is the exponential DOD term. And just to see what the effects would be of charge rate and discharge rate, I threw those in as linear combinations at the end of the equation to see how the computer would handle it.

Now, I say these are linear terms, but they are multiplied times each other, which makes them really interacting terms. And if you interact recharge — looking at this as a quadratic, if you recharge multiplied by temperature comes out as one of the terms with b_2 as a coefficient, we are not holding them only to linearity. They can be having some interactive parabolic effects in here, or hyperbolic effects.

Here are the predictions that come out, limiting this equation only to b_1, b_3, and b_4, which is a constant term out here, no recharge term, keeping temperatures in the equation and a depth of discharge. So this case really shows only DOD and temperature.

This case shows it with recharge. This shows it also with charge rate and discharge rate.

Now the coefficients themselves change quite radically. Some of them do, but these don't. The predictions of the normal packs don't change that much.

Now this 86 is the pack that Dr. Landers predicted what, 22,000?

LANDERS: No, I didn't predict it. There were already three cell failures on it.

McDERMOTT: Three cell failures starting around 18,000 which is where cell failures start.

LANDERS: Two of them still going beyond 24.

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McDERMOTT: And these, in my IE CEC paper from which this slide comes out of, I tried to see where this — well it's obviously too low a prediction. What may come out of this equation is a very conservative prediction, about the lower limit at which you would anticipate cell failure.

My predictions don't get anywhere near what Dr. Landers' does in terms of $0°$ C. Forty-six to fifty thousand is probably the highest my prediction is going to run. And I guess this is probably 10 years. Would that be a 10-year prediction, something like that?

All right.

Now what I have done is I have taken the regression equation and now where do we go from here in terms of designing a new accelerated test?

I took that regression equation with only DOD and temperature. We have to give up some of our accelerating parameters simply to limit the number of packs that we would have on test.

I agree with Dr. Landers, we should limit it to temperature and DOD which have most of the predictability base for a reasonable estimate.

I rearranged the equations so that temperature would be on one side and everything else on the other. Here is DOD. I put charge rate and discharge rate in here simply to estimate the time of the cycle. I am not using those as accelerated in terms of the data, but simply to put into the equation how much each cycle is going to take.

I have plotted temperature versus DOD. If you anticipate the test to only last one month, three months, six months, nine months or a year.

So what I am doing is parametrically looking at, suppose I want a 6-month accelerated test, what should I put the half dozen packs at in terms of temperature and DOD?

What you can do essentially is pick a temperature, 10 degrees here. This is based on the Crane data. That is, the coefficients I would use in this equation are from the Crane data. What this says is, if I took that generation of cells, 1970 GE with nylon separators and so on, and if I ran them at 10 degrees and 80 DOD, they should fail in six months. If I took $20°$ C at 70 DOD, they would fail in 6 months, and so on.

So the idea is, try to set up a test matrix where most of the cells are going to fail around the same time, or within a couple of months of each other, so that you do not overstress them so that they fail too quickly. And don't understress them so that they are lasting two years.

You are trying to pick a time within which you would need to get results. Say if you were doing some program management and you wanted to select six months as the time for your accelerated tests, then you could make some judicious choices in terms of setting up the matrix.

Here is a table for several different combinations of charge rate and discharge rate. Here is the DOD, and these would be the temperature. This is based on a six-month test.

Suppose we want a six-month test, 70 DOD, and 23° C would be where you would set the parameters for that particular pack; 60 and 32, 50 and 39. So you might set up, for example, five packs that would vary temperature; interact essentially temperature and DOD. Then you would use these cycles to failure; the data for cycles to failure and plug it back in the reduced regression equation. By reduced is meant the only variables that you are interacting are temperature and DOD. Therefore, the equation would turn out to be a constant minus temperature times the exponential function of DOD.

You would essentially fit three coefficients, and then using those coefficients you would predict how the cells that you have on test would last in less extreme conditions, say 20° C or 0° C and 20 to 40 DOD.

I suspect that when using this process you are going to end up with predictions that are much lower than Dr. Landers', because what I have done is try to map that range below 20 degrees with an equation which is going to ultimately deliver what we would estimate is a reasonable failure in normal life.

DISCUSSION

LEAR: Pat, your equations up there, or your summation said your recharge rate — you got a fair indication from recharge rates from 110 to 200.

What about below 100?

McDERMOTT: Well, we don't actually know that except to say that my predictions in case 2 were based on a linear function. And my predictions are coming out low.

So I would suspect between 110 and 100 percent recharge, that it is increasing there, possibly dramatically, that I don't see, in other words, to explain the difference between what we are actually seeing with the normal packs. So it might be that that recharge rate, or the interaction of that recharge rate below 110 is fairly important.

I would probably set up an accelerated test. I would take recharge out of it, and I would not use a constant current charge. Also, as Dr. Landers has suggested, I would just have a voltage cutoff or something like that. I would take charge rate and recharge out of it as far as accelerated parameters, and just lean heavily on temperature and DOD.

LEAR: Now, I have a second question for temperature. You were referring to temperature. What is that temperature? Is it an absolute temperature, is it an ambient of the test specimen? What?

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McDERMOTT: The samples are in a temperature box that are set at so many degrees C. So it is, yes, based on degrees Centigrade. It is the temperature of the environmental box that they are in.

There was some range in terms of the thermistors that were on the battery itself. I think they ranged up to five degrees outside of that, and that's one of the problems with trying to look at this too precisely and saying this is it at 10 degrees and this is it at 20 degrees. It might be you are looking at 12 1/2 to 13 degrees and 23 degrees or so in the actual environment.

That is why I keep it in what I call first-order effects; not trying to compress too tightly what you consider is the sensitivity of even the prediction equations to those variables themselves. For example, DOD; if you take it as an absolute, then 100-percent DOD is only taking out six ampere hours in the cell, which has a capacity of seven or eight.

But in the regression equation, factors like that really come out in terms of the coefficient so that the coefficient takes care of differences in capacity. I am just saying you don't want to think that your test is actually being performed at 10° C exactly. It is not.

RITTERMAN: Your parameters are based on the treatment of the cells with the exception of the one with the electrolyte.

Nickel-cadmium cells have been changing in the last few years. Teflonated coating on the negative electrode, we have lighter load, we have different toxic center, and we have different toxic risk. We are going toward electrochemical impregnation on the positive electrodes.

Would you say that your model is valid for these newer types of cells, especially since the basis of your model is 67 to what, 78 or something like that?

McDERMOTT: What I would say is the form of the equation is a problem, but the coefficients would have to be determined by actually putting yourselves on test.

RITTERMAN: *So you cannot make any prediction on a new type of cell based on . . . .*

McDERMOTT: I would take the coefficients we got at Crane and use those as the first approximation to determine whether you want your test to last six or eight months. Your test may actually end up lasting a year if your cells are twice as good.

But it is trying to get a first approximation for how you should set up your matrix, and then you run your test matrix. You get your results, you recalculate the coefficients and then you . . . .

RITTERMAN: You have to test the new cells.

McDERMOTT: You have to test the new cells. I don't see any way of taking these results and making a prediction on your cell. I just don't think it is going to work. A lot of this was outlined in the IE CEC paper, if you want to look at the actual methodology I would use to set up the test. I just didn't have time today to actually go into that.

GENERAL OBSERVATIONS
ABOUT ACCELERATED TESTING

LESSON 1   DO NOT MAKE YOUR ACCELERATED TEST TOO COMPLICATED

-- TOO BIG A TEST INCREASES RISK OF ERROR
-- TOO MANY FACTORS COMPLICATE THE ANALYSIS

LESSON 2   DO NOT MAKE YOUR ACCELERATED TEST "TOO SHORT"

== OVER STRESSING THE CELLS DISTORTS RESULTS
== FAILURE MODE NOT NATURAL

LESSON 3   STAY AHEAD OF THE DATA

-- PREPLAN THE END USE OF THE DATA AND DO NOT RECORD EVERYTHING
-- EDIT AND "CLEAN UP" DATA AS YOU GO

LESSON 4   SCHEDULE ACTIVITIES PROPERLY

-- PRETEST - RESOLVE HARDWARE PROBLEMS AND DISAGREEMENTS ABOUT
      TEST OBJECTIVES HERE
-- TEST - CONCENTRATE ON DATA ACQUISITION
-- POST-TEST - CONCENTRATE ON DATA ANALYSIS

LESSON 5   DO NOT OVERESTIMATE COMPLEXITY OF THE BATTERIES TO FRUSTRATE
YOUR EFFORTS

-- BUILD IN TEST FLEXIBILITY
-- LOOK FOR FIRST ORDER EFFECTS

LESSON 6   CHOOSE YOUR STRESS FACTORS CAREFULLY

-- LIMIT SIZE OF TEST MATRIX

Figure 5-21

ACCELERATED TEST PARAMETERS

PARAMETER	RANGE IN TEST	VARIATION OVER THE RANGE*	USEFULNESS AS ACCELERATOR AND PREDICTOR
DEPTH OF DISCHARGE	20-100%	13,000 CYC. - E	VERY GOOD
TEMPERATURE	20-60°C	4,700 CYC. - L	GOOD
RECHARGE RATE	110-200%	1,800 CYC. - L	FAIR
CHARGE RATE	C/4 - 4C	2,700 CYC. - P	PROBLEMATIC
DISCHARGE RATE	C/2 - 8C	1,500 CYC. - P	PROBLEMATIC
PRECHARGE	2.2 - 3.3 AH	1,000 CYC. - P	PROBLEMATIC
% KOH	22-38%	1,500 CYC. - P	PROBLEMATIC
VOLUME KOH	17.5 - 21.5 CC	800 CYC. - L	NEGLIGIBLE

* E = CYCLE LIFE EXPONENTIALLY INCREASING TOWARD LOWER STRESS

L = APPROXIMATE LINEAR INCREASE TOWARD LOWER STRESS

P = PARABOLIC IN NATURE WITH HIGH POINT AT MID RANGE

Figure 5-22

PREDICTIONS BASED ON NON-LINEAR REGRESSION

Cycles to

REGRESSION EQUATION

$$\text{Failure} = (b_1 + b_2 \ RC) \times (b_3 - T) \times e^{b_4 \ DOD} + b_5 \ DCR + b_6 \ CR$$

RC = Recharge Rate   DOD = Depth of Discharge
CR = Charge Rate   T = Temperature
DCR = Discharge Rate

NORMAL PACK'S CYCLING PARAMETERS

PACK	TEMP.	DOD	RC	DCR	CR
86N	20°C	40%	105%	C/1.2	C/4.0
83N	0°C	40%	105%	C/1.2	C/4.0
84N	20°C	20%	105%	C/2.4	C/2.4
85N	0°C	20%	105%	C/2.4	C/2.4

	Old Eqn. + 50% Case 1	Add RC Term Case 2	Add DCR & CR Terms Case 3
b_1 =	1,000	2,100	3,083
b_2 =	—	6.6	10.3
b_3 =	70.0	66.0	62.0
b_4 =	-0.038	-0.037	-0.045
b_5 =	—	—	30.6
b_6 =	—	—	34.6

PREDICTION OF CELL FAILURE

Case 1	Case 2	Case 3
15,000	14,700	14,350
20,400	21,800	21,120
33,750	33,900	34,600
46,500	44,700	51,030

Figure 5-23

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