

## PREFACE

This, the 12th Annual Battery Workshop was attended by manufacturers, users, and government representatives interested in the latest results of testing, analysis, and development of the sealed nickel cadmium cell system. Also included were sessions on metal hydrogen and lithium cell technology and applications. The purpose of the Workshop was to share flight and test experience, stimulate discussion on problem areas, and to review the latest technology improvements.

The papers presented in this document have been derived from transcripts taken at the Workshop held at the Goddard Space Flight Center on November 13 to 15, 1979. The transcripts were lightly edited with the speaker's vugraphs assembled at the end of each presentation for uniformity.



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## INTRODUCTION

G. Halpert  
Goddard Space Flight Center

Welcome to Goddard Space Flight Center and the 1979 NASA/GSFC Battery Workshop. We have planned an interesting electrochemical cell and battery technology program.

To begin, R. Riebling from NASA Headquarters will describe the present NASA electrochemical research and development effort. Secondly, L. Slifer from GSFC will summarize the results of the OSTA Power Subsystems Committee which met in August. The third event will be a panel discussion on a subject of much concern, "Bridging the Gap between Technology and Flight Hardware." Panel dialogues have been successful in past workshops, and this year's panel should continue the trend. The lithium cell application and safety session follows.

Wednesday morning the subjects will be cell and battery technology and test and flight experience. The accelerated test analyses continue, and their results will be the subject of an expanded session on Thursday, as well as continuing discussions on nickel hydrogen cell and battery design and test results.

We at NASA/GSFC again welcome you and hope that through your active participation you will find this year's workshop to be beneficial.

For your information, we have included a list of the acquisition numbers for all workshop proceedings dating back to 1970.

### BATTERY WORKSHOP PROCEEDINGS

		Doc. No.
1978	Workshop	79N28669
1977	Workshop	79N21565
1976	Workshop	77N21550
1975	Workshop	76N24704
1974	Workshop	75N16976
1973	Workshop (1st Day)	75N15152
	Workshop (2nd Day)	75N17808

		Doc. No.
1972	Workshop (1st Day)	73N21956
	Workshop (2nd Day)	73N21957
1971	Workshop (Vol. 1)	72N27061
	Workshop (Vol. 2)	72N27062
1970	Workshop (1st Day)	71N28659
	Workshop (2nd Day)	71N28672

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SESSION I

TECHNOLOGY DEVELOPING FLIGHT HARDWARE

F. Ford, Chairman  
Goddard Space Flight Center



## OVERVIEW OF NASA BATTERY TECHNOLOGY PROGRAM

R. Riebling  
NASA Headquarters

I am going to be highlighting OAST's technology program in batteries for space applications. I will be presenting highlights only, not only because of the time constraints, but also because many subsequent speakers will be presenting details of the program elements, and because there will be an article in the special January issue of the "Advanced Battery Technology Newsletter," which will discuss the mass of OAST battery technology programs in greater detail.

The electrochemistry program in OAST includes not only batteries but also fuel cells and electrolysis technology. Because this is a battery workshop, I am going to be restricting my remarks today only to the battery portion of the program.

And finally, I will be discussing only the technology work that we are sponsoring. The flight experience will be discussed on Wednesday.

The OAST battery technology program is funded at roughly \$2 million a year, and in FY 80 that level of funding will be continued. Of that amount, approximately two-thirds is managed and spent by the Lewis Research Center in Cleveland; and one-third, by the Jet Propulsion Laboratory in Pasadena, California. Of that same total of \$2 million, approximately one-half is in-house work, and the remaining half is contracting with industry and is awarded as grants to universities.

(Figure 1-1)

This vugraph indicates some of the program elements or what is in the program. First, we have advanced ambient temperature alkaline secondaries, which are primarily nickel-cadmium cells in batteries.

Then, we have secondaries with multi-kilowatt-hour storage capacity primarily for lower orbital applications that we see in the future. Those are mainly toroidal nickel cadmium, and there is a fuel cell electrolizer program going on at the Johnson Space Center. But, since that is not a battery program, it will not be discussed today.

The program also includes ambient temperature lithium batteries, both primary and secondary, high-energy density, higher than ambient temperature secondaries. Finally, metal-gas secondaries, primarily silver hydrogen, and high-capacity nickel hydrogen are included in the program.

(Figure 1-2)

The general objectives of all these elements of the technology program are to increase the useful energy density; to increase the storage capacity, primarily for lower orbital applications; to

extend the useful life; to extend the cycle capability for secondaries, of course; and to always improve the reliability and the safety of these devices.

(Figure 1-3)

This chart summarizes some of our near-term specific objectives. In the interests of time, I am not going to cover every cell in this matrix, but this chart will be in the proceedings.

By the near term we mean the mid-1980s for the most part. By 1983 to 1985, we would hope to have brought the technology along to the state where electrochemical systems would have these particular characteristics for our applications.

The first column on this chart indicates what those applications are. As you can see, it spans the spectrum of all the regions of space in which we are interested from low-Earth orbit all the way out to geosynchronous planetary orbiters, landers, and probes. Each of those has its own special requirements in terms of capacity and energy density.

The second column indicates the major electrochemical system which is being advanced for those applications. You can see that we have some nickel-cadmium work going on, as well as some silver hydrogen sodium chalcogenide and several lithium systems.

Among these specific objectives, with the exception of the low-Earth orbiters where our major objective is the 100-ampere hour capacity, the primary near-term objective for all of the other application systems are the cell energy density and the battery life. The numbers in those columns represent our near-term objectives.

For completion, we have indicated cycle life and corresponding depth of discharge to add some meaning to those numbers.

(Figure 1-4)

In the remainder of my presentation, I want to cover just some of the highlights of these different program elements. In advanced alkaline secondaries, two primary objectives are to develop a fundamental understanding of nickel cadmium, cell degradation, and failure mechanisms and to embody these in some kind of a useful, reliable, predictive model that users can actually employ.

Also, we would like to achieve longer life, i.e., greater than 900 or 1000 cycles, greater than 10 years, and get the specific energy up greater than 26 watt-hours per kilogram with the nickel-cadmium system.

An approach to this is improvements in separator technology, technology of electrodes, and reconditioning procedures. Most of that you will hear about subsequently.

There has been a good deal of progress going on in this entire program, but in limited time, it is very difficult to convey all of that progress. Fortunately, a number of the speakers who will follow me over the next several days will be highlighting their progress in a lot more detail.

Recent progress in nickel cadmium, however, includes the attainment of superior hydrogen recombination rates under reversal conditions. It has been demonstrated by Lewis, PRW, in C/2 discharge rates and some new experimental cell design, which I understand will be discussed on Wednesday.

Also, a failure model for nickel-cadmium cells has been developed and partially validated at JPL, and that will be discussed on Thursday.

(Figure 1-5)

The objective of multi-kilowatt-hour storage technology is to establish the feasibility of a greater than 100-ampere hour, greater than 5-year life, and relatively low-cost nickel-cadmium cell of a toroidal configuration relatively soon, by the end of this fiscal year. Then, depending on how feasible it looks, further development may be undertaken.

Also, NASA/OAST is interested in a preliminary evaluation of nickel-hydrogen batteries somewhere in the range of 65 watt-hours per kilogram for high capacity, lower orbit applications. While most of that work is being conducted by the Air Force for tracking, there is a small in-house program going on at Lewis to take a closer look at that technology for our applications.

Recent progress in this area includes the design of a toroidal cell and investigation of fabrication, and sealing techniques have been initiated by Lewis.

(Figure 1-6)

Lithium systems—Work is going on both in primaries and secondaries. One objective is to demonstrate a safe 300 or more watt-hour per kilogram primary battery for probe applications with a 5-year storage life at relatively high drain conditions by the end of FY 84.

Another objective is to demonstrate a 220-watt-hour per kilogram secondary battery for lander applications by the end of FY 82. It may turn out that a target of 150 watt-hours per kilogram might be more reasonable. That is under consideration.

The approach in the lithium program is, first of all, to gain a fundamental understanding of the physical and chemical processes which are unique to lithium-based systems; also, to develop and characterize new or improved electrodes, electrolytes, and materials; and third, to develop a NASA in-house capability to fabricate prototype cells and to write design specifications.

In the past, NASA's lithium technology program has been, in my estimation, overly beholden to contractors and their capabilities. We now feel NASA would benefit from having a stronger in-house capability in lithium systems. Consequently, the lithium program has been reoriented along those lines within the past 6 months.

Recently, lithium anode conducting film modeling has been going on at JPL. Lithium hexafluoroarsenate has been selected as a primary candidate electrolyte for study in secondary cells. These will be discussed in more detail by several speakers this afternoon.

(Figure 1-7)

In the high energy density secondary systems, we have an objective of establishing the feasibility of 5-year again graded in 200 watt-hour per kilogram energy density secondary batteries by the end of FY 82. This work is being carried out at the Lewis Research Center. The approach centers about the use of liquid sodium anodes, thin beta alumina solid electrolytes, and solid transition metal, chalcogenides for reversible intercalation of sodium ions.

Recent progress has been a demonstration of the feasibility irreversibly intercalating up to two equivalents of sodium ion in vanadium disulfide and  $\text{NiPS}_3$  at high temperatures.

(Figure 1-8)

Finally, in the metal gas secondaries, we want to complete both our preliminary evaluation of a 77-watt-hour per kilogram 50-ampere hour silver hydrogen cell this fiscal year and that evaluation of nickel-hydrogen batteries which I discussed earlier. This subject overlaps that of the multi-kilowatt-hour energy storage program element.

Recent progress at the Lewis Research Center includes demonstration of a 50-ampere hour 80-watt-hour per kilogram silver hydrogen cell which has completed 600 cycles. Also, in more basic research at that center, certain silver electrodes have demonstrated 1500 cycles in single cell tests.

Before concluding, I should point out that NASA is also advancing the technology of secondary nickel-zinc systems for terrestrial applications under its technology utilization program. This is work which is not directly sponsored by OAST. NASA is also responsible for several electrochemical technology programs or projects which are being carried out for the Department of Energy.

These generally center about batteries for electric and hybrid vehicles and energy storage for utility power generation. But our emphasis, or at least the emphasis in my presentation, has been on space technology, so I won't discuss those any further here.

## DISCUSSION

LEAR: I would like to ask you about the silver hydrogen tests that were conducted at NASA Lewis. What sort of criteria were you testing with the silver hydrogen cells?

RIEBLING: I regret I cannot give you very many details of that, but there is a representative from Lewis in the audience. I would like him to identify himself and hopefully respond to that question.

SMITHRICK: The question that was asked on the silver hydrogen cycle life data, as I remember it, was what were the specific test conditions for the cycle life?

Well, it was an accelerated synchronous orbit test, an 8-hour cycle, consisting of 6.8 hours of charge and 1.2 hours of discharge. The discharge and charge were both at constant currents, and



the depth of discharge was 75 percent. If the voltage should drop below 0.9 volt, that is defined as the end of life.

The data presented was for a 50-ampere hour cell. There is also some data for a 35-ampere hour cell. The 35-ampere hour cell was cycled for over 960 cycles, and the test is still being continued.

LEAR: What was the constant current rate that you had during the charge and the discharge?

SMITHRICK: The cell that was presented was a 50-ampere hour cell. So, the current is 50-ampere hours divided by 1.2 hours, whatever that number comes out to. You know for a 75-percent depth of discharge, I don't have a calculator with me, but that is the way we figure it out. Of course, the same thing would be for the charge.

You take 50-ampere hours and multiply it by 0.75 and that comes out to—well, whatever it comes out to, and just divide that.

RIEBLING: I should say that the silver hydrogen work is not a large or major element of our technology program. This work is nearly complete and is being phased out. The primary reason is that the metal gas cells are being developed by other agencies, and probably the nickel-hydrogen systems are the ones that will likely find themselves in use in the near term, so the silver hydrogen is being relinquished to the back burner for a while.

PROGRAM ELEMENTS

- ADVANCED AMBIENT-TEMPERATURE ALKALINE SECONDARIES
- MULTI-KWH CAPACITY SECONDARIES
- AMBIENT-TEMPERATURE LITHIUM PRIMARIES AND SECONDARIES
- HIGH-ENERGY-DENSITY, ABOVE AMBIENT TEMPERATURE SECONDARIES
- METAL-GAS SECONDARIES

Figure 1-1

GENERAL OBJECTIVES

ADVANCE PRIMARY AND SECONDARY SPACE BATTERY TECHNOLOGY TO INCREASE:

- ENERGY DENSITY
- STORAGE CAPACITY (LEO)
- USEFUL LIFE
- CYCLE CAPABILITY (SECONDARIES)
- RELIABILITY AND SAFETY

Figure 1-2

NEAR-TERM SPECIFIC OBJECTIVES

PRIMARY APPLICATION	ELECTROCHEMICAL SYSTEM	CAPACITY Ah	CELL ENERGY DENSITY, Wh/kg	BATTERY LIFE, YR	CYCLE LIFE	DOD %
LOW EARTH ORBITERS	Ni-Cd (TORROIDAL)	100	30	5	25,000	20
GEOSYNCHRONOUS ORBITERS	Ag-H <sub>2</sub>	50	66	10	1,000	75
	Na/CHALCOGENIDE	100	300	5-10	1,000	75
PLANETARY ORBITERS	Li-TiS <sub>2</sub>	5-10	220	10	500	65
PLANETARY LANDERS	Li-TiS <sub>2</sub>	5-10	220	10	5,000	35
PLANETARY PROBES	LiSOCL <sub>2</sub>	20-50	330	5	PRIMARY	80

Figure 1-3

ADVANCED ALKALINE SECONDARIES

POTENTIAL APPLICATIONS

- GEOSYNCHRONOUS ORBITERS
- NEAR-TERM PLANETARY ORBITERS

OBJECTIVES

- DEVELOP FUNDAMENTAL UNDERSTANDING OF NiCd CELL DEGRADATION AND FAILURE MECHANISMS, EMBODY IN PREDICTIVE MODEL
- ACHIEVE LONG LIFE (>900 CYCLES, >10 YR) AND HIGH SPECIFIC ENERGY (>26 Whr/kg) WITH NiCd BATTERIES THROUGH IMPROVEMENTS IN SEPARATORS, ELECTRODES, AND RECONDITIONING PROCEDURES

RECENT PROGRESS

- SUPERIOR H<sub>2</sub> RECOMBINATION AT  $\leq 0V$ , DEMONSTRATED BY LeRC/TRW AT C/2 OVERDISCHARGE RATES IN NEW EXPERIMENTAL CELL DESIGNS
- FAILURE MODEL FOR NiCd CELLS DEVELOPED AND PARTIALLY VALIDATED AT JPL

Figure 1-4

POTENTIAL APPLICATIONS

- LOW-EARTH ORBITERS

OBJECTIVES

- DETERMINE FEASIBILITY OF  $>100$  A-HR,  $>5$ -YR LIFE,  $<\$30$ /W-HR TORROIDAL  $\text{NiCd}$  CELL BY EOFY'80
- COMPLETE PRELIMINARY EVALUATION OF  $\text{Ni-H}_2$  BATTERIES FOR HIGH-CAPACITY LOW-EARTH ORBIT APPLICATIONS IN FY'80

RECENT PROGRESS

- DESIGN OF TORROIDAL CELL, INVESTIGATION OF FABRICATION AND SEALING TECHNIQUES INITIATED BY LeRC

Figure 1-5

## HIGH ENERGY DENSITY SECONDARY SYSTEMS

POTENTIAL APPLICATIONS

- GEOSYNCHRONOUS, PLANETARY ORBITERS

OBJECTIVE

- ESTABLISH FEASIBILITY OF 5-YR,  $>200$  WH/KG SECONDARY BATTERY BY EOFY'82

RECENT PROGRESS

- FEASIBILITY OF REVERSIBLY INTERCALATING UP TO 2 EQUIVALENTS OF  $\text{Na}^+$  IN  $\text{VS}_2$  AND  $\text{NiPS}_3$  AT  $130^\circ\text{C}$ . DEMONSTRATED BY LeRC/EIC.

Figure 1-7

POTENTIAL APPLICATIONS

- PRIMARY - PLANETARY PROBES
- SECONDARY - PLANETARY ORBITERS, LANDERS

OBJECTIVES

- DEMONSTRATE SAFE 300 WHR/KG PRIMARY PROBE BATTERIES WITH 5-YR STORAGE LIFE AT C/1 BY END OF FY'84
- DEMONSTRATE 220 WHR/KG SECONDARY LANDER BATTERIES BY END OF FY'82

RECENT PROGRESS (PROGRAM REORIENTED LAST QTR OF FY'79)

- LITHIUM ANODE CONDUCTING FILM MODELING INITIATED AT JPL
- $\text{LiAsF}_6$  SELECTED AS CANDIDATE ELECTROLYTE FOR STUDY IN SECONDARY CELLS

Figure 1-6

## METAL-GAS SECONDARIES

POTENTIAL APPLICATIONS

- GEOSYNCHRONOUS, LOW-EARTH ORBITERS

OBJECTIVES

- COMPLETE PRELIMINARY EVALUATION OF 77 WH/KG, 50 AH  $\text{Ag-H}_2$  CELLS IN FY'80
- COMPLETE PRELIMINARY EVALUATION OF  $\text{Ni-H}_2$  BATTERIES FOR HIGH-CAPACITY LOW-EARTH ORBIT APPLICATIONS IN FY'80

RECENT PROGRESS

- 50 AH, 80 WH/KG  $\text{Ag-H}_2$  CELL HAS COMPLETED 600 CYCLES AT LeRC

Figure 1-8



RECOMMENDATIONS OF OSTA FLIGHT TECHNOLOGY  
IMPROVEMENT WORKSHOP - POWER SUBSYSTEMS PANEL

L. Slifer  
NASA/GSFC

(Figure 1-9)

This presentation discusses the recommendations of the Power Subsystems Panel of the Office of Space and Terrestrial Application Workshop, which was held in July and August 1979. The primary thrust of the workshop was directed at radiometric problems which have been showing up. But, in the process, several panels were developed to contribute to this workshop.

(Figure 1-10)

The Radiometric Instruments and Calibrations Panel, as I said, was the primary one. There was also concern for electromechanical subsystems, attitude control and determination, and power systems in that each of these subsystems affects what happens with the experiments and instruments on board a spacecraft. If these systems are not working properly, the experiments and instruments are not working right.

(Figure 1-11)

This report is essentially the report from the power panel, which, as you can see, consisted of a large variety of power systems people from the various users, both government and industry.

(Figure 1-12)

The objective of the workshop was to identify the technology needs that become apparent through previous problems. I might say that throughout the workshop, there was a lot of difficulty with how to talk about problems versus failures versus anomalies, and so forth, because of sensitivities of people there. It was related to past and ongoing missions. In other words, problems that have not been completely solved in the past, new problems that we are facing right now, and near-future potentials; not problems that are going to come up because we are going to have space platforms or highly advanced technology requirements coming up in the more distant future.

In the process, though, we could not ignore the direction that things are going. Since we were looking at past problems and the direction they are leading, obviously the future could not be totally excluded.

We did consider both the spacecraft power subsystem and power supplies for the experiments and instruments. The real bottom-line objective was to come up with recommendations for technology development, essentially define areas that needed development. We did not come up with a

specific program. I should emphasize that these conclusions and recommendations come from the power panel, not from NASA, not from Goddard, not from me, but from the panel as a group working together.

(Figure 1-13)

The approach used was to identify technology problems. Just about everyone on the panel made a presentation based on problems that had been seen at his agency or with regard to particular spacecraft that he has worked on, or was associated with.

We also looked at papers from the other panels to see where there were relationships between power system problems and other panel problems. Initially, we categorized them by areas.

(Figure 1-14)

Essentially, the basic areas are the power subsystem, the system, the array, the batteries, and so forth. Then, these problems were translated into technology development requirements.

(Figure 1-15)

We classified the requirements into a second group of work categories, and then we did some prioritizing.

(Figure 1-16)

This is the set of work categories, listed in priority order, indicating the areas that are problem areas. The ones noted with an asterisk are those which relate, in one way or another, to batteries themselves.

(Figure 1-17)

We did note particularly two other problem areas. In the one area, the lightweight structures of the arrays cause problems with spacecraft orientation and control systems. In the other area, thermal control can be very serious as far as battery performance is concerned. It is a very important area, but it is not something that battery people can do much about. It is up to thermal control systems to give us good thermal control.

(Figure 1-18)

Now, we get into the specific categories in a little more detail. Although it is currently primarily a problem with solar arrays, there are requirements for analytical modeling in batteries. It is not only a matter of the DC modeling, but we are getting into the area where AC problems require solution. We need to know the AC analytical model for batteries.

There is very little data that exists, and it is a very difficult field to work in right now. The payoff on work in this area is that we safeguard against bus instability. We have run into that in flight spacecraft and can avoid harmful interactions between the array and filter components. By defining the source impedance at the load bus, we could model the spacecraft power system better. We really need this model because the whole systems are getting so large that all-up system tests cannot be performed anymore.

(Figure 1-19)

A second area is the state of health monitoring. The conclusions of the power panel indicate the need for a better state of health monitoring, more detailed monitoring of what is happening in the power system in flight.

There are a couple of reasons for this: One is that we are getting away from the point where we are in constant contact with the spacecraft. In order to have the spacecraft power system functioning properly, we need more monitoring of what is going on, and, in fact, onboard processing of what is going on in order to handle the power subsystem when we cannot handle it from the ground. Extensive ground monitoring has been required in the past, and a lot of ground analytical work has been required, to the extent of actually flying the spacecraft by wire, you might say, continually controlling it from the ground in order to keep things working. On some recent spacecraft this has been particularly a result of unanticipated poor performance of the battery compared to the desired performance.

(Figure 1-20)

I will not go into much new component development for high voltage and high-power components. The only thing that does relate to the battery is that the power subsystems on the larger spacecraft are getting up to the point where tremendous currents are required. Unless the bus voltages go up, the currents result in tremendous weight penalties.

With the increasing bus voltages, it means either circuitry to take care of it, boost circuitry, or more cells in series in the battery. That, in turn, says something about reliability; also, in turn, says something about the problem of flying multiple batteries to back each other up.

(Figure 1-21)

The high voltage technology was really a matter of reliable-type technology related to spacecraft experiments.

(Figure 1-22)

Array cell testing is related to the solar array, its cells, and the testing in order to get reliability from the array.

(Figure 1-23)

Nickel-cadmium battery manufacturing and application—the consensus of the power panel was that efforts in understanding completed cell, and so forth, should be somewhat modified into the direction of having more basic studies of what is going on within the cells, actually, the electrochemistry and the electrochemical and physical analysis of just what is happening within the cells, so that we can better understand the cells, better know how to manufacture them, and come out with more consistent cells in the long run. Part of this would lead to less requirements for selection if there is more uniformity in the batteries.

(Figure 1-24)

Substorm plasma effects have to do with the high voltages generated on the spacecraft surface primarily in geosynchronous orbit during the geomagnetic substorm periods.

(Figure 1-25)

The engineering data base is listed as moderate priority. I might say that the way priorities were set, it is very difficult to set anything as a low priority once you have identified problems in space that have occurred. So, when we list high priority, moderate priority, low priority, what we are really talking about is the highest of high priority items and the lowest of high priority items.

This area, which the panel discussion will get into quite a bit further, essentially is becoming a very difficult area, because as new technology comes up, it either is unacceptable for the flight programs because the project managers cannot be convinced that it is ready for flight, or if used on the flight programs, it is used with quite a bit of risk because the new technology item has not been fully characterized and we don't really know how it is going to work.

A case in point might be the nickel-hydrogen batteries. They look good, but we really don't know enough about them to dedicate them as the storage system, the sole storage system for spacecraft. So, development of the data base from the development point of the item over to the flight applications point, what you might call the engineering development, has pretty much been dropped as a research phase or development phase.

The engineering development from the research item to the flight item is kind of missing. When it does come in on a flight project because it is mandatory that we use that new equipment, that new battery, and what have you, the engineering data base is developed for that specific flight project and is not directly applicable to all other flight projects.

(Figure 1-26)

Rotary joint for power transfer—this is transfer from the array to the spacecraft, so you essentially get the power from the solar cells into the main spacecraft itself.

(Figure 1-27)



On array power management was a kind of a blue sky type of thing. There is a need for better management before it gets into the spacecraft, better management of the power in order to keep initial high-power levels down. But, we really, as a panel, could not come up with anything really definitive as to how this would be done effectively. That was the reason it was given a low priority.

(Figure 1-28)

This list of references indicates the breadth of how many papers were presented at the workshop, and these were all done on the first morning or the first day of the workshop. The listing will be in the proceedings in case you want to look at any of them in more detail.

## DISCUSSION

FORD: Lou, I believe, correct me if I am wrong, that there will be a publication out very shortly?

SLIFER: The proceedings will be published. The schedule given out at the workshop called for the proceedings to be published in December. It looks like they are running perhaps 2 weeks behind the detailed schedule. So, to me, it still looks like December. But, it looks like a real possibility for even picking up those 2 weeks. It may be late November, even. The entire proceedings of the workshop, the results from all four panels, will be published at that time.

GROSS: I saw very little relationship between the problems that you identified in the research program and Bob Riebling set forth.

SLIFER: This is really because of the first objective, to look at what has been happening in the past, where are our problems. That is really what we started with. The papers that were presented at the workshop essentially presented the problems that we have been having or that we are having right now.

Bob Riebling's program is directed to the future, 1983, 1985, and as near-term and in the far-term program.

Now, Headquarters has taken a very serious look at these recommendations. I don't know what they are going to decide about them, but I do know that they certainly are not ignoring them. They are looking at them very closely.

RIEBLING: Sid, I have to agree with you, and I think this points out the gap that we see existing between the technologists and the users. One of the first things that we are doing about it is that I asked to have the panel discussion this morning to attempt to bring together technologists and users and to see if we cannot find a way of bringing these people closer together and narrowing this gap. It is something that we recognize as a problem.

VASANTH: You have mentioned that more basic studies related to reactions within the cells including nickel-cadmium batteries are required. Can you throw more light on what specific areas

you would recommend research activity? Have you had any problems in those nickel-cadmium batteries?

SLIFER: Well, I would have to pass that on to someone who is more expert in the specifics of what is inside the battery and how these chemical reactions take place. Not only the chemical reactions you intend to take place, but also the ones that result from materials that are in there which you really did not want in there.

I think from the panel discussion it really comes out with the electrodes, the separators, and the electrolyte, and all three need better understanding as to the electrochemical and physical processes.

RIEBLING: I would like to add a bit to what Lou just said. It is my personal opinion that many of the flight problems that were discussed at the referenced workshop, the problems lie not necessarily with technology, but rather with manufacturing. There is a difference between understanding the technology or the science of an electrochemical system and being able to reproducibly produce these in small quantities for a small buyer such as NASA.

So it may not always be technology, but it may be production problems in there, and we need again to bring the technologies of manufacturers and users all closer together.

RECOMMENDATIONS OF THE  
OSTA FLIGHT TECHNOLOGY IMPROVEMENT WORKSHOP  
POWER SUBSYSTEMS PANEL  
JULY 31 & AUG. 1, 2, 1979

PRESENTATION TO:  
NASA/GSFC 1979 BATTERY WORKSHOP

L. SLIFER  
11/13/79

Figure 1-9

WORKSHOP PANELS

RADIOMETRIC INSTRUMENTS AND CALIBRATION  
ELECTROMECHANICAL SUBSYSTEMS  
ATTITUDE CONTROL AND DETERMINATION  
POWER SUBSYSTEMS

Figure 1-10

## POWER PANEL

<u>ORGANIZATION</u>	<u>NAME</u>
NASA-GSFC	L. SLIFER (CHAIRMAN)
NASA-OAST	L. RANDOLPH
NASA-GSFC	F. FORD
NASA-GSFC	J. WESTROM
NASA-MSFC	J. MILLER
NASA-LARC	E. KELSEY
WPAFB-APL	R. BARTHELEMY
NRL	J. WINKLER
AEROSPACE CORP.	H. KILLIAN
JPL	M. SWERDLING
COMSAT LABS.	W. BILLERBECK
BOEING AEROSPACE	S. SILVERMAN
FORD AEROSPACE	H. MCKINNEY
GENERAL ELECTRIC	S. PECK
HUGHES AIRCRAFT	J. HAYDEN
MARTIN-MARIETTA	M. IMAMURA
RCA	P. NEKRASOV
TRW	R. SPARKS

Figure 1-11

OBJECTIVES

- o TO IDENTIFY TECHNOLOGY NEEDS THAT HAVE BECOME APPARENT THROUGH A REVIEW OF PROBLEMS THAT OCCURRED ON PAST AND ON-GOING SPACEFLIGHT MISSIONS, (NOT FUTURE POTENTIALS)
- o CONSIDER BOTH SPACECRAFT POWER SUBSYSTEM AND EXPERIMENT/INSTRUMENT POWER SUPPLIES
- o TO RECOMMEND A TECHNOLOGY DEVELOPMENT PROGRAM TO ACCOMMODATE THE IDENTIFIED NEEDS

Figure 1-12

TECHNOLOGY PROBLEM AREAS

1. POWER SYSTEM
2. SOLAR ARRAY
3. BATTERY
4. POWER DISTRIBUTION (SWITCHING, FAULT PROTECTION, CABLES, HIGH VOLTAGE)
5. POWER CONDITIONING ELECTRONICS
6. HIGH VOLTAGE POWER SUPPLIES
7. POWER TRANSFER
8. GENERAL PROBLEMS (DATA, QUALIFIED PARTS, ETC.)

Figure 1-14

APPROACH

- IDENTIFY TECHNOLOGY PROBLEMS
  - PRESENTATIONS (SEE REFERENCES)
  - PAPERS FROM OTHER PANELS
- INITIAL CATEGORIZATION BY AREA
- TRANSLATE PROBLEMS INTO TECHNOLOGY DEVELOPMENT REQUIREMENTS
- CATEGORIZE REQUIREMENTS
- PRIORITIZE REQUIREMENTS

Figure 1-13

INTER-PANEL PROBLEMS

- |                     |   |   |
|---------------------|---|---|
| SENSORS             | - | OUTGASSING  |
|                     | - | NOISE   |
| ELECTRO-MECHANICAL- |   | HIGH VOLTAGE (STAR TRACKER) CORONA DISCHARGE/ARCING     |
|                     | - | SLIP RING - BRUSH TRANSFER                              |
|                     | - | DEPLOYMENT AND ORIENTATION                              |
| ATTITUDE CONTROL    | - | POWER SUPPLY OSCILLATION                                |
|                     | - | ARRAY DRIVE STEPPING                                    |
|                     | - | ARRAY BLOCKAGE  |
|                     | - | PARTICLE CONTAMINATION IN TUBES AND INTEGRATED CIRCUITS |
|                     | - | STABILITY OF POWER TO DEFLECTION COILS OF STAR TRACKER  |
|                     | - | COLLECTOR TO BASE SHORT IN TRANSISTOR                   |
|                     | - | FLEXIBLE STRUCTURE DYNAMICS                             |
|                     | - | FEASIBILITY ----- PRODUCTIVITY                          |

Figure 1-15

PRIORITY LISTING

HIGH PRIORITY (NEW)

- \*ANALYTICAL MODELING
- \*STATE OF HEALTH MONITORING
- NEW COMPONENT DEVELOPMENT
- HIGH VOLTAGE TECHNOLOGY

HIGH PRIORITY (INCREASE EMPHASIS)

ARRAY/CELL TESTING

HIGH PRIORITY (MODIFY)

- \*NICD BATTERY MFG. AND APPLICATION

HIGH PRIORITY (CONTINUE)

SUBSTORM PLASMA EFFECTS

MODERATE PRIORITY

- \*ENGINEERING DATA BASE
- ROTARY JOINT FOR PWR TRANSFER

LOW PRIORITY

ON ARRAY POWER MANAGEMENT

Figure 1-16

INTERDISCIPLINE DEFICIENCIES

LIGHTWEIGHT STRUCTURE (ARRAYS)

THERMAL CONTROL (BATTERIES)

Figure 1-17

\* ANALYTICAL MODELING

RECOMMENDATION:

1. DEVELOP AC MODELS FOR POWER SUBSYSTEM COMPONENTS
2. SYNTHESIZE ANALYTICAL MODEL FOR POWER SYSTEM
3. DEFINE NECESSARY PARAMETERS FOR ELECTRONIC SIMULATION OF AC SOLAR ARRAY MODEL

RATIONALE:

VERY LITTLE AC DATA AVAILABLE FOR COMPONENTS AND SYSTEM

EXISTING DATA NEEDS REVIEW, REVISION, REFINEMENT AND UPDATING

GUIDELINES NEEDED FOR ACCURATE ELECTRONIC SIMULATION

ELECTRONIC ARRAY SIMULATION IS NEEDED - ONLY KNOWN WAY TO "INCLUDE" LARGE ARRAYS IN GROUND TESTS

PAYOFF:

SAFEGUARD AGAINST BUS INSTABILITY

AVOID HARMFUL INTERACTION BETWEEN ARRAY AND FILTER COMPONENTS AT OUTPUT

DEFINE SOURCE IMPEDANCE AT LOAD BUS

SUPPLEMENT INADEQUATE DC ARRAY SIMULATORS WITH MORE ACCURATE AND REALISTIC AC SIMULATION

Figure 1-18

NEW COMPONENT DEVELOPMENT

RECOMMENDATION:

DEVELOP HIGH VOLTAGE - HIGH POWER COMPONENTS

DEVELOP PARTS

DETERMINE SCREENING TECHNIQUES

FLIGHT QUALIFY

RATIONALE:

HIGH POWER LEVELS REQUIRE INCREASED BUS VOLTAGE (150-400V)

NO QUALIFIED HIGH VOLTAGE - HIGH CURRENT PARTS AVAILABLE

PAYOFF:

REDUCED SIZE AND WEIGHT OF POWER SYSTEM

AVOIDS POTENTIAL DESIGN OR RELIABILITY COMPROMISES

SETS GROUNDWORK FOR FUTURE VERY HIGH POWER MISSIONS

Figure 1-20

\* STATE OF HEALTH MONITORING

RECOMMENDATION:

1. DEVELOP IMPROVED TECHNIQUES FOR ON-BOARD MONITORING AND CONTROL OF POWER SYSTEM AND ITS COMPONENTS  
SOFTWARE/HARDWARE TECHNIQUES TO MINIMIZE IMPACT ON DATA HANDLING AND COMMAND SYSTEM GROUND OPERATIONS  
IDENTIFY REQUIRED STATE OF HEALTH DIAGNOSTIC MEASUREMENTS  
DEVELOP SENSING TECHNIQUES AND SENSORS FOR DETECTING PARTIAL FAILURES  
DEGRADATION
2. DEFINE TECHNIQUES FOR REDUCING COMPLEXITY OF MANAGING DEGRADED SYSTEM/COMPONENTS FROM GROUND

RATIONALE:

EXISTING ON-BOARD SENSORS/MEASUREMENTS INADEQUATE FOR ACCURATE DEFINITION OF STATE OF HEALTH  
GROUND MONITORING AND ANALYSIS IS INADEQUATE AND EXPENSIVE  
GROUND CONTROL IS COMPLEX AND SLOW TO RESPOND  
INADEQUACIES AFFECT MISSION PLANNING AND FLIGHT OPERATIONS  
REAL EFFECTS OF ENVIRONMENT ON SYSTEM ARE NOT KNOWN

PAYOFF:

LOWER GROUND SUPPORT COST  
IMPROVED RESPONSE IN COMPENSATING FOR PARTIAL FAILURE/DEGRADATION  
IMPROVED DESIGN CAPABILITY  
IMPROVED MISSION OPERATIONS  
LOWER POWER SYSTEM COST AND WEIGHT  
SIMPLIFICATION IN C & DH SYSTEM

Figure 1-19

HIGH VOLTAGE TECHNOLOGY

RECOMMENDATION:

1. DEVELOP A DETAILED HIGH VOLTAGE DESIGN GUIDE HANDBOOK
2. DEVELOP A MODEL DETAILED HIGH VOLTAGE PROCUREMENT SPECIFICATION

RATIONALE:

HIGH VOLTAGE SYSTEMS ARE FAILING

LACK OF UNDERSTANDING

LACK OF DATA BASE FOR MATERIALS, ANALYSIS, AND DESIGN/APPLICATION TECHNIQUES

PAYOFF:

INCREASED RELIABILITY AND LIFETIME OF HIGH VOLTAGE CIRCUITRY

PREVENT FAILURES DUE TO LACK OF KNOWLEDGE

BASELINE TESTING REFERENCE PROVIDED

USE OF VERIFIED TECHNICAL GUIDELINES IN PROCUREMENTS

PROVIDES CRITERIA FOR SELECTION, SCREENING, AND ACCEPTANCE OF COMPONENTS

Figure 1-21

## ARRAY/CELL TESTING

### RECOMMENDATION:

CONTINUE (WITH HIGH PRIORITY) DEVELOPMENT OF SPECIFIC TECHNIQUES FOR CONTROLLING PROCESSES INVOLVED IN MAKING RELIABLE INTERCONNECTS/ INTERCONNECTION, FOR VERIFYING INTERCONNECT INTEGRITY, AND FOR PERFORMING ACCELERATED CORROSION TESTING OF SOLAR CELL CONTACTS

### RATIONALE:

CURRENT METHODS ARE LABOR INTENSIVE - TIME CONSUMING AND COSTLY  
METHODS OF VERIFYING REQUIRED NEW TECHNOLOGY ARRAYS (WELDING ON FLEXIBLE SUBSTRATES WITH PRINTED CIRCUITS) ARE UNKNOWN  
RELIABILITY AS RELATED TO MISSION NEEDS IS UNCERTAIN

### PAYOFF:

INCREASED CONFIDENCE IN IMPLEMENTATION OF NEW TECHNOLOGY  
REALIZATION OF BENEFITS INHERENT IN NEW TECHNOLOGY  
HIGH EFFICIENCY  
HIGHER RELIABILITY  
LOWER COST

Figure 1-22

## \*NI CD BATTERY MFG. AND APPLICATION

### RECOMMENDATION:

1. CONTINUE (WITH HIGH PRIORITY) TECHNOLOGY DEVELOPMENT FOR RECONDITIONING AND FOR CELL MANUFACTURING PROCESS OPTIMIZATION
2. MODIFY ON-GOING PROCESS SELECTION AND STANDARDIZATION WORK TO EMPHASIZE DEVELOPMENT OF ELECTRO-CHEMICAL AND PHYSICAL ANALYSIS METHODS

### RATIONALE:

PERFORMANCE OF NI CD BATTERIES HAS BEEN INCONSISTENT AND IS ONE OF THE MOST COMMON CAUSES OF DEGRADED SPACECRAFT OPERATION  
RECONDITIONING HAS BEEN USED TO IMPROVE PERFORMANCE BUT WITH VARIABLE SUCCESS AND IS POORLY UNDERSTOOD  
CELL PERFORMANCE OVER LIFE HAS BEEN INCONSISTENT AND BELOW MISSION NEEDS

PROCESS AND PROCESS CONTROL SUSPECTED  
FUNDAMENTAL UNDERSTANDING INADEQUATE  
IMPROVED UNDERSTANDING WILL IMPROVE BOTH THE MANUFACTURING PROCESS AND THE RECONDITIONING METHODS

### PAYOFF:

IMPROVED BATTERY LIFE AND VOLTAGE REGULATION  
IMPROVED UTILIZATION - REDUCED WEIGHT  
REDUCED GROUND STATION OPERATIONS  
INCREASED PAYLOAD OPERATION IN ECLIPSE  
REDUCED COSTS - REDUCED MANUFACTURING FAILURES

Figure 1-23



## SUBSTORM PLASMA EFFECTS

### RECOMMENDATION:

ENHANCE THE SPACECRAFT CHARGING PROGRAM (CURRENTLY PERFORMED AT LERC)  
BY ADDING DEVELOPMENT OF SPACE PLASMA ENVIRONMENT SIMULATION FOR GROUND  
TESTING OF POWER SYSTEMS TO INCLUDE ENERGY PROFILES, WHERE IT FLOWS, AND  
HOW IT IS DISSIPATED

### RATIONALE:

FAILURES AND DEGRADATION DUE TO PLASMA EFFECTS HAVE OCCURRED  
CURRENT SIMULATIONS ARE INADEQUATE FOR STUDY OR TESTING OF EFFECTS ON  
POWER SYSTEMS  
ACCURATE PREDICTION OF SYSTEM OR COMPONENT PERFORMANCE CANNOT BE MADE  
DEFINITION OF SYSTEM AND COMPONENT DESIGN REQUIREMENTS IS NEEDED  
REFINEMENT AND UPDATING OF ACTUAL ENVIRONMENT IS ALSO NEEDED

### PAYOFF:

ELIMINATE FAILURE MODES OF SPACECRAFT  
DESIGN DATA AVAILABLE FOR SURVIVAL IN PLASMA ENVIRONMENT  
CHECKOUT OF SPACECRAFT CHARGING PROBLEMS BY ANALYSIS/SIMULATION  
BECOMES POSSIBLE

Figure 1-24

## • ENGINEERING DATA BASE

### RECOMMENDATION:

DEVELOP A DOCUMENTED AND BROADLY DISTRIBUTED ENGINEERING DATA  
BASE ON EMERGING TECHNOLOGIES

### RATIONALE:

TIME GAP EXISTS BETWEEN NEW TECHNOLOGY AVAILABILITY AND THE  
APPLICATION DATA NEEDED TO USE IT ON FLIGHT PROGRAMS  
DATA BASE IS NEEDED FOR NEWLY DEVELOPED SOLAR CELLS AND THEIR  
PERFORMANCE CHARACTERISTICS UNDER MANY DIVERSE EXPECTED OPERATING  
AND ENVIRONMENTAL CONDITIONS  
NICKEL HYDROGEN CELLS MUST SIMILARLY BE CHARACTERIZED  
IN ADDITION, RECONDITION METHODOLOGY AND MAINTENANCE DURING  
DORMANT PERIODS MUST BE ESTABLISHED  
APPLICABLE DATA ON SUCH POWER RELATED DEVICES AS POWER MOS  
TRANSISTORS, MICROPROCESSORS, AND HIGH VOLTAGE COMPONENTS IS  
REQUIRED IMMEDIATELY TO PROPERLY APPLY THESE COMPONENTS

### PAYOFF:

FEWER MISTAKES AND FAILURES IN THE APPLICATION OF NEW TECHNOLOGY  
AND DEVICES  
MORE RAPID TRANSFER OF NEW TECHNOLOGY INTO ONGOING PROGRAMS  
INCREASED COST EFFECTIVENESS AND SCHEDULE CONFIDENCE IN THE  
UTILIZATION OF NEW TECHNOLOGY

Figure 1-25

### ROTARY JOINT FOR POWER TRANSFER

RECOMMENDATION:

DEVELOP A COMBINATION ROTARY POWER AND DUPLEX TRANSFORMER CONFIGURED TO PROVIDE FOR HIGH POWER AND HIGH DATA RATES WITH INCREASED RELIABILITY AND REDUCED NOISE

RATIONALE:

MECHANICAL SLIP RINGS CONVENTIONALLY USED

SLIP RING PERFORMANCE WILL NOT INSURE RELIABLE DATA TRANSFER AT HIGH DATA RATES

SLIP RINGS AND NEWLY DEVELOPED ROLL RINGS HAVE CHARACTERISTIC NOISE AND VOLTAGE DROP MODES

ROTARY TRANSFORMERS, WHICH HAVE BEEN PREVIOUSLY USED FOR TRANSFERRING MULTI-CHANNEL DATA ACROSS A ROTARY INTERFACE IN BOTH ANALOG AND DIGITAL FORM WITH A MULTIPLEXER FOR TRANSMISSION AND DEMULTIPLEXER FOR RECEPTION, ARE NOT CURRENTLY CAPABLE OF OPERATING AT FREQUENCIES BEYOND THE 15 KHz RATES

PAYOFF:

LONGER LIFE

HIGHER RELIABILITY

IMPROVED DATA RETURN QUALITY

HIGHER DATA RATE

Figure 1-26

### ON-ARRAY POWER MANAGEMENT

RECOMMENDATION:

DEVELOP COMPONENTS/DESIGNS TO PROVIDE BASIC POWER MANAGEMENT ON THE SOLAR ARRAY RATHER THAN WITHIN THE SPACECRAFT

RATIONALE:

VARIABILITY OF ARRAY POWER OUTPUT RESULTS IN EXCESSIVE REQUIREMENTS FOR BOTH ELECTRICAL POWER CONTROL AND THERMAL CONTROL SYSTEMS TO ACCOMMODATE

PAYOFF:

SIMPLIFY POWER SYSTEM

REDUCE THERMAL CONTROL REQUIREMENTS

Figure 1-27

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Figure 1-28



PANEL DISCUSSION: BRIDGING THE GAP  
TECHNOLOGY DEVELOPING  
FLIGHT HARDWARE

Chairman, F. Ford  
NASA/GSFC

I would like to welcome each and every one of you to Goddard Space Flight Center. I think this is the 11th year that we have had a meeting here on batteries and the 10th year officially where it was called a workshop.

I would like to know how many are here this morning for the first time. Would you just raise your hands. Well, that is quite a large percentage of the group. I hope you enjoy the workshop. We try to vary the format from year to year, and this year for reasons stated earlier, we have a panel discussion.

Lou Slifer has given you the background on the OSTA workshop that was held this summer. There were four different disciplines discussed at this workshop. They were power which Lou has covered, electromechanical, attitude control, and radiometric instruments.

It so happened that the initial call for the workshop was on radiometers or radiometric instruments, but because of ongoing flight spacecraft, different problems with different missions, it was decided to expand the workshop into the other areas. As with the design of the satellite, the last thing thought about was the power system workshops. So, we somewhat got into the tail end of it.

Having been a participant in that workshop, it was very worthwhile. We found out that we are not flawless, we do make errors in design and we make errors in judgement. But, the proof of how good a technical group we are is to learn from these past mistakes, and that is what the workshop was all about.

To further that discussion, I have requested people from private industry and government labs to sit in and to assist me in establishing a dialogue with the people in the battery community, particularly defining the problem, trying to come up with some recommendations, and bridging the technology gap. Out of these four workshops, there was one very common theme: that is technology gap. Or, better said, the lack of engineering data base. Where is the line drawn between R&D laboratories saying, yes, this is developed technology, and the project manager saying, yes, we are ready to fly?

What is very real is that there is a large gap in that area. We find that, and I am sure most of you have been in this situation, you have something that looks good, you follow it from development for 4, 5, maybe even 10 years, and you sit down with a project manager and say, "We think this is what you need for your mission. It has the peculiarities necessary to solve your problems."

The project manager asks that question, "Where has it flown before?" Well, it probably has not. But yet he has a need, and you would like to see him use the technology. So you both have a vested interest. The real problem comes when the project manager then says, "Yes, I would like to fly it, but let's see some data on it. Let's see that engineering data base which I can make a decision on."

So you go back to the literature, you make a few frantic phone calls, and you find out, yes, there is a data base; it is rather fragmented, there is no real, solid core from which you can make up your story and provide a convincing argument that this is where we got to go and this is what we have to substantiate our claim.

With the emphasis on cost-effectiveness programs, low risk and long life, there has got to be a better solution than the piecemeal effort I think we have had in the past. The question is, what constitutes flight readiness?

Certainly, our project manager is very reluctant to take on a development program and a piece of spacecraft hardware. I distinguish that between a flight instrument, because use of flight instruments is just that they are pushing the state of the art. Very few project managers are willing to push the state of the art in the spacecraft design.

So, the question is, where is this engineering development going to come from? Who should do it? Should private industry, government labs, or who? That is what the topic this morning is.

I would like at this time to introduce the panel members. I think you know most of these people, the ones that have been here before.

On my left is Dr. Steve Paddack. Dr. Paddack has been with Goddard for a number of years. He is like myself, he does not talk about how many years any more. He is the deputy for technical on the COBE project, and he is here to represent the project viewpoint on the question that I have raised.

We also have Jim Masson from Martin Marietta. Jim has been working in NiCad for a number of years, and I am sure he has experienced some of the problems I have already mentioned.

We have Dr. Badcock, Aerospace Corporation. Chuck and I have sat across the table a few times with unresolved problems that we wished to resolve before the launch.

We have Fred Betz, Naval Research Lab. Fred is one of the few who have been able to sell his project on flying the state of the art, since Fred was one of the first, or the first to get a nickel-hydrogen battery on a satellite and still working successfully.

We have Bill Naglie, Lewis Research Center. Bill is more or less to represent the research end of the discussion.

Then, I have Gert Van Ommering, Ford-Philco, Ford-Aerospace almost at Comsat. Gert comes to us with kind of a mixed background, so I think he can speak from either side of the subject.

Ed Kipp, TRW. Ed's background is in aerospace batteries. He has been in it for a number of years. He works off in the manufacturing and applications end.

And, of course, Dr. Dave Pickett, TRW. I am sorry, I knew I was going to miss one this morning—Hughes.

With that I have asked each panel member to be prepared to give us a 2- to 5-minute discussion of his viewpoint on the issue.

After the panel members give their viewpoints, we will then open the discussion for questions and general dialogue from the floor. I encourage and will seek your participation. Steve, I would like for you to initiate the discussion, if you would.

## DISCUSSION

PADDACK: I have the uncomfortable feeling that I am the only member of the user community group. I use your batteries, and a lot of the things that Floyd was saying really rings true. We find ourselves in very awkward situations. I have dealt primarily with missions that are made here at Goddard, so I am more familiar with in-house projects than I am with the projects that are made out.

We find ourselves in a situation in which we want to fly a real good spacecraft for nothing. Like, reduce the cost to practically minimum. You would like to develop new technology, but they say, "Take high risks. But, if you fail, you are in trouble." That is the vice. They want success, they want to keep the manpower costs down and the hours cost down, and it is a very difficult situation.

Everybody gives a lot of lip service to new things, where we often find ourselves in situations in which we would like to fly things and try new things. The remarks that Ford was making about the engineering development phase, the data base and the information, we find ourselves in a situation often in which a new technology, a new thing, a new device we would like to be used in a spacecraft, and the project officer says, "Has it flown before?"

And the answer may come back, "Well, not really. You know, we have changed it a little bit, we have got this new thing called a lithium battery, and it is great." Or, "silver hydrogen," or whatever.

We say, "Well, good, we will talk about it and maybe develop some kind of a phase." Then we say, "We would like to test it" and the manufacturer that produces the battery wants to test it and will say, "Here is our environmental test program."

We will say, “We would like to test it like we fly it.” But, we find for a variety of reasons we cannot do that, and we cannot test it like we fly it, so we go off with a pretty substantial risk. It makes us very nervous to fly new technology from that point of view.

I don’t know what the solution to this kind of problem is. I have been involved with cases where we fly new technology, and I guess a case in point is related to solar cells. We had to have a new spacecraft, the whole surface of which was conductive. Well, that is kind of a bizarre thought to start with. How do you handle a totally conductive surface of a spacecraft?

Well, they get the solar cells and the antennas; the whole thing starts developing. In particular, with the solar cells—and I see Dr. Gaddy smiling up there—he was put into it up to here, and we did not know whether it was going to work. But, we had to put the cover on these solar cells to transmit charge from one place to another. We were not talking about much charge.

But, we were finding that the stuff that we coated the cells with changed its characteristic. It was not always the same resistance. Then, we had to tie each solar cell to the next, and we would run into such simple problems, the kind that you would run into at home with your kid at dinner time.

You would give Mark his glass of milk and you say, “Don’t spill it. You spilled it last night.” He reaches over and his coat sleeve knocks over his glass of milk. You say, “Spilled your milk again.” And you get angry.

Well, this happens with the spacecraft. We have technicians who wear lab coats, and we say, “Look, delicate stuff, don’t touch.” Lab coat drags across the solar cells and breaks the little conductive wires that connect.

These are the kinds of things that rather get you. You cannot test something. You want it to be a success, and when you are all done, you look through your development program, you say, “What do we have?” You say, “Well, I have got a battery I think is going to work, and I have a system that looks good.”

Readiness Review Committee says, “Let me see your test program.” You know it always comes back to that thing. And you say, “If we had a few more dollars.” You don’t get a few more dollars. “If I had some more time.” You don’t get more time.

It is really a tough problem. It reduces to the thing where we would like to, from a conservative point of view, go down to Sears and buy a Diehard. Look, we got a 5-year guarantee. It is kind of like the conservative person.

But, on the other hand, the big panacea comes, shuttle. We have got his wonderful shuttle that is going to solve all our problems. Weight is no problem. All of a sudden, weight is a problem. So, we are pressed back into weight. They keep nibbling away at us. We feel very uncomfortable with it.



Would we like to find new technology? Yes. I would like to do it here at Goddard. I would like to see new technology flown on the spacecraft here at Goddard. I was encouraged to see that Fred Betz has got nickel hydrogen into orbit. I hope it works.

BETZ: I cannot do it alone.

PADDACK: However, that is the kind of thing that we are into. It is a trap. It is a dilemma situation.

BETZ: It is funny. I think I missed only one of these workshops and that was the first one, so I have been here a long time.

This is not a new problem. It was a problem when I was working with batteries 10, 11, and 12 years ago, getting new technology on. And the problems have been the same: It is developing the data base.

We, at NRL, together with Comsat Labs, did get nickel hydrogen flying without a data base, without a voluminous data base that is required for most programs. We did it with a backup system with nickel cadmium to back up the nickel-hydrogen system. So, that made it relatively easy.

Also, I represented the project officer at the same time I represented the people responsible for the power system, so we could do pretty much what we wanted to do. We had that kind of flexibility in our organization.

Comsat Laboratories had developed the technological element, and we, together with Comsat, aggressively said, "Hey, we want to fly this stuff." It was not a case of the project office saying, "We don't want to fly it." Or, "We are afraid of it." We went after it aggressively, and that is the difference.

However, when we proposed NTS-3, we said, "Let's leave the nickel cadmium battery off. If we are going to fly just nickel hydrogen, we are going to make it failure-proof. We will put bypasses on the cells." And our management said, "Wait a minute. The last one worked so well, we are not going to change it." NTS-3 got cancelled.

But it is amazing how the inertia of the system developed through one program. "You flew nickel hydrogen, fly it again, but fly it the same way, don't change anything." And money came into the picture. We did not have the money to run a new development program for bypass.

I think that new technology will come in where it is mandatory. The Galileo program, perhaps, will force the lithium system into spaceflight. Where the needs are mandatory, yes, you will get it; where the needs are not mandatory, alternative approaches today seem to be the way to go.

Now, the only way around this that I see is for the organizations that do technology development sponsor it. The organizations that launch spacecraft which are the same organization, primarily the Department of Defense and the Air Force—pardon me, the Air Force and the Department of

Defense—and NASA, who do the technology development and end up primarily responsible for flying spacecraft to force the issue in technology development. I will propose that those people target these new developments directly into their future programs and force them along.

You are saying that there is a cost benefit in the future for these programs, for this new technology. The cost benefit is in the future. The corporate payoff is in the future for NASA and for the Air Force. But, you guys don't want to invest the dollars for the program manager to bring it along into his program. He says it costs too much and it is a risk.

Take the risk out by funding the development from the technology right through the flight, to the flight on a given program. Then you have bridged the gap.

KIPP: When Floyd asked me to sit on this panel, I somewhat got to reminiscing, because I can go back to about 27 years into the mid to late 1950s when we started in the early ballistic missiles programs at the General Electric Company. When I started thinking about this and thinking about the change in atmosphere and the climate that has taken place between those days and what we are looking at today when it comes to flying hardware.

I am sure that anything that any one of us will say here today will be an oversimplification of what the problem really is. When each of us in his own way and in his own shop tries and finds ways of convincing program managers to fly different kinds of hardware, it seems as if we had lost some of the spirit of adventure.

Back in those early days, it was not a matter of having to develop so much of a data base. It was finding something to fly. Finding someone who could make something that you thought might work.

Well, we did. Earlier our goal was, "If I can get something to fly for 3 months, that would really be neat." We found something that would fly for 3 months. Then, we flew 3 months, it lasted 6 months, it lasted 3 years, and we were very elated.

Also, in those days, there was lots of money available. Program managers at that time were not so profit-oriented as they are today. They were success-oriented, as far as getting something that would fly, and fly and last for 3 months or 6 months.

Today, the climate is totally different. Speaking from the commercial end of the world if you will, at TRW, where we are in the business to make a profit and to have successful programs, the climate has truly changed. Today, you have to be a darned good salesman to convince a program manager that what you are proposing will work and that it will work successfully.

We have gone through this stage where we have been flying nickel-cadmium batteries for the most part in supporting low-Earth orbit and geosynchronous kind of orbit missions, and we have got them working for 5 years, 6 years, and in the area of 7 and 8, even though there have been a lot of problems come along when we get to the 6-year and 7-year point.

As Fred said, it has been working, you face a program manager with a silver hydrogen, nickel hydrogen, or something else, and he says, "Prove it to me fellows. You know I got something that works; I know it worked for 7 years or 6 years." You have got to be a darned good salesman in today's climate. You have got to start your selling very early. You have got to sell. If you are working with a government agency, try and sell them on the idea that it is a feasible idea; if you develop the necessary data base, it will work. You carry your selling right along.

You sell in-house people; you sell your own functional management to get the money to start something, to develop the data base, to buy the hardware; and then you start working on the program manager end of it.

Right from the beginning to the end it is a matter of convincing someone that it is a good idea, that it will work, and that the payoff is there.

PICKETT: Along the same lines, I would like to mention that in selling the technology sometimes you get so enthusiastic about it, sometimes it is oversold a little bit, and it is sometimes hard to live up to the expectation once you get some real test data on the article.

It is very difficult to develop a data base for new technology. Most program managers want to see real time, live testing on the component or cell that you are trying to introduce into their program. This is not always possible. By the time you get the real-time test data on the thing, the technology is almost obsolete to satisfy some people anyway.

Really what is needed—the Air Force and NASA have recognized this for quite some time—is accelerated testing, so one doesn't have to go through the arduous process of going through the real-time test every time you want to put a new battery, cell, or whatever it is on the spacecraft.

We, at Hughes, are still continuing in this line. We have got some accelerated testing going in our R&D, and we continued to watch with interest the research that goes on with the NASA program.

Accelerated testing has got a bad name in the Air Force to some extent. When I was with Wright Patterson, it was very difficult, if not impossible, to sell anybody on an accelerated test program for nickel-cadmium batteries. It was only with NASA's cooperation that any kind of a sizable program was developed and proceeded with.

Generally, everybody uses accelerated tests. But trying to get government agencies to fund them, because of all the money that has gone into it, is sometimes difficult.

Changing the subject just a little bit, my experience, mainly with new technology, is trying to introduce electrochemically impregnated plates into nickel-cadmium batteries. That's where I started out.

If the nickel-hydrogen system had not come along, we might still be struggling with it. But, it was found out that this type of electrode was ideal for the system. The point I am trying to make

here is there has to be a definite need. We have to have some kind of driving force to get the new technology into a system. Just because it is an improvement, it will not happen. There has to be some type of driving force or basic need to get it done.

MASSON: I guess I would like to make a couple of the same points that Fred did.

When you are trying to make a transition from the new technology, any kind of new technology toward flight hardware, there are a couple of different paths you can take, ranging anywhere from government or industry-funded R&D efforts, to direct funding by the user program.

Of course, the path you take depends on awful lot on the technology that you are looking at. Technology has to be evaluated in terms of the potential benefits, development costs, and the risk. If the potential benefit of a given technology becomes essential to meet the basic requirements of a particular program, then, in a lot of cases, you can expect the program to pick up the responsibility and the cost of funding that technology development up to flight status.

A good example of that kind of development effort was the development of the battery in the Viking program. By international agreement, there was a requirement that the Viking spacecraft had to undergo heat sterilization at 135°C before launch to prevent contaminating the Martian environment. The Viking program undertook the development of a nickel-cadmium cell that was heat sterilizable and was successful, I might add. Those cells are still operating after 3½ years on Mars.

The same kind of technology development that is funded by our program organization might be applicable, as Fred mentioned, to some of the new lithium systems in which the stand life, or the extremely high energy densities that are potentially available, might really become essential to meet some of the new requirements.

Other kinds of technology development, such as improvements in nickel-cadmium systems or the development of metal-hydrogen systems, face a little bit different problem. In a lot of cases, their application is not essential to a given program, so the program will tend to evaluate those in terms of potential benefit versus risk. And, in a lot of cases, what they are doing is competing with existing "flight-proven" hardware designs. That becomes another kind of a problem.

I guess the point of all this is that there are a couple of different ways to get from a new technology system to flight hardware, and you really have to look at the individual technology to determine what the right path is for that development. In some cases it is easier than others, and again it depends a lot on how necessary or how much a given program hinges on that technology.

VAN OMMERING: I would like to use my few minutes to illustrate this whole question with an actual example that I am involved in at Ford Aerospace that has to do with bridging the nickel-hydrogen gap.

They have taken a system here that has been proven in the lab quite a few years. As we heard earlier, Fred Betz had the guts to put it on NTS-2, and it is working there really well. So, we are

looking at a situation in which we have a reasonable data base that allows us to seriously consider doing something like that on an actual working commercial spacecraft.

Fortunately, Intelsat decided this was the time to do it, Intelsat 5, for some late problems and other improvements that we would like to see, particularly in the lifetime of the spacecraft. It was decided in the middle of the Intelsat 5 program that we were going to try to introduce nickel hydrogen as a sole energy storage system on the spacecraft.

Now, Intelsat took the approach of making essentially a near-zero risk situation. We are now involved in a program of developing nickel-hydrogen batteries for Intelsat 5, but at the same time we are committed to building nickel-cadmium batteries right alongside it for the same spacecraft that they are going to put nickel hydrogen on.

That's rather an interesting situation because it takes a bit of the pressure off the schedule requirements. If nickel hydrogen has some technical problems that you still need to solve, we have the option of slipping it on the spacecraft and using nickel cadmium.

It also takes the pressure off entirely in the area of technical success. If a real snag develops, you have the backup system there and you can put it on the spacecraft at a fairly late stage, a few weeks before launch.

So this is really an ideal way to bridge that gap. All that it takes is a lot of money and a lot of confidence on the part of the eventual spacecraft user. I think, in the case of synchronous spacecraft, the payoff appears to be large enough in terms of added years of operation and added general reliability, as well as the weight advantage that we have in nickel hydrogen, that it is worth the \$5 to 6 million that Intelsat has pumped into this program or is going to pump into this program and bring it on line.

When you consider the payoffs once you get into Intelsat 6, 7, and on stage, I think a general approach to this new technology is to look at those benefits very simply in cost terms. If we can lay some money on the line right now in the development of a usable spacecraft stage, there are tremendous payoffs in the long run.

In some cases that may not be true, and I think that has got to be based entirely on that sort of an argument.

**BADCOCK:** My comments are really from the end user. You have something that has been developed, and you have to find someone that has the need. Having done that, you have a sponsor. I am going to address some of the questions that sponsors are going to ask and expect to have answered. All of these are, again, motherhood statements. They do have a lot of bearing on how happy he is going to be with whatever your new development is, and he is willing to pay for it.

I guess the first thing is, you know he needs it, that is why it is there. He should understand that he is going to buy the pain that is involved in bringing this new development on line. It is not the same as the last one, it is new. There are going to be a lot of little things around that are going to give you at least intermittent grief.

So, what does he expect to see? Well, we have talked about the demonstration base. That is very important. But included in that you need to be able to demonstrate what it is going to play with the rest of the system, whatever it is. If you have a battery that works well, why you should also be able to demonstrate that it is going to interface with this system properly. So, between the system and the batteries, they are not going to kill one another, either immediately or several years downstream.

The sponsors also should ask for the failure mechanisms, and you should be able to tell them. You cannot say, "Oh, it doesn't fail." You should be smarter than that. So, you should define these failure mechanisms. You know how it is going to fail, but still it is a better product.

I guess the two final things, early in development you want to start talking about are aerospace quality specifications. It is your development, you built this, you built that, and so on. But, as you come along, you really should start considering aerospace or flight quality specifications to be written in the program and things to be built to that, and not let it come after the fact. This adds costs. All these things add costs, but they are really important if you want to demonstrate to the end user that he should buy your product.

Along the same line, you want to get a manufacturer into this. If you are the manufacturer, great. But you want to get the manufacturer into this at an early stage, so you can demonstrate you can make a lot of them, or as many as are needed.

Other than that, I think those are the kinds of things that you wish to get from the standpoint of the guy who is going to use it in the end. These are the things he wants to see to demonstrate that this is a better mousetrap, or whatever.

NAGLIE: Let me go way back. I represent the technology end. Our workhorse system, the nickel-cadmium system, has not yet been characterized from the inside to the point at which you can design a battery for a particular mission.

In the beginning, they flew many NiCad cells for 20,000 cycles at very shallow depth in low-Earth orbit. There comes a time they put it in synchronous orbit, and they got into trouble. Why? There is no actual data base system from the standpoint of how the electrodes are impregnated, whether they are impregnated fully or shallow, or what kind of current densities any particular electrode will stand.

The batteries themselves are not designed for the mission. Even in the workhorse system, the nickel-cadmium system, we do not have that data base.

The technology end of it has not developed it, and it is not that hard a thing to do. It has been rejected back in the 1960s several times, and I am mad about it, of course. But, let us go on to future systems.

I still think we need the NiCad data base, and we should develop it for any given method of impregnation in the electrodes and any given method of making the electrodes. It is only a matter

of doing the work and building a character box. All right, we are going to fly this mission; therefore, we need this nickel electrode, this cadmium electrode, and this separator.

Probably it is as extensive as the accelerated testing program, but it still is not available and it should be if we are going to fly NiCads.

Now, going back to getting the program manager to accept new technology, in the NASA organization, we failed several times with new technology. We failed the silver zinc getting on the Viking. That was a little problem with economics. We do have a silver zinc cell. Some of them are still alive now after 11 years being sealed and sterilized. It is a new separator development that we worked out at Lewis.

The thing that has to happen for new technology to get on a mission is at the time, even before the mission is approved, when it is conceived with mission analysis people, the technology people have to be informed of it and develop a parallel technology program so that they have the data base. When it is approved, now they have the data, and they can convince the program manager that this is the electrical storage system that should go on a spacecraft. It takes a lot of data to convince the program manager. Not just the NASA program manager but the industry program manager has to be convinced.

KILLIAN: As technologists, we work on new technology for a long time to try to get it into spacecraft. As has been pointed out, the program managers are reluctant to receive it. So, we think, my God, something is wrong and we should be doing something else. I would like to inject the thought that perhaps nothing is wrong at all and that we are perhaps more enthusiastic than we should be. It is just nature taking its course. It is difficult to get these things into the spacecraft.

I would like to quote a famous saying by Lou Gomberg at RCA. He had an Air Force DMSP program. He says, "Better is the enemy of good." Whether he is correct or not is based on a lot of experience. So, I would just like to inject that thought. Perhaps I don't think it is wrong at all.

GROSS: I would like to say amen to the remarks of Bill Naglie, and perhaps restate some of the things he said and build on what he said a little bit.

Certainly, making the transition from old technology to new technology has its own set of problems. But, in general, they are usually able to get this work properly funded. Possibly not at the rate we would like, but we are usually able to get new technology aboard. The problem is to avoid making the same mistakes in new technology that have been made in the past.

The nickel-cadmium system, for example, has been in space for 20 years, and we know very little about it. We do not at this time have any formal methods to characterize electrodes for this system; we cannot tell good from bad; and we cannot find any way to determine if electrodes made from one batch are the same as another batch. But we have many problems with this system continually failing prematurely. And, year after year, the government research decisions take the view that the nickel-cadmium technology is a developed technology, it is established, and there is no need to spend more money in this area. So, very little research gets done.

The Air Force, for example, sponsored Dave Pickett's work. But, right at the point when he got to start learning a lot about it, they cut off the basic research.

NASA Lewis people have always said that more basic work is required in the nickel-cadmium area, but they have never been able to sell it to get it sponsored. It has not been recognized as an important area.

I am pleased to see Lou Slifer's summary today, pointing out the great need to get more basic understanding of this old system. With regard to the data base, the data that is needed is not simply cycle life data, but it is also basic understanding of the old system.

OTZINGER: With regard to the data base, a lot of companies have, I think, their own data bases that they consider to be somewhat proprietary. I think there is a data base. Unfortunately, it is not generally available.

One thing that maybe would pay off in a workshop much like this one is that we could identify some of the kind of characteristics we are looking for in R&D. You could have people present papers pretty much one area, and the data base becomes generally available.

I think, my comment there again, there is data around but it is not accumulated by any particular source. What is needed is someplace where everybody can go to say, "This is our data base, an agreed-upon data base."

No one wants to believe anyone else either. We do our forecasting in our lab and say, "Well, it means something over there, but you know we don't believe everything they do."

So I think, if we could bring up data here in a particular area, say nickel hydrogen, for example, cycle life, each year we would have four or five companies all testing. Like the Air Force, they have Applied Physics Lab (APL) WPAFB, and made cells available to a lot of different companies to test. Now, if each one of those companies were to test somewhat the same area and then present the data, we could sift through it and say, "Okay, this is what we agreed is the acceptable data base."

Another comment is that with regard to flying things and saying, "Well, we have flight history." I think we have an opportunity in the near future of putting experiments on the shuttle and actually conducting tests, going up there and having a dedicated test that would demonstrate the feasibility, demonstrate that you have a workable system.

I suggest this now to the NASA and to the Air Force, to people that present the money for this kind of R&D work.

Now, as I say, that is a suggestion and that would be one way that you could get on lithium. You would get some of the more controversial systems up there, you could get some data, and everybody could see where you are.



KIPP: I think Burt has got a good comment when he talks about the fact that we all do our own thing.

I have been coming to these workshops for a long time, and I propose we have another gap: the gap I see is the gap between people and all the different government areas and industry doing their own thing, but having a reluctance to sharing that information with everyone else.

I think we need more different kinds of meetings where we can share that information and find out how we get people to break down the reluctance to share that information with everyone else. We all do have a common purpose, but we seem to have a reluctance to share that information.

BARNARD: When you take these high risks, who carries the can? Where does the warranty come in? Is it the responsibility of the company if something goes wrong with it, or does the user pay?

BETZ: The user pays.

FORD: I think the answer to that could be twofold. But, yes, ultimately, the user does pay and the user, meaning a satellite program that has invested its resources and is willing to take a certain amount of risk. Then, once the satellite is up there, you have found out the emphasis of resources and risk was somewhat out of perspective apparently, because the risk somewhat overshadowed all the spending you did to get a successful satellite.

I might point out that I think a point we made earlier about the changes in environment, that in the early part of the program we were looking for something that worked, and today we are dealing with, primarily, two classes of satellites; those that are operational satellites that are put up there for scientific purpose. The ones most familiar to you in the audience are the weather satellites that are put up there and they are operational. They want low risk, they want cheap satellites, but they want a 10-year mission.

Now, talking about the other satellites which are scientific in nature, they are very much research oriented as the Viking program and some of the astronomy programs. And these program managers recognize there are risks that can be taken, but they usually are willing to take the risk in the instrument field, not in the spacecraft field, not in the design of components for the spacecraft.

SEITZ: Fred Betz, you mentioned the Galileo program with forced lifting into spacecraft. I am wondering what were the requirements in the Galileo program to do this, and what sort of lifting systems do you see?

BETZ: I would like to pass that one since I am not personally involved in the Galileo program. Dave Pickett is probably familiar with that, and I will pass the ball to him and let him tell you.

PICKETT: I think the reason is simply that the state of the art in batteries just would not suffice to complete the mission.

Now, as far as the batteries themselves and that type of thing are concerned, we have a gentleman here from Honeywell who is going to talk about the cells and that type of thing later on in the program.

That is the best answer I can give you in a nutshell. Stan Krause has been running the Galileo program at Hughes. I have not been involved with it. When I took over as head of the section, that program was split out with Stan paying personal attention to it. So I haven't had the opportunity to spend the detail with it that I would like to give you a more specific answer to your question. But, you can talk to Stan, and he can fill you in on the details.

LEAR: I would like to voice a couple of comments that the panel had brought up about the low risk in the NiCad system, and also the low cost of flying a NiCad system on board the spacecraft.

You have to be a very good salesman nowadays when you are working proposals for spacecraft applications. You go to your program manager and say, "I would like to run an on-line test for a peculiar situation we are in," or the test that is required to substantiate flying a spacecraft in that particular orbit that you are working on.

Because of the data base that we are supposed to have with the 20 years of background testing and all that we have done on NiCads, the program managers are not willing to support our cases now, and they say, "Well, new technology is coming along. Nickel hydrogen has got a zero data base. But we have got NiCads that have got 20 years. So, we don't need to run a test."

Therefore, the cost is out. No more testing. You have got a data base. So, we have to educate the program managers as well as the customers because he is also trying to cut down when you are substantiating a data base.

HALPERT: When the technologist attempts to sell his product to management, he has to speak from a position of strength. I will have to allude to another gap that we have, and that is between the scientist and the technologist.

There are 100 papers on the nickel-hydroxide electrode, and yet we don't go back into the basic data to understand how the nickel electrode is working. All we want to do is keep testing the batteries, keep testing the cells.

It is understandable how some of the project managers can look at that and say, "My God, another test program. What are we going to get out of it the next time we buy it as something new?"

So, I think we need some interpretation of people from the basic sciences, the guy who is working at the microelectrode level on up to the hardware item, to extend that technology or to extend that science to the technologist so that he can then speak from a position of strength.

NAPOLI: Among the users and manufacturers of various agency representatives that we have here, there is a wide data base of nickel-cadmium cells that exist, and there is also a wide variety of types of cells that have flown. So, you have a big choice of cells in the data base to look back on in history. I think you will find if you look at the various programs, Air Force and NASA commercial programs, you will find that some cells are performing better than others.

What I haven't seen come out, except at a last SAMSO workshop, is that there was a general agreement as to what should be done to improve the longevity and reliability of cells. I don't see coming out of this, particularly the Goddard battery workshop, people getting together and saying "Look, that company, that group, or that agency did something right. What did they do that is different?"

Okay. "Why don't you try to investigate that, and if they are doing something that is right, how come we cannot do that?"

I think the problem why that does not come out is the old "NIH Syndrome" that seems to prevail throughout the industry. Not only is it an "NIH Syndrome," but there is also a feeling of pride and sensitivities in some of the programs that exist. One company does not want to exchange data with another company. There are many users here who just don't want to show their data until maybe 8 or 9 years after the program is past and gone.

So, I think the problem you have to overcome is the "NIH Syndrome," for one thing. If GE has a power system, TRW has a power system, and Hughes has a power system, some way you will see some of those power systems – when I say "systems," it is ultimately a system problem – are working better than other spacecraft or other programs. And yet, someone does not go back and say, "What are they doing different?" "How come we don't do that?"

Again, it is the old NIH problem. So, I think we should all take a little bit, sort of an in-depth look at what we can do to change that. Unfortunately, it is beyond us on the working level. It is more on the corporate level that you have these resolutions come to a head.

GASTON: I heard the comment made by several gentlemen this morning of use of accelerated testing to build up a data base relatively quickly.

I am all for that. I would like to caution people. You have to be able to correlate it with real-time factors, degradation rates, and so on, because there have been some real wrong conclusions drawn based on accelerated testing. We have to understand the mechanisms which occur and possibly correlate them with the component degradation inside, or compare very carefully with real tests, because that is a dangerous road.

SCHULMAN: I would like to propose a question to the panel. You know we hear quite a bit about battery anomalies. Unfortunately, the only channel most of us hear about these is through the channel of industrial gossip.

With all these battery anomalies that seem to exist, I would like the panel's opinion as to whether they are caused by an inherent fault within the nickel-cadmium battery itself, or an inherent fault with the system engineer who has applied his experience to the utilization of this battery.

FORD: That is a big task. Which of the panel members would like to field that?

BETZ: I will take that. Irwin, you have really got a good question there. But let me say this: Somebody mentioned very early in the session, I think it was Sid Gross, who said that years ago we flew batteries and they got 20,000 cycles on them. And a lot of batteries got 20,000 cycles. They only expected 6 months and they got 18 years, this kind of thing.

What is different between then and now? The batteries have improved; the power systems have improved. The difference is that management thinks we can use the batteries more and more. They are forcing the engineers to 80-percent to 90-percent depth of discharge. They are forcing more cycles at higher depths of discharge, and the battery engineer really has his back to the wall.

That is the way I feel. The battery fails because you push it too far. You have to understand the limitations of the battery because you cannot change the battery. You have to understand its limitations and to work within its limitations. If management pushes too far, it is going to fail. So, we have an anomaly.

KIPP: One thing about Irwin Schulman is that he knows how to ask the right questions. There are many paths for the answer to that question. If you are looking at the military that has a requirement for a spacecraft, one of their requirements is that your exposure to it, your availability to look at that spacecraft and to look at what it is doing is extremely limited.

They want a spacecraft that will fly virtually hands off, so you design systems that will do that job. You work with all the power system people, and you come up with systems that will do that job. Maybe 5, 6, or even 4 years later you will find, "Gee, there is something we didn't look at because we are not all instantly superintelligent. We designed systems 5, 6, and 7 years ago that we thought would do that job. We are finding today. . .," and here are specific references to anomalies. "We are finding we didn't know all the things that we should have known or would have liked to have known about how to use those systems in that kind of mode."

Now, you look at the other side of the coin where you have scientific kinds of satellites, a lot of them are operated by NASA where you can look at them constantly, 24 hours a day. You have on-line programs to look at the data; you have off-line programs to massage the data. In many cases you will not have the same problems with the spacecraft you can look at 24 hours a day, that you have with those you cannot look at.

So, we have more than one kind of problem here that we have to address.

FORD: Yes. In response to your question, Irv, I might point out that at the workshop there was a broad cross section of reasons for the problem. There was no one area that we pointed out that we don't understand the technology as a specific cause. When you look at it, there are many reasons that we have problems in orbit.

One of the things that was mentioned early, and I believe Chuck mentioned this, I believe it should be looked at. This is in light of the data base that we have. We are comparing what we are doing today, what we have done in the last 3, 4, and 5 years, with what we did 10 or 15 years ago.

Sure, there is a whole wealth of information or data based in the NiCad field. But, the question you always have to ask yourself is, "How relevant is that to what I am doing now?"

And that is where the real clincher comes, because you find out that, by and large, there have been changes in the manufacturing process; maybe a manufacturer has totally relocated his plant; and we have people who get involved which also affect the builder's ability to produce the product.

Getting to the economy, Chuck, I believe it was you who said something to the effect that perhaps early in the program, "to establish the confidence, you need to start even a development program or research program" – more specifically research – to start doing those in the area of quality, make sure you have got someone to manufacture the technology you are looking at. Don't wait until the project manager says, all right we are ready to buy, and then say, "My God, who have we got to make this thing now."

I think there is an area there we have really got to be sensitive to. In other words, you can do a lot in the R&D labs, but bring along the capability of a manufacturer to transfer or to infuse in that manufacturer the technology and development you need later.

BADCOCK: May I comment? First I would like to answer Irv's question. Yes. One of the things we have talked about here that needs to be pointed out, there needs to be a trade-off between fundamental understanding and testing. I bite my tongue here because I like the fundamental understanding. But, you can only trade that so far. People talk about, you know, if we understood everything, we would not have to test. I don't think that is true. Nobody is going to buy that.

So you have a region in the middle here with testing on one side and fundamental understanding and research on the other. You have a region in the middle where you can move these back and forth. So, I think, with NiCads, we are pretty much to the testing side at this point because we keep changing these things.

BLAGDON: The Galileo program is using a modular concept in its battery design power environments. That has already offered some system flexibility to the systems people, design flexibility that would not have been there had we selected or chosen a singular battery package for the thing.

I like the comments of the panel relative to the modular concept to power systems design. With respect to establishing a common data base industrywide, I think it has some definite advantages and has some system flexibility.

One other comment I would like to make is that the current Galileo program has been stretched out. That stretch-out gives us the opportunity to establish some real-time data that we did not have in the original program which, we believe, is going to lower the risk on the overall program.

So my comment basically is that time and sponsorship are also very, very critical in establishing this data base that we are looking for. You can accelerate test programs, but absolute confidence from an end user who does not necessarily fundamentally understand the system is only going to come with some real-time data.

But I would like to comment relative to the modular design concept, relative to establishing a common data base.

FORD: I would like to summarize. I think we have heard a large variety of inputs, all of which have to be taken collectively. And it may well be that we, in the technical field, have the same problem that you find in management by the mall distribution principle. That is, basically, you only have 20 percent of the information you need to make 80 percent of the decisions you have to make.

LITHIUM CELL TECHNOLOGY AND SAFETY REPORT OF  
THE TRI-SERVICE LITHIUM SAFETY COMMITTEE

E. Reiss  
ERADCOM

What I would like to talk to you about today is the Tri-Service Lithium Safety Committee. This is a fairly small phase of a many-faceted problem that face all of us here.

This particular committee was initiated in September 1977 when representatives of the Army, the Navy, and the Air Force recognized that the lithium batteries are becoming the major military power source and that procedures should be established so that lithium batteries may be safely and responsibly employed.

(Figure 1-29)

This committee suggested that a tri-service group be established for the purpose of exchanging information on lithium batteries.

(Figure 1-30)

There is a fourfold purpose. The first was to exchange information on lithium batteries. Another area was to examine common areas of concern to the three services. The third was to provide guidance to the users. And the last was to set up common procedures where applicable, for the safe handling, deployment and disposal of lithium batteries.

(Figure 1-31)

Formally, this committee was organized in December 1977 as Lithium Battery Safety Group under the Joint Deputies for Laboratories Committee, Subpanel on Batteries and Fuel Cell Technologies.

(Figure 1-32)

Under a joint memorandum of agreement on batteries and fuel cell technologies, the Army is designated as the joint service focal point for lithium batteries and was appointed as the head of the safety group.

By July 1978, a charter for the group was officially accepted and extended to include NASA, the Department of Transportation, and other government agencies.

During the last 2 years, several key areas have been discussed at great length. These are shown on the figure, and I would like to expand upon each of these categories briefly for you and to tell you what conclusions we have been able to reach in a short period of time.

The first area is on transportation. When the committee was first initiated, we were talking about the first revision to the Department of Transportation Exemption No. 7052. Today we are looking at the seventh revision to Exemption 7052.

This safety group has been able to keep its members updated on each change, has been able to alert members when necessary, who need to be granted a party status to that exemption, as well as to our contractors.

And we have provided an opportunity for the members of the various services to meet with the Department of Transportation representatives to discuss the rationale and interpretation of those exemptions.

The second area of transportation concerns the FAA. One of our members, Paul Neumann, has been able to keep the services fully aware of the safety problems which have occurred in emergency locator transmitters.

The FAA has also been responsible for fostering and publishing an airworthiness directive and a technical specification order concerning lithium sulfur dioxide batteries for use in aircraft. Through this committee, the members have been fully aware of proceedings through the FAA.

The next area I would like to briefly touch on is disposal. Various reports, rumors, and opinions exist on the recommended methods for disposal of lithium batteries. This safety group has attempted to clarify within itself the issue of disposal. Success has only been marginal.

A major stumbling block of this committee is assessing the degree of hazard as defined by the EPA in their "Guidelines for Hazardous Waste Disposal" published in December 1978.

Adding to this problem is the multitude of chemistries, designs, manufacturers and users of lithium batteries. For example, there are at least 12 different chemistries of lithium cells in batteries.

One of these chemistries and designs was examined by Vasar, Inc., in Springfield, and they concluded that lithium sulfur dioxide cells of a balanced design did not contain significant concentrations of cyanide. In their report, this was so stated. An analysis of this report by the New Jersey Department of Environmental Protection concluded that sanitary landfills could be used for the disposal of balanced cells in batteries.

But, as I mentioned, there are at least a dozen different chemistries, and not all of the lithium sulfur dioxide chemistries have a balanced design.

As a committee, an Interim Guideline for Lithium Sulfur Dioxide Batteries was agreed upon to be followed until either firm clarification of the EPA Guidelines is established, or until specific testing against the EPA Guidelines establishes the degree of hazard. This is being looked at under an Army contract with LaPor, Inc., in Chevy Chase, Maryland.



(Figure 1-33)

The group's Interim Guidelines state that no more than 200 pounds of batteries shall be disposed of in a sanitary landfill per day.

Second, all disposal actions will be cleared with each state environmental protection agency. As I mentioned, the Vasar Report was looked at and evaluated by the State of New Jersey. Additional opinions may exist in various states throughout the country, and we felt it imperative that each state give their own opinion. What is good in New Jersey may not be good in California, or vice versa.

Next, cells, batteries will not be compacted or crushed or placed where they may be crushed.

And lastly, the landfill operators would be advised that cells contain lithium and acetonitrile, which are both possibly reactive and ignitable.

(Figure 1-34)

The next area I would like to talk about is storage. How shall we store lithium batteries, what shall we tell the users?

This question was asked at the first few meetings and discussed many times. Two aspects of storage became apparent: Should we protect the battery from the surroundings, or the surroundings from the battery? In part, as you know, the Department of Transportation Exemption 7052 describes packaging and materials and specific methods on sealing the batteries in plastic, cardboard, etc.

To further answer this question, though, several members of the safety group through their own agencies have begun studies and inquiries to assess this problem. The Army has determined that three depots have storage areas which will afford an acceptable level of safety. These are the Sharpe, Red River, and New Cumberland Army Depots. Characteristics of these areas are shown.

All the areas are to be well ventilated. Temperatures are to be less than 55°C. In effect, we are saying there that refrigerated storage is not necessary, but high temperatures must be avoided. The facilities may be either sprinkler protected or in noncombustible structures. Batteries should be segregated from other commodities, other flammables.

We have defined a 2000-square foot per pile stack limitation on batteries. We specified a minimum of two-foot clearance between the walls and any of the batteries. And lastly, since it is a flammable material, smoking is prohibited in the warehouse area.

Further, we have recommended that batteries should be disposed of as soon as possible after use and not returned to storage.

In the area of individual testing and test results, we found that this is the greatest area for data exchange. Programs from each Service have been updated at almost every meeting. It has happened that topics focused on lithium sulfur dioxide batteries and lithium thionyl chloride batteries in the three areas of experimental cells, service casting, and building reports.

This opportunity to share information in the area of lithium batteries, in particular safety, has resulted in several programs aimed at resolving common problems. One of these problems that will benefit the three Services, NASA, the FAA, and possibly industry, is the program I mentioned with LaPor.

In the area of battery design, thorough and complete discussions have existed. Proper and safe battery designs and acceptable procedures for using the batteries have been extremely important. Though, as you may have guessed, we all don't agree on any one design or any one chemistry, many commonalities have existed. These concerns have been incorporated into a NAVSEA Instruction No. 9310.1 issued in March 1979.

(Figure 1-35)

In addition to this, similar information can be obtained from the different Services or is being coordinated at this time.

*Key areas of design that we are looking for are that all cells shall have a case-to-cover seal continuously welded. This, in conjunction with the next point that the seal between the electrodes and the cover shall be glass or ceramic metal tight, should give us an hermetically sealed cell. For each particular cell we are recommending that a safety venting device be installed and incorporated into the design.*

The next point is that all metal parts of the cell or battery should be secured to prevent possible movement or shorting. In the area of battery design, we are recommending that each group of cells be connected in series with a fuse in series with a string of cells.

The next point is that whenever possible, completed battery assemblies should be procured from battery manufacturers. This is opposed to having cells sent out to an independent assembler who then constructs a battery in any configuration that he deems necessary.

In keeping with that, the last point is that assemblies should be by experienced – should not be by inexperienced personnel.

The last two points really go together. That we would prefer, whenever possible, to have the battery manufacturers who have the expertise, to actually construct the batteries.

In other areas covered by the NAVSEA Instructions, I mention them briefly here so that you are aware of them:

(Figure 1-36)

They pertain somewhat more to the Navy than the three Services. However, there are points that can be adhered to by the various users.

*Qualification Procedures and Documentation* – That is a major portion of the document, but it specifically talks about how the Navy will go to procure batteries. The same way with acquisition.

Under “Use,” they have a section which defines the proper means of selecting a battery, testing that should be done with the battery or cells to qualify that the battery is being used properly. Packaging, marketing, transportation, storage, and disposal are similar to the other comments that I have mentioned today.

I would like to conclude by stating that the important point of this group is that the various services and government agencies are developing a unified approach to deal with the design and use of lithium batteries. Each agency will still have its unique requirements, and exceptions will abound no matter what the committee can come up with.

Nonetheless, the frequent exchange of information of controversial or state-of-the-art issues provides a more meaningful data base from which future programs will be planned.

## DISCUSSION

OTZINGER: It looks like you are starting out in the right direction here. One of the things I noticed that was under “Design,” one of the problems they are having with lithium or one of the corrections to a problem with lithium, was not having positive limit in the design.

Now, you know the welded header is a step in the right direction. The seal takes care of the seal problem, and also terminals are ceramic or glass. I am surprised, was it an oversight or did you purposely not include positive limiting as a design feature?

REISS: It is not an oversight. The reason it was not considered in the specific guidelines is that many different applications may exist for the lithium batteries. There are some places, particularly in the Navy, where they are talking about sonobuoy applications where their safety criteria are considerably less than NASA or the Army might have.

Therefore, as an overall guideline, we would not recommend that all cells go to the ballast or lithium limited design if we are talking about sulfur dioxide. It is a topic that has been discussed frequently, and, when applicable, this is a general guidance. But, I excluded it from the NAVSEA Instructions. It is not covered in the NAVSEA Instructions, but it is being considered by the various services.

OTZINGER: My understanding is that you have pretty well solved your disposal problem by just simply discharging the cell all the way down.

REISS: In the lithium sulfur dioxide system, it eliminates the generation of cyanide, which is the key toxic point.

OTZINGER: My only other comment was, are these instructions going to be put out for people to comment on and to feed back to you any suggestions?

REISS: No. The NAVSEA Instructions is a public document. It is finalized. It can be updated, I would assume, as necessary. But it is not out for general comment with a known date for comment period.

BARNARD: You gave instructions for storage of batteries in bulk. Now, what happens when you have a lot of items with batteries inside them. What about storage of those, any particular problem?

REISS: I cannot comment specifically on sonobuoys. It has been my understanding that batteries are not normally stored in equipment, particularly in the Army. I have to speak from that background. There might be somebody here from the Navy.

BARNARD: Yes, they would be stored in sonobuoys.

REISS: I would assume the same general characteristics would exist. You would need well ventilated areas segregated from other combustibles, flammable materials.

BARNARD: One of the requirements for a sonobuoy is that it goes up to a temperature of 70°C. It cannot be stored in that temperature?

REISS: That would be unique then for the sonobuoys. What I have tried to do is give general guidelines that have come out from the committee. There are exceptions to every phase of this.

If we talk about the sonobuoys in particular, I just mention that they may not have a balanced chemistry, balanced cell design. That makes them unique. And because of that uniqueness, other considerations may have to be given to them.

For the Navy, you might try to get in contact with Tony Sliwa at Crystal City. He might be able to give you the more specific information on the Navy's viewpoint on the sonobuoys.

JOHNSON: My question relates to the NAVSEA instruction, particularly the safety venting instruction. Is the NAVSEA instruction oriented toward all lithium cells, or is it specifically for the sulfur dioxide system only?

REISS: No, it is a general statement for all lithium batteries, various chemistry designs.

JOHNSON: I see. Do you plan to have specific instructions for specific systems later on? In particular, the carbon monofluoride system? Will there be special instructions for the safety in that system?

REISS: As a committee, at this point we don't have any items on the agenda to answer that question directly. We will be addressing the chemistries in time, but at this point we don't have a specific item to look at just that from the safety viewpoint.

BADCOCK: Two comments: It is unusual to see water reactor things like thionyl chloride with lithium stored in a sprinkler protected room. You might want to comment on that. Why don't you call that a hermetic seal rather than just a continuous weld?

REISS: To answer your first question, the committee for the various Services have seen pieces of data which indicate that lithium batteries, lithium cells, are not an extreme hazard when exposed to water. In fact, we have, in the various Services, done experiments where we have extinguished lithium battery fires with water. Water does reduce the hazard.

What we are doing with the water, in effect, is lowering the temperature and reducing the cardboard or other packing material from burning. It lowers the whole hazard associated with the batteries. And you can put out lithium fires with water.

BADCOCK: But there are better fire extinguishing agents which probably should be used.

REISS: The better agent we have discussed in something called Lithex, which is a powder, a graphite-type powder. It does put out lithium. However, it is not readily available in all of the warehouse areas throughout the Services, at least.

We have found that water does prevent significant damage to the surroundings, and therefore, if there is a fire, we are willing to say a certain quantity of batteries is lost. We are not going to use them again electrically. If they burn, fine. The hazard is controlled to a small area, and we accept that risk.

SEITZ: You would not require a safety vent, for example, on a lithium iodide button cell, would you?

REISS: No, probably no.

TAYLOR: Just one question with regard to the design. I am wondering, should you, in fact, have some statement about heat dissipation? For example, if you get a battery, should your instructions include the fact that one should not pot it in solid potting material? That was missing from the NAVSEA specifications.

REISS: The NAVSEA Instructions actually have some wording in there about potting a battery. The specific wording I don't remember, but it states that potting may be used provided the vents are not obstructed.

As far as heat dissipation is concerned, it is not covered in the specific NAVSEA instructions. However, it has been discussed by the various Services and incorporated into some of the different designs. Some of the discussions we have had with battery manufacturers in particular for the specific applications.

It has not been ignored. But it is a general guideline. It is not complete as we may like to see.

TRI-SERVICE LITHIUM SAFETY COMMITTEE

INITIATED: SEPTEMBER, 1977

FORMALIZED: DECEMBER, 1977

Figure 1-29

LITHIUM BATTERIES SAFETY GROUP

JOINT DEPUTIES FOR LABORATORIES COMMITTEE  
SUB-PANEL ON BATTERIES AND FUEL CELL TECHNOLOGY

CHARTER ACCEPTED - JULY, 1978

Figure 1-31

PURPOSE OF LITHIUM SAFETY GROUP

EXCHANGE INFORMATION

EXAMINE COMMON AREAS OF CONCERN

PROVIDE GUIDANCE FOR USERS

SET-UP COMMON PROCEDURES

HANDLING, DEPLOYMENT, DISPOSAL

Figure 1-30

KEY TOPICS

- TRANSPORTATION
  - DOT EXEMPTION 7052
  - FAA
- DISPOSAL
- STORAGE
- INDIVIDUAL TESTING/TEST RESULTS
- BATTERY DESIGN - USAGE

Figure 1-32

## INTERIM DISPOSAL RECOMMENDATIONS FOR LITHIUM SULFUR DIOXIDE BATTERIES

1. NO MORE THAN 200 POUNDS PER DAY SHALL BE DISPOSED OF IN ANY SANITARY LANDFILL.
2. ALL DISPOSAL ACTIONS WILL BE CLEARED WITH EACH STATE ENVIRONMENTAL PROTECTION AGENCY
3. CELLS/BATTERIES WILL NOT BE COMPACTED OR CRUSHED OR PLACED WHERE THEY MAY BE.
4. LANDFILL OPERATORS WILL BE ADVISED THAT CELLS CONTAIN LITHIUM AND ACETONITRILE, BOTH POSSIBLY REACTIVE AND IGNITABLE.

Figure 1-33

## SUMMARY OF NAVSEA INSTRUCTIONS 9310.1

### DESIGN

ALL CELLS SHALL HAVE CELL CASE TO COVER SEAL CONTINUOUSLY WELDED.

THE SEAL BETWEEN ELECTRODE AND COVER SHALL BA A GLASS OR CERAMIC TO METAL TYPE.

EACH CELL SHALL HAVE A SAFETY VENTING DEVICE.

ALL METAL PARTS SHALL BE SECURED TO PREVENT MOVEMENT AND POSSIBLE SHORTING.

EACH GROUP OF CELLS CONNECTED IN SERIES SHALL CONTAIN A FUSE.

WHENEVER POSSIBLE COMPLETED BATTERY ASSEMBLIES SHOULD BE PROCURED FROM A BATTERY MANUFACTURER.

ASSEMBLY BY INEXPERIENCED PERSONNEL SHOULD BE AVOIDED.

Figure 1-35

## STORAGE FACILITIES

- WELL VENTILATED
- TEMPERATURES LESS THAN 130°F (55°C)
- SPRINKLER-PROTECTED OR NONCOMBUSTIBLE STRUCTURE
- SEGREGATED FROM OTHER COMMODITIES
- LIMITED TO 2000 SQUARE FEET PER PILE/STACK
- A MINIMUM OF 2 FEET CLEARANCE BETWEEN ANY WALL AND BATTERIES
- SMOKING PROHIBITED

Figure 1-34

## OTHER AREAS COVERED IN NAVSEA INSTRUCTIONS 9310.1

- QUALIFICATION PROCEDURES, DOCUMENTATION
- ACQUISITION
- USE
- PACKAGING, MARKING
- TRANSPORTATION
- STORAGE
- DISPOSAL

Figure 1-36





## NASA/MARSHALL'S LITHIUM BATTERY APPLICATIONS

E. Paschal  
NASA/MSFC

(Figure 1-37)

This first chart consists of items I will cover in my presentation today. I gave you a presentation about 2 years ago on the NASA/Marshall battery applications, different battery applications. Today I am going to expand a little bit on what I gave previously.

The items will be a brief summary of the applications, general battery description, and in particular, I will discuss a particular battery, the IECM battery, design and construction details, thermal vacuum test, projection tests, and acceptance tests.

(Figure 1-38)

The second chart lists the various program applications. In most cases, these batteries are being flown on the SRB, an external tank. In particular, the SRB has one range safety battery. The external tank has two range safety batteries. So, there are four on each flight.

Also, in the SRB on the frustum, there are two frustum location "A" batteries. The IECM experiment will fly in Earth orbit, the same for the TCSE. IECM formation has induced environmental contamination monitors.

TCSE is an experiment thermal controlled services. Generally, all these batteries are lithium carbon monofluoride types rated 18 ampere-hours and have 13 cells in each housing.

In all cases, with the exception of the IECM battery, a NylaFil composition of fiberglass and nylon housing is utilized. Aluminum housing is used for the IECM batteries. All qualification tests each of these batteries have been completed.

(Figure 1-39)

Turning specifically to the IECM battery, I have shown a top view of the battery, looking down from the top. You will note that the cells are viewed looking down from horizontal. On the far end up there is an open cavity of space there, and the vents are facing in that direction.

There is a safety protection on the end of the vents to keep anything out of it. This area in here is what I am referring to as being an open area. And on this end we have it vented, as you will see later on another figure there, just where that vent is.

Between each of these rows is an aluminum fan that comes up through here and that way. This one here comes down, up this way here. That is welded to this side and to this side.

Down here is a thermostat.

(Figure 1-40)

This one shows the battery looking from the side. As you see, the cells are stacked on top of each other. This area here is the void area I mentioned. Here is a fuse and here is a connector.

This is a pressurizing valve and cover seal.

(Figure 1-41)

This is a view looking at the end. Here is the crosshatch. You will see that the aluminum fans are designed to carry the heat to the outside housing. These fans come down and are welded to the base of the battery. The cells are against the aluminum fan. They also have an insulated thermal trip over the cells and over the wire there to protect them.

There again you see the fuse, the connector on this end here. This part in here is the relief part, right in here. That is a protection cover over there to keep anything from getting into it.

From this lower point back, all of this area is potted with a wax to aid in thermal control.

(Figure 1-42)

Here is a simplified schematic of the battery. As you see, there is the fuse. Seeing these with the cells and a thermostat there protect against all the temperatures.

Also, there are two thermistors used in this experiment. These thermistors are routed to the experiment electronics package. At the present time, they are not utilized to turn off the experiment, but they could be turned off. This thermostat is set to open at  $175 \pm 5^\circ \text{ F}$ .

(Figure 1-43)

On this chart I have listed some of the thermal vacuum tests that we have drawn on the battery. There are two series of tests. Certain ones are going to be done at the plant and others are done at Marshall on full battery.

In addition to the thermal vacuum test, of course, we are going to chart vibration tests. These tests are basically the same. There is a little difference in the test. For example, on the vendor test the vacuum is  $1 \times 10^{-4}$  torr. On the Marshall test it is  $1 \times 10^{-6}$ .

The side temperatures are slightly different; the cold plates are slightly different. The load currents that we run are slightly different.

You will note that in each case, it started out as a higher current and dropped off. The higher current is used for 5 to 15 minutes, 15 minutes over there and 5 minutes here, and has dropped down. Using it at the lower test, it will run 3 to 4 hours apiece.

A single battery goes through a cold test and a high-temperature test. As I pointed out, the thermostat is designed to open at  $175 \pm 5^\circ\text{F}$ , so  $180^\circ\text{F}$  is maximum.

(Figure 1-44)

As part of the acceptance test on the batteries, there is a cell block test which is used to measure capacity, using a cell out of a particular block from which the battery is from. The minimum is 18 ampere-hours.

There is a cell impedance test performed, also a dielectric strength insulation and resistance test, thermistor test, pin case voltage test, dimensional check, battery seal, and battery case seal. This consists of pressurizing the housing to 12 psig and holding that. The case should hold that pressure for 5 minutes without a drop in pressure in tests of 0.1 psig.

The final battery case seal consists of putting the battery in  $160^\circ\text{F}$  thermal vacuum chamber for 4 hours. There is to be no wax leak when the battery is turned on its side.

At Marshall, an outgas and leak test was also performed on the battery. This test is  $158^\circ\text{F}$ , 48 hours at  $1 \times 10^{-6}$  torr. There is no wax leak within outgas specifications.

From the typical data that we picked up on some of our test batteries, the seals number 7, 8, 9, and 10, the cell block tests range from about 20 to about 23 1/2. The voltage was a little higher at the beginning of the test. At the  $158$  to  $160^\circ\text{F}$  temperature following this test, there is a matter of open circuit voltage.

(Figure 1-45)

Following all of these individual battery evaluation tests, we performed several systems tests in which the batteries were installed on an actual flight IECM package and were installed in the thermal vacuum. They are old batteries on the IECM, and they all figured through the isolating valve to a common bus.

The test setup was such that the systems had capability of running some items from ground power with the battery turned off. One of our batteries saw something like 15 cycles ranging from 0 to  $70^\circ\text{C}$ , estimated 300 to 400 hours under  $70^\circ\text{C}$ . There was a hold somewhere on the order of 10 to 24 hours. In some cases that elevator jumped.

On the first systems test, the total output recorded was 42 ampere-hours. With four batteries on board, the total capacity was 72 ampere-hours.

It was somewhat surprising that the capacity was so low. But, in going back and looking at the records, it was determined that there were some periods of time when they were performing ground tests or ground trials, the batteries were actually on low.

So, we probably don't know exactly what the total capacity was on a good many batteries. It was supposed to have been off. We know it was much higher than the 42 ampere-hours. That is just what was observed. So when the batteries are turned off now, they are off.

The second test was done a little later and was still in the same category 0 to 70°C. The capacity was 66.43 ampere-hours, about 10-percent total capacity there. We expected to get some reduction in capacity due to the high temperature and the higher discharge rate. So that was considered and checked for.

The system itself, maximum experiment, uses something like about 55 ampere-hours.

In each of these tests, two of the batteries were discharged completely. Those two that discharged did vent. There was no indication or institution of any high temperature. No knowledge of this venting was revealed until the batteries were removed from the system and the cover was removed.

The other two batteries on each of the two systems had residual capacities left in them. There was no cell venting in the case of either of the two batteries with residual capacity.

We have yet to evaluate the amount of capacities left on the systems test.

## DISCUSSION

HESS: Two questions: What were the discharge rates on these systems tests?

PASCHAL: Systems tests with about 0.8 of an ampere-hour per battery.

HESS: What were the stoichiometric proportions of the lithium?

PASCHAL: I can't answer that. I don't have that figure with me.

BENNETT: Can you tell me what the weight of the battery system was?

PASCHAL: About 12-1/2 to 13 pounds.

It was caused to be a little heavy. It was necessary to put wax in it in order to get the long, 3- to 4-hour usage.

GROSS: Several questions. First, the cells did vent under full discharge? I presume this is unacceptable. Is this correct?

PASCHAL: The two that were discharged on the systems test did vent.

GROSS: Yes. My question is, do you consider this unacceptable and therefore you will do something in the program to correct the design so that won't happen in the future? Or, do you consider this satisfactory?

PASCHAL: At this particular point in time we do not contemplate doing anything.

The reason we don't is that this venting occurred at what appeared to be without any generation of heat at a point when the batteries were pretty well impinging. It was not known that it did not vent gas out of the battery housing. So, there was no contamination.

Incidentally, this experiment is an IECM, Inducement Environmental Contamination Monitoring, and it is extremely important that we not vent outside the housing. Actually, the housing will vent at about 52 psig.

GROSS: My second question was regarding voltage.

When you operate over a large temperature range of approximately 170 or 180°F down to 32 degrees, as I understand the ranges from the chart, there would be a very large voltage change just due to the very thermodynamic behavior of the system. And second, this is, of course, aggravated by a range of discharge currents.

So, my question is, what voltage range did you experience on the system, and, secondly, what if anything was done in the design to minimize the voltage?

PASCHAL: The voltage was between 26 and 32 volts, which were the requirements set up on the system. I haven't looked at all of the data, but as far as I can recall, they are all within the range of 26 to 32 volts. The colder temperatures results in colder voltage there until you got real high. Temperatures on the battery started coming free, and then, of course, the voltage dropped. The systems tests terminated around 26 volts.

GROSS: That is one of the important problems with this system in a lot of applications. And it is worth looking at closely.

OTZINGER: Last year, during the lithium session, we had people from NASA Headquarters, discussing safety requirements. One of the things they pointed out was that for vehicles leaving KSC — and I believe this being shuttle as well — the design will have to be submitted to the safety group at KSC for their approval.

Has this been done and has this battery been approved for flight?

PASCHAL: We have received several preliminary approvals of the system. Final approval has not been given at this time. We are in the process of discussing it with JSC. Most likely, we will want to run some supplemental tests over what we have done. But, to answer your question, it has been submitted to JSC. Final approval has not been received.

HALPERT: Is there a lot qualification? In other words, have you put separate ones aside that are going to fly, or are they going to fly new ones all over again?

PASCHAL: There is a qualification for the batteries, particular battery design. We have qualified a certain number of batteries for the design of the system. Then, of course, we run through the check, including the precase venting test and the high-temperature thermal vacuum at both Marshall and at the vendor's plant. All of that constitutes an acceptance of each specific battery.

HALPERT: But you are going to buy a new lot for the actual mission?

PASCHAL: Well, yes. There is a new lot for each — for several batteries. This group that I showed you had several lots involved.

ORGANIZATION: EC12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME I. E. PASCHAL DATE NOVEMBER 1979
<p>1. SUMMARY OF MSFC APPLICATIONS</p> <p>2. GENERAL BATTERY DESCRIPTION</p> <p>3. IECM BATTERY</p> <ul style="list-style-type: none"> <li>o DESIGN &amp; CONSTRUCTION DETAILS</li> <li>o THERMAL VACUUM TESTS</li> <li>o BATTERY ACCEPTANCE TESTS</li> <li>o SYSTEMS TESTS</li> </ul>		

Figure 1-37

ORGANIZATION: EC12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME I. E. PASCHAL DATE NOVEMBER 1979												
<p><u>SUMMARY OF MSFC APPLICATIONS</u></p> <table border="0"> <thead> <tr> <th><u>PROGRAM</u></th> <th><u>FUNCTION</u></th> </tr> </thead> <tbody> <tr> <td>SRB</td> <td>FRUSTIUM LOCATION AIDS (FLA)</td> </tr> <tr> <td>SRB</td> <td>RANGE SAFETY</td> </tr> <tr> <td>ET</td> <td>RANGE SAFETY</td> </tr> <tr> <td>IECM</td> <td>PAYLOAD EXPERIMENT POWER</td> </tr> <tr> <td>TCSE</td> <td>PAYLOAD EXPERIMENT POWER</td> </tr> </tbody> </table> <p><u>GENERAL BATTERY DESCRIPTION</u> - ALL APPLICATIONS</p> <p>BATTERY TYPE: 13 - 18 AH LI/CF CELLS</p> <p>VENDOR: EAGLE PICHER</p> <p>HOUSINGS:</p> <p>FLA, RSS, TCSE: G4/45 NYLAFIL</p> <p>IECM: ALUMINUM</p> <p>QUALIFICATION STATUS: COMPLETE</p>			<u>PROGRAM</u>	<u>FUNCTION</u>	SRB	FRUSTIUM LOCATION AIDS (FLA)	SRB	RANGE SAFETY	ET	RANGE SAFETY	IECM	PAYLOAD EXPERIMENT POWER	TCSE	PAYLOAD EXPERIMENT POWER
<u>PROGRAM</u>	<u>FUNCTION</u>													
SRB	FRUSTIUM LOCATION AIDS (FLA)													
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ET	RANGE SAFETY													
IECM	PAYLOAD EXPERIMENT POWER													
TCSE	PAYLOAD EXPERIMENT POWER													

Figure 1-38

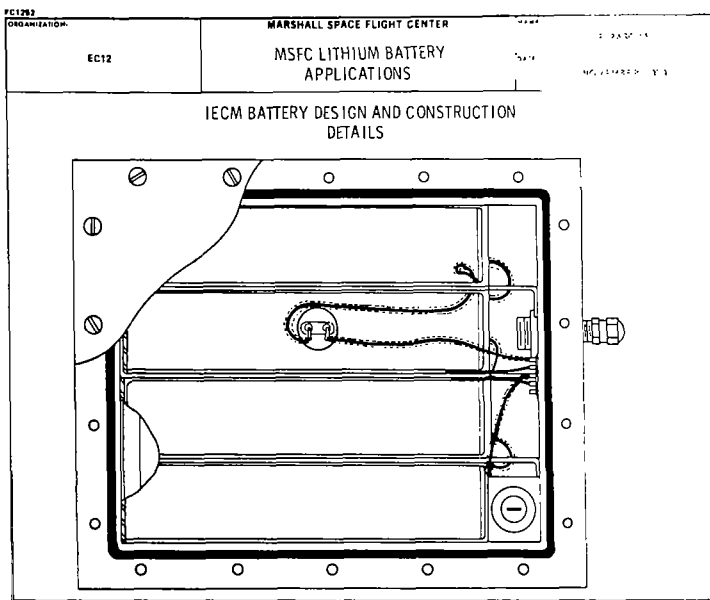


Figure 1-39

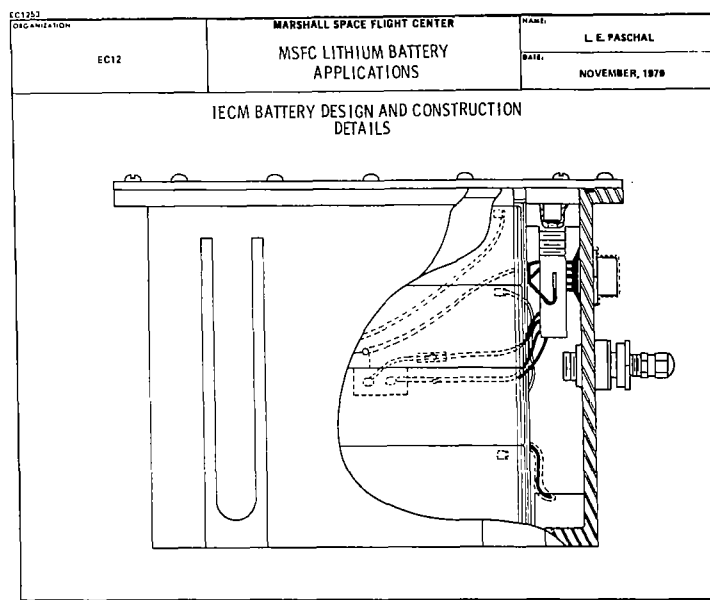


Figure 1-40

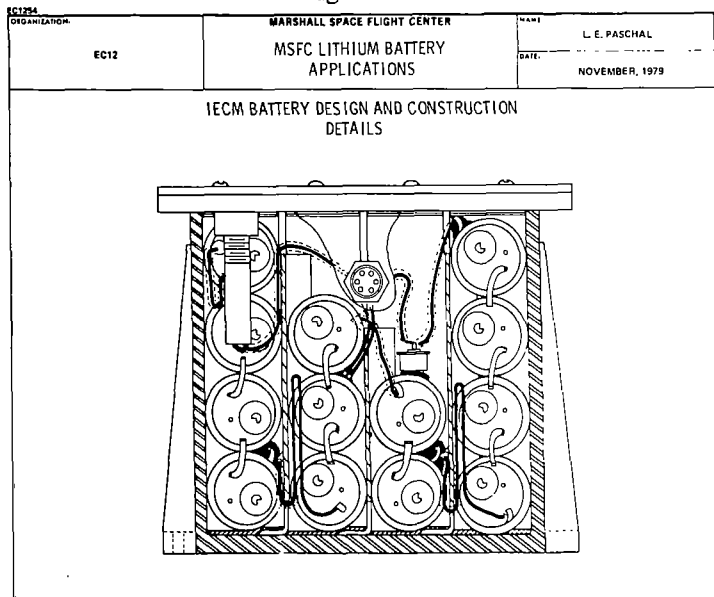


Figure 1-41

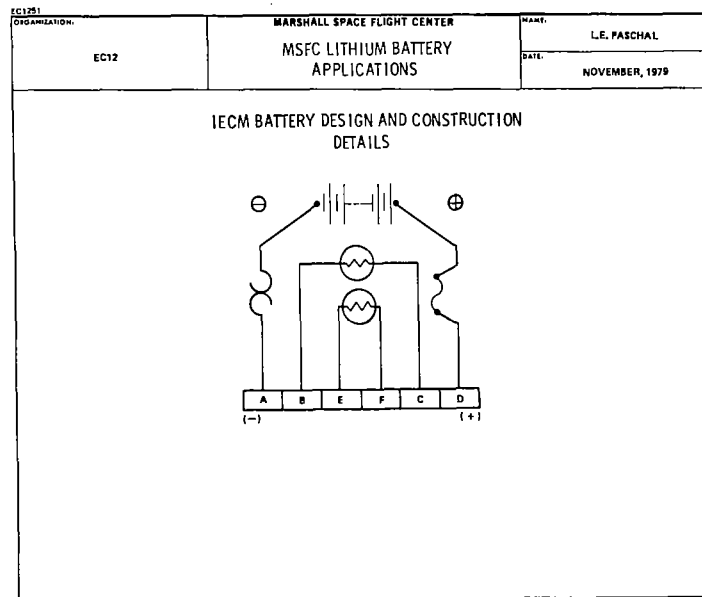


Figure 1-42



ORGANIZATION: EC12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME: L. E. PASCHAL DATE: NOVEMBER 1979
<u>THERMAL VACUUM TESTS</u>		
<u>VENDOR TESTS</u>		<u>MSFC TESTS</u>
1 X 10 <sup>-4</sup> TORR SHROUD -300°F MOUNTING: CELL HORIZONTAL		1 X 10 <sup>-6</sup> TORR MOUNTING: CELL HORIZONTAL & VERTICAL
<u>COLD TEMP. - COLD PLATE</u> 32° +5°F -0		<u>COLD TEMP. - COLD PLATE</u> 20°F ±5°F
2.3 AMPS - 5 MIN. 1.6 AMPS - 4 HRS. - 50 MIN. 1.5 AMPS - 1 HR.		1.72 AMPS - 15 MIN. 1.3 AMPS - 1 HR. - 45 MIN. 1.2 AMPS - 3 HRS.
AMBIENT TEMP. & PRESSURE 1.4 AMPS - 1 HR.		
<u>HIGH TEMP. - COLD PLATE</u> 100° +0°F -5		<u>HIGH TEMP. - COLD PLATE</u> 104°F ± 2°F
2.3 AMPS - 5 MIN. 1.6 AMPS - 4 HRS. - 50 MIN. 1.5 AMPS - 1 HR.		1.2 AMPS - 1 HR. 1.72 AMPS - 15 MIN. 1.3 AMPS - 1 HR. - 45 MIN. 1.2 AMPS - 3 HRS.
AMBIENT TEMP. & PRESSURE 1.4 AMPS - 1 HR.		AMBIENT TEMP. 1.2 AMPS - 1 HR.
MAX. BATTERY TEMP. 180°F		

Figure 1-43

ORGANIZATION: EC 12	MARSHALL SPACE FLIGHT CENTER MSFC LITHIUM BATTERY APPLICATIONS	NAME: L. E. PASCHAL DATE: NOVEMBER 1979		
<u>ACCEPTANCE TESTS</u>				
CELL BLOCK CAPACITY		>18 AH		
CELL IMPEDANCE		<1.0 OHMS		
DIELECTRIC STRENGTH (500 V, 60 HZ/60 SEC)		<.5 MA		
INSULATION RESISTANCE (100 V DC/2 MIN)		>50 MEGOHMS		
THERMISTOR TESTS		PER CALIB. CURVE		
PIN/CASE VOLTAGE TEST		<250 MV		
DIMENSIONS		PER DRAWINGS		
BATTERY CASE SEAL PRELIM. (12 PSIG)		<.1 PSIG DROP/5 MIN		
FINAL BATTERY CASE SEAL (160°F/4 HRS; 1 X 10 <sup>-4</sup> TORR)		NO WAX LEAK		
MSFC OUTGAS/LEAK TEST (158°F/48 HRS; 1 X 10 <sup>-6</sup> TORR)		NO WAX LEAK; WITHIN OUTGAS SPECS.		
<u>VENDOR/MSFC DATA:</u>				
SERIAL NO.	7	8	9	10
CELL BLOCK AH	23/23.5	21.5	21.25/21.5	20.0/20.5
VOLTAGE PRE-OUTGAS	39.0	39.1	38.1	38.3
VOLTAGE POST-OUTGAS	38.2	38.3	37.3	37.2

Figure 1-44

ORGANIZATION:  EC12	<b>MARSHALL SPACE FLIGHT CENTER</b>  MSFC LITHIUM BATTERY APPLICATIONS	NAME: L. E. PASCHAL
		DATE: NOVEMBER 1979

SYSTEMS TESTS

○ THERMAL VACUUM

- PART OF FULL IECM TEST
- 1 X 10<sup>-6</sup> TORR
- 4 BATTERIES (72 AH TOTAL CAPACITY) ON BUS
- 15 TEMPERATURE CYCLES 0 - 70°C (ESTIMATED 300/400 HRS. UNDER 70°C)
- HOLDING 10 - 24 HOURS

○ TEST 1 RESULTS

- KNOWN DISCHARGE CAPACITY 42.0 AH (20/21 AH AT 70°C)
- UNKNOWN DISCHARGE CAPACITY DUE TO INSTRUMENTATION PROBLEM
- TWO BATTERIES DISCHARGED - CELL VENTING
- RESIDUAL CAPACITY TWO OTHER BATTERIES - NO CELL VENTING

○ TEST 2 RESULTS

- KNOWN CAPACITY DISCHARGE 66.43 AH
- TWO BATTERIES DISCHARGED - CELL VENTING
- TWO BATTERIES - RESIDUAL CAPACITY - NO CELL VENTING

SESSION II

LITHIUM CELL TECHNOLOGY AND SAFETY

G. Halpert, Chairman  
Goddard Space Flight Center



## HIGH ENERGY DENSITY BATTERY DEVELOPMENT STATUS REPORT

A. Willis  
NOSC

(Figure 2-1)

Looking at the Navy applications for high energy density batteries, you can see quite a range of applications, rates, and capacities; anywhere from remote sensors with the low rate, low capacity to the vehicular propulsion, which is high rates and high capacities.

(Figure 2-2)

As a net result, we have been looking or have developed a family. The largest one is a low-rate undersea implementation type of battery. Then, you see the 120-kilowatt-hour high rate for undersea propulsion. We have the 1.2-kW high rate battery for economeasures equivalent 600-watt-hour medium rate battery for a manpack for the Marine Corps.

In the middle of the illustration there are various cell technologies including the prismatic, the D sizes, and other assortment of button assortments and discs.

The film I have is what we did almost a year ago in the development, testing the first developmental cells of a large 17-inch thionyl chloride cells.

May I have the film, please?

(Film)

I defy any of the other cells you have to come through this test equally well. The interesting thing, the cell that went bad in reverse voltage gave this characteristic.

(Figure 2-3)

The important thing, of course, is this point right here. We have done a considerable amount of investigation, and we find that there is a critical point here in the neighborhood of -0.9 volts. Every cell that has ruptured in reverse voltage has gone to this point just prior to rupture.

So, it is important if you don't have an internal means of protecting or preventing that voltage appearing in the reverse direction on any of the lithium cells, you should have a Shockley diode to parallel it and prevent that voltage.

(Figure 2-4)

As a result of this test which was a 500-ampere hour, 17-inch cell, we decided on an improvement effort to obtain full capacity which means from 1/2- to 1-3/8-inch thick cell, from 500 ampere-hours to 1500 ampere-hours ambient temperature.

Obviously, we needed some work done on the vent relief device. We need a higher current feedthrough. And we had to improve the reverse voltage technique and to reduce the case weight.

(Figure 2-5)

A review of the safety problems indicates that three things can occur. Explosion occurs when the lithium melts, and the resolution of this, of course, is to prevent the lithium from melting. Release reactive materials from the cell before the lithium melts or control the lithium when it melts.

Explosion can occur when the cells are deeply discharged, and you have to provide some electrical controls either internally or externally to prevent voltage reversal. Hazardous materials are expelled from the cells during adverse conditions. We can contain, dilute, or minimize the quantity of hazardous materials and increase the tolerance for adverse conditions.

(Figure 2-6)

We said we were going to do some additional tests in the fall of 1978. Well, this is fall of 1979, so 1 year later and \$1 million later we now have a new set of cells.

This is a typical and desirable set of curve that we are looking for. This particular curve was on one of the smaller cells, a 2 1/2-inch diameter cell performing at 0°C.

Thus, you will notice here that we started the open circuit voltage, and it drops down to the 3 volts, a fairly high rate. That is a 2-ampere rate on the 5-ampere hour cell. Now down to about 3 volts, it stays here and falls off rapidly. Passes through 0 to about -0.1 at which time it locks up an internal switching device and holds it constant for as long as you want to go.

Interesting, we took temperature at the same time and the normal heating during discharge, as it came to the point where there is no more lithium, the internal resistance went up. And being a constant current drive, the temperature was increased until the lockup took place, and then the normal cooling curve resulted.

(Figure 2-7)

We had four more cells of the large configuration just this month – let's see, about the latter of September. This is a 17-inch cell under the same conditions of 12-ampere rate at 0°C. Again, it gave pretty near the flat configuration we have looking at this curve in here as to why that dropped off.

It fell off rapidly at a predetermined time. It dropped momentarily to the last – the neighborhood to 0.1 to 0.3, then locked up and stayed constant for the rest of its life. This is about 150 to 180 percent of the ampere-hour rating of this cell, and that is a safe discharge reverse voltage condition.

(Figure 2-8)

We are now really looking at the future, and we see a sort of family of applications or a family of cells. This should meet most of our applications ranging from low rate, medium rate, high rate, and the very high rate which is usually the reserve cell, the small, medium, and large capacity. This is sort of a family of cells that we think are immediate to the Navy applications.

#### DISCUSSION

OTZINGER: Will you describe how you achieve lockup?

WILLIS: This is essentially proprietary information with ALTUS.

OTZINGER: I see.

LEAR: When you did the discharges after storage or whatever, did you notice any of the lag in the voltage coming up through the potential?

WILLIS: Every cell that we discharge we do a depolarization curve to measure that time element, and the most severe that we have seen has been 12 seconds between the time the load was up high and the voltage was up above 3 volts. Normally it is in the order of 1 second.

LEAR: I have one other question. These were 150-, 120-ampere hour cells?

WILLIS: 1500-ampere hour cells.

LEAR: Why did you go so long in reverse direction with the voltage continuing on?

WILLIS: When a cell is in a battery configuration, it can see 100-percent ampere-hour capacity.

Assuming a cell is dead due to long period of storage and internal leakage of some sort, when you put the battery in service, the maximum it will be able to see is 100-percent rated capacity.

We take it into 150, maybe 200 percent just as a safety factor, just to prove that the thing is not really working.

ANGRES: Have you had any accidents lately with cells in reversal? And question number two is, is there any significant physical data of the reproducible Altus technology? I have not seen anything.

WILLIS: As I said, we received four more of the experimental cells in the larger configuration at 1500 ampere-hours. We put all four of them on discharge and reverse voltage. One did rupture, but it was predictable.

(Figure 2-9)

In the early physical measurements of the cell, which is cell No. 94 there, you can see it was lightweight, about half a pound lightweight. And then we put that one on discharge and reverse voltage with this result.

(Figure 2-10)

You will notice that there was number one, a discontinuity during the discharge which, again, flagged that one as a bad cell, I will say. Went down into reverse voltage and got very erratic here.

Not it lasted in excess of 150 percent of its capacity. But in order to obtain data as to what causes reversals – I mean explosions – and how long it would go before it would happen, we let the thing continue. And again, as soon as we hit -0.9 volts, it went.

So, it was predictable. We watched it, we knew it was going to happen, and that is it.

LEAR: Is the discharge rate the same after you go into reversal?

WILLIS: It is 12 amperes constant current.

LEAR: Totally? In other words, you took out more than 2400-ampere hours capacity out of that cell?

WILLIS: Yes. Well, we did not take it out. It was driven at 12 amperes. After reversal it is driven at 12 amperes.

LEAR: You took out roughly 1100 ampere-hours of capacity, 96 hours.

WILLIS: Say this was the cutoff point . . .

LEAR: 95 hours. About 1100 ampere-hours of that cell.

WILLIS: *Actually to the cutoff point. Now I don't have the discharge capacity there.*

(Figure 2-11)

This is the setup we used in which we take a power supply and actually drive it at a constant controlled 12 amperes during the whole cycle. It is 12 amperes because this particular cell is rated at 1200 ampere-hours at 0°C. 1500 ampere-hours at ambient temperature.

BENNETT: Have you got any shelf-life data on these at all at any temperature conditions? Have you noticed any ceramic seal problems or GTM problems?



WILLIS: We do not have any shelf-life data on the large cells. It is the same ceramic that is used in small cells. We have had them around for a maximum of 2 years with no deterioration whatsoever as far as the seals are concerned.

BENNETT: Can you tell me what orientation they were in?

WILLIS: Usually they are just horizontal, flat.

BENNETT: With the seal upright?

WILLIS: With the seal upright.

BENNETT: Have you ever done any inverted?

WILLIS: Not specifically.

SLIWA: Have you prepared any, or are you preparing any information on the safe way in which you dispose of these batteries once they are developed? Also, what would be the storage requirements?

WILLIS: On storage, the primary purpose, of course, is to prevent short circuit. It is to protect the terminal.

Secondly, this particular chemistry, as I understand it, is damaged with continued storage in excess of 130°F. As far as disposal is concerned, we find that they dispose very readily at sea.

We have done experiments by submerging the cells in salt water in barrels where we can observe it. In answer to this morning's question about using water to extinguish fires in relationship to the unit, apparently what happens is that the water will percolate or go into whatever opening is on the cell. In our case, it actually generated its own opening through electrolytic action on the case, and then it percolates. A little water goes in, and as soon as it hits the lithium or whatever elements are inside, it generates a gas and blows the water back out again. A little water goes in and then percolates back out, and it keeps that up over a long period of time.

And at no time is there any thermal runaway or major reaction. So, at sea disposal, seems a very convenient way for us, anyhow.

SLIWA: For shore disposal we would still have to consider this hazardous waste, just as the Navy considers all lithium sulfur dioxide, and any other lithium battery is considered hazardous waste under any conditions.

WILLIS: Not really. They are not a pressure vessel. If they had been discharged all the way down, there would be little or no toxic material in it and no pressure in it. So, while I would recommend handling them with reasonable amount of care, I see no reason why they cannot be disposed of as industrial waste.

SLIWA: We will have to pass this through the EPA.

WILLIS: Yes.

There is no toxic materials in the sense that it is injurious to the health, long leaching problems, or anything like that. No sign of that.

SLIWA: Concerning your tests, do you expect to continually add more tests as your test series goes on? Or, do you feel that the tests that you are now conducting will be complete life-cycle type testing that is required?

WILLIS: We have to obviously test more cells to get a statistical base. We are going on to additional testing using multiple cells in a battery configuration. The first one will be a three-celled battery configuration which is scheduled to go on at Wiley Laboratories.

(Figure 2-12)

This is the sort of matrix that we normally use; discharge rates at primarily 0°C, which is our underwater application. Then, we have vibration and shock, trying to get statistical information on reverse voltage and some of the hazard evaluation. And the last three cells on this test have a battery configuration.

SLIWA: How does this compare with the technical standard that we have to have and some other test requirements?

WILLIS: I think although it does not address specific shipping containers and things like that, it does take us far in excess of anything they are requesting. Our vibration and shock, for instance, is far in excess of any of those specific applications I have seen.

Dry battery specification Mil B-18 takes the low frequency and high frequency vibrations. It also takes the drop, as you saw it, of 250 gs.

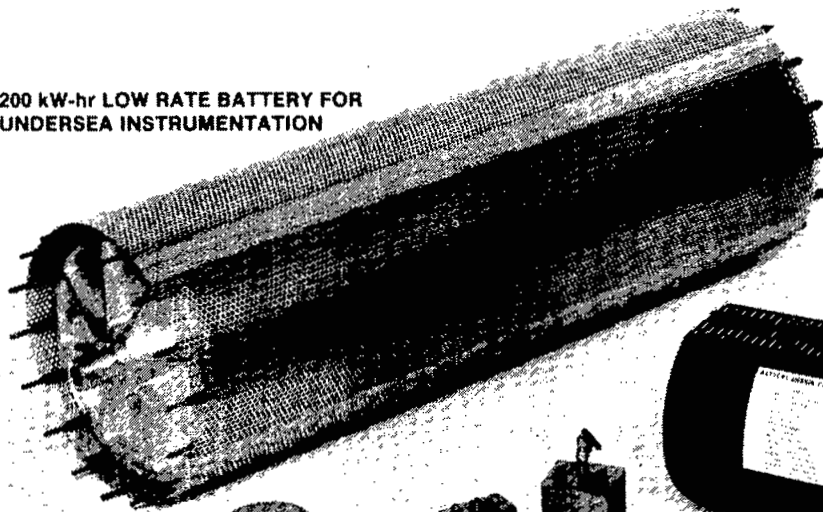
# NAVAL APPLICATIONS OF HIGH ENERGY DENSITY BATTERIES

Rate \ Size	Small (~ 10 AH)	Medium (~ 100 AH)	Large (~ 1000 AH)
Low (100 hr)	Experimental Equipment Remote sensors		Remote sensors Mines Aids to navigation Standby power
Medium (10 hr)			Submersibles
High (1 hr)	Sonobuoys, Portable communications	Countermeasures Decoys	
Very high, reserve (0.1 hr)	Missiles Countermeasures	Torpedoes Targets	

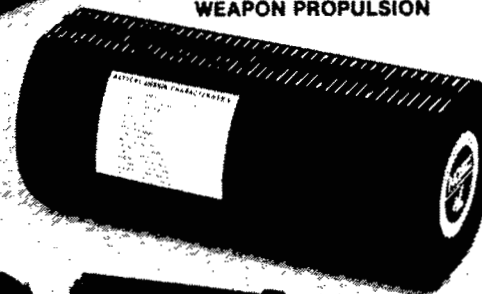
Figure 2-1

**NOSCO** LITHIUM THIONYL CHLORIDE BATTERY  
DEVELOPMENT PROGRAMS

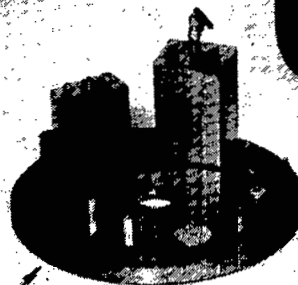
200 kW-hr LOW RATE BATTERY FOR  
UNDERSEA INSTRUMENTATION



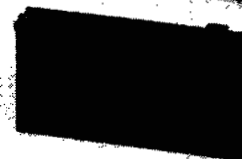
120 kW VERY HIGH RATE  
BATTERY FOR UNDERSEA  
WEAPON PROPULSION



1.2 kW-hr  
HIGH RATE  
BATTERY FOR  
ELECTRONIC  
COUNTERMEASURES



LISOCI<sub>2</sub> CELL TECHNOLOGIES



600 W-hr MEDIUM RATE BATTERY  
PACK FOR FIELD TRANSCEIVER

Figure 2-2

# TEST CELL DISCHARGE/REVERSE VOLTAGE PROFILE (OVERALL)

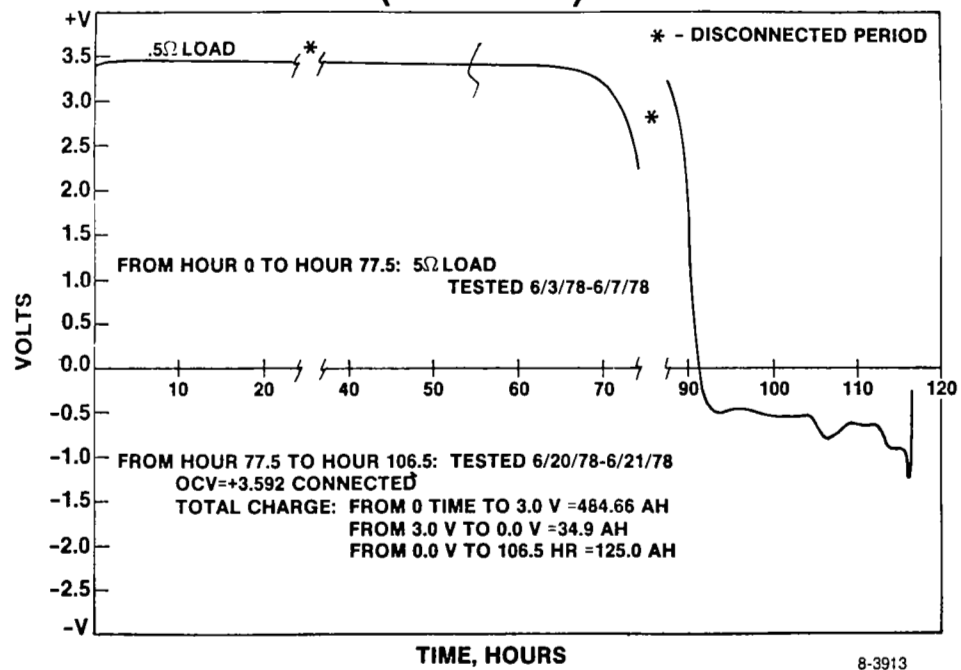


Figure 2-3

# HEDB PROGRAM CELL IMPROVEMENT EFFORTS

1. Obtain full capacity
2. Develop reliable pressure relief vents
3. Develop high current electrical feed-through
4. Develop anti-reverse voltage technique
5. Reduce case weight

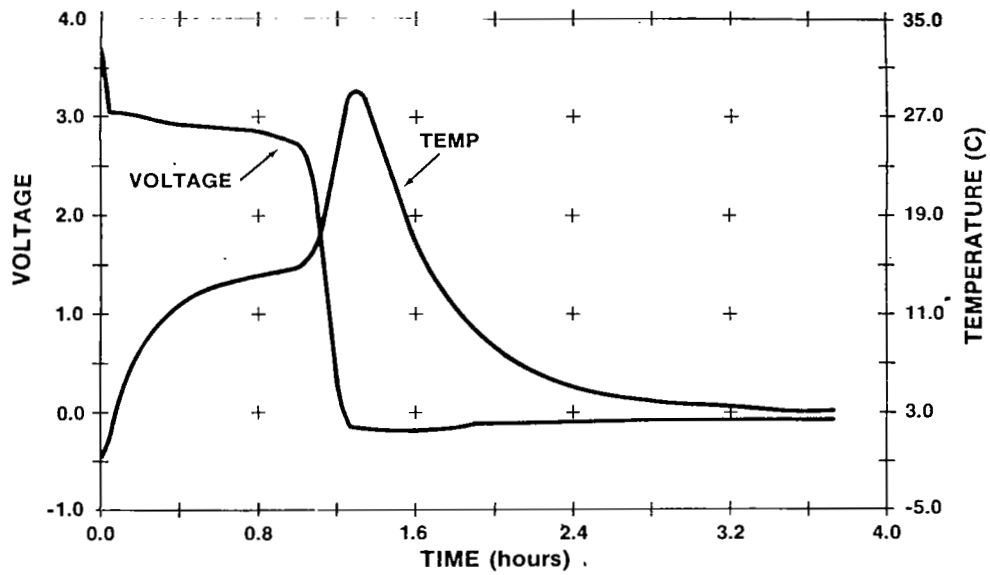
Figure 2-4

## SAFETY SITUATION

PROBLEM	SOLUTION
● Explosions occur when lithium melts	● Prevent lithium from melting ● Release reactive materials from cell before lithium melts ● Control the lithium when it melts
● Explosions occur when cells are deeply discharged	● Provide electrical controls to prevent voltage reversal
● Hazardous materials are expelled from cells during adverse conditions	● Contain or dilute expelled products ● Minimize quantity of hazardous materials ● Increase the tolerance of cells to adverse conditions

Figure 2-5

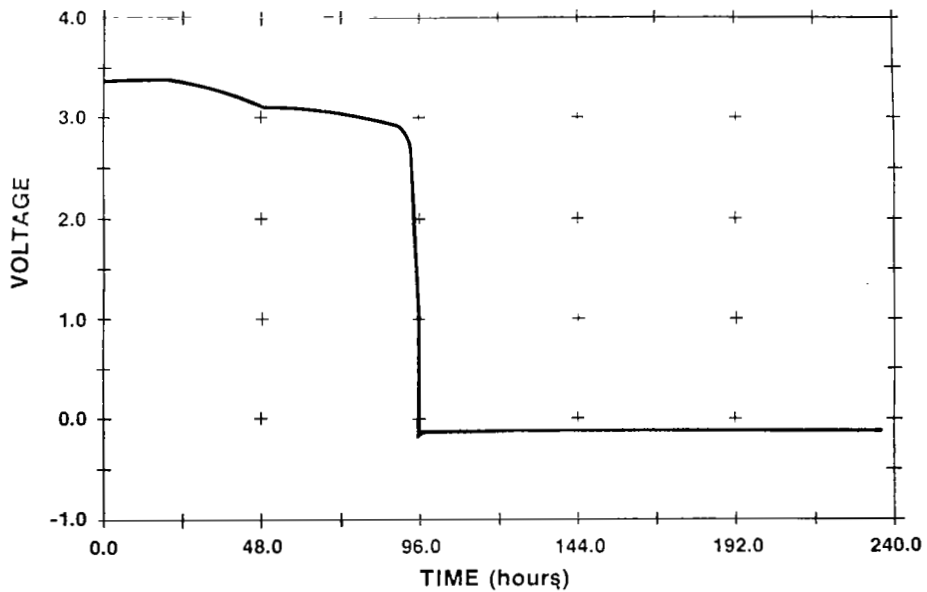
### TYPICAL DISCHARGE CURVE WITH TEMPERATURE



0 degree PERFORMANCE TEST, 22 AUG 79, 2 amp RATE  
 ALTUS AL-250, LITHIUM THIONYL CHLORIDE, SERIAL #187

Figure 2-6

### TYPICAL DISCHARGE PROFILE



0 degree PERFORMANCE TEST, 12 amp RATE, 3 OCT 79  
 ALTUS 17 inch CELL, LISOCL2, SERIAL #91 (3)

Figure 2-7

# TYPICAL APPLICATIONS OF LITHIUM PRIMARY CELLS

Application	Rates	Capacity (AH)
Remote sensors	Low	10-100
Countermeasures & decoys	High	10-100
Portable communications equipment	Medium	20
Vehicle propulsion	High	1000-3000
Sonobuoys	High	10
Targets	High	1000
Torpedoes	Very high	50-300
Mines	Low	500
Missiles	Very High	10
Ordnance fuzing	Very High	1
Data links	Low	100
Tactical data terminals	Medium	10
Standby power	Low	10-10k
Portable lighting equipment	Medium	20

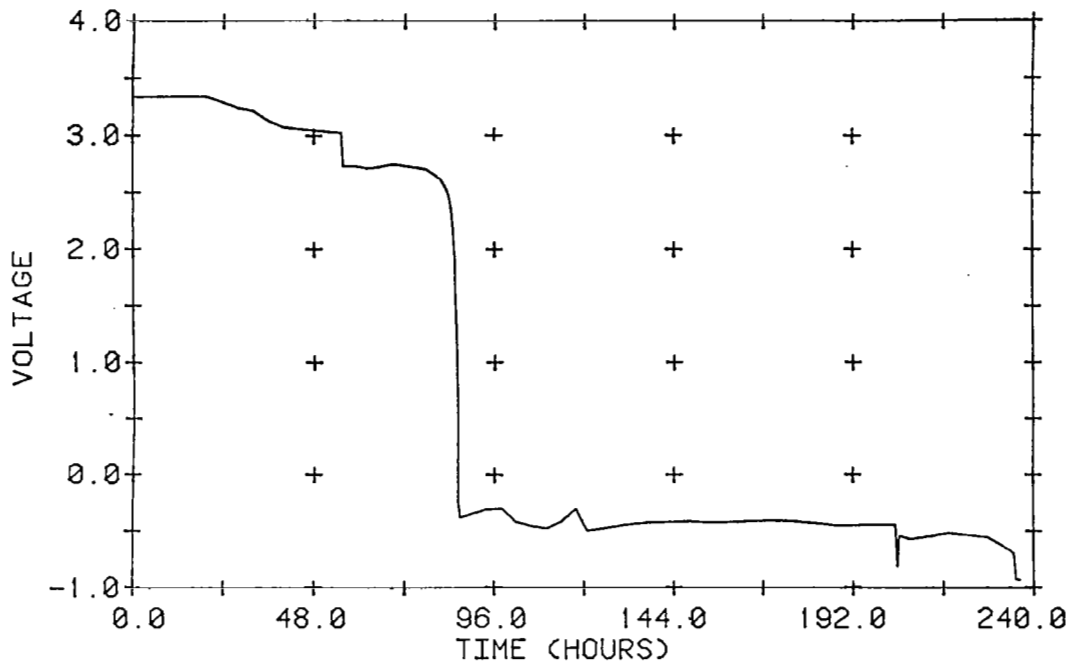
Figure 2-8

TABLE 2. ACCEPTANCE INSPECTIONS & TESTS SUMMARY

CELL NO.	DIMENSIONS (IN.)				WEIGHT (LBS.)	OPEN-CIRCUIT VOLTAGE	SURFACE PH LEVEL (ppm)	WORKMANSHIP	COMMENTS
	DIA. O.D.	DIA. I.D.	THICK-EDGE	THICK-BULGE					
89	17.0	2.658	1.40	1.65	29.55	3.636	5	OK	Leakage from Vent. Reject
91	17.0	2.655	1.409	1.629	29.175	3.644	5	OK	Passed
94	17.0	2.658	1.40	1.625	28.89	3.632	5	OK	Passed
95	17.0	2.658	1.398	1.637	29.23	3.625	5	OK	Passed
100	17.06	2.660	1.410	1.672	29.41	3.621	5	OK	Passed

Figure 2-9





0 DEGREE C PERFORMANCE TEST, 12 AMP RATE, 3 OCT 79  
 ALTUS 17 INCH CELL, LISOCL2, SERIAL #94

Figure 2-10

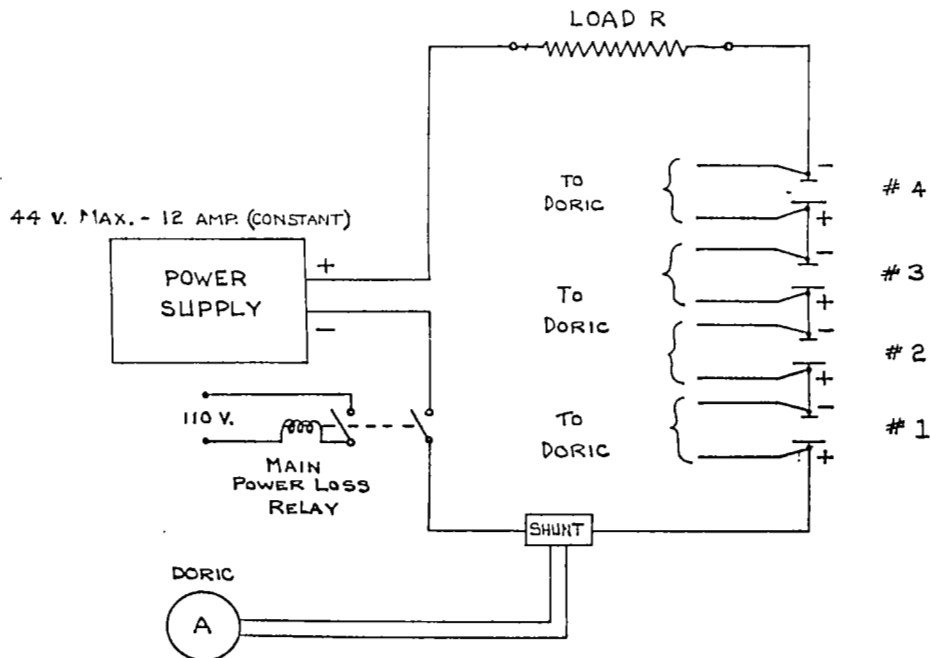


Figure 2-11

TABLE 1.

HEDB ALTUS 17", 13-CELL TEST PROGRAM MATRIX

TESTS	CELL NUMBER												
	1	2	3	4	5	6	7	8	9	10	11	12	13
<u>ACCEPTANCE INSPECTIONS</u>	①	①	①	①	①	①	①	①	①	①	①	①	①
<u>PERFORMANCE</u>													
CAPACITY @ 0°C. (12 AMP. RATE) VER.	②	②											
CAPACITY @ 0°C. (12 AMP. RATE) HORIZ.			②	②		③	③						
CAPACITY @ AMBIENT (12 AMP. RATE)					②					②			
1/2 DISCHARGE @ AMBIENT (12 AMP. RATE)											②	②	
<u>ENVIRONMENTAL</u>													
VIBRATION											③	③	②
SHOCK											④	④	④
ALTITUDE											⑤	⑤	⑤
HYDROSTATIC & DISCHARGE (TO 2V)											⑥	⑥	⑥
REVERSE VOLTAGE	③	③	③	③		④	④				⑦	⑦	⑦
POST REVERSE VOLTAGE SHOCK											⑧	⑧	⑧
OVERCURRENT (100 AMP., -30 SEC.)													
DROP - 5						②							
<u>HAZARD EVALUATION</u>													
EXTERNAL HEAT													
PENETRATION					③					③			
DROP - 6	④	④	④	④		⑤	⑤			④			
SHORT CIRCUIT										②			
<u>DISPOSAL</u>	⑤	⑤	⑤	⑤	④	⑥	⑥	⑤	④		⑨	⑨	⑧

MORRIS DAM ↕ SPARE ↕ WYLE LABS.

① - DENOTES TEST SEQUENCE FOR EACH CELL.

Figure 2-12

## GALILEO LITHIUM/SO<sub>2</sub>

L. Blagdon  
Honeywell

I would like to present today the general requirements of the Galileo lithium SO<sub>2</sub> battery, the current status on that program, as well as some general comments relative to the experiences we have already gone through in the development of that battery.

I will start, first of all, with the discussion of a general review of the specification requirements for this device.

(Figure 2-13)

First of all, it is a modular concept. The full battery is three modules. Our responsibility is for developing a single module which, in the system, three modules will be hooked in parallel and the diode isolation of those modules is included in the systems design.

The electrical characteristics required are 7.2-ampere hour minimum capacity at a minimal voltage of 28.05 volts. That is being accomplished with 13 high-rate D cells.

Capacity from module to module must be within 5 percent of each other in lot acceptance testing. Voltage delay requirements are required less than 100 microseconds voltage delay to 28.05 minimum voltage. Single point failure requirements required that bypass diodes, shunt diodes be placed on each cell in the series connected string.

The batteries also required to have a pyrotechnic tap in the 14- to 24-volt range, which runs up at about 7 amperes for 30 milliseconds. The actual discharge rate or discharge profile for the battery runs anywhere from a cruise timer load of 0.5 milliamperes on the module for 150 days up to 3.27 amperes at the end of discharge life, or at the end of the mission. And there are a number of steps between there as additional testing equipment comes on line.

The storage requirement is 5.4 years, basically under a controlled environment of 0°C. There is some 40°C requirement during some uncontrollable chipping times or while it is on the launch pad. But something over 4 years of that time is spent at 0°C.

Specification also requires that during that time there is 2.5 percent per year maximum, 2.5 percent per year capacity loss.

Reliability predictions required are 0.99 probability of completing the mission. The mission is defined right now at 6.65 ampere-hours. So, the total mission is under the minimum ampere-hour capacity requirements.

(Figure 2-14)

The basic configuration of the module is a rigid vented case that has to support its environment, mechanical environment in a beam type of mounting configuration. I have got a drawing a little later showing the general configuration of the module, and you can see what I am talking about there.

Maximum weight is 2.5 kilograms. Environments that it must survive are both sine and random vibration. Deceleration is at 410 gs for 30 seconds. There is a 150-g lateral shock load and a 30-grms random vibration requirement that the module must survive. It also must survive a low-rpm spin around the center of gravity of the probe. It must withstand radiation exposure, cobalt 60 up to 200 kilorads, and a pressure on entry into the Jupiter environment. Qualification is 16 bars, and acceptance is 13 bars.

(Figure 2-15)

Basic cell configuration used is a high-rate D cell jelly-roll configuration active, hermetically sealed. The header is laser welded into the case. Case and header materials are 304 stainless steel. The glass-to-metal seal uses a tandem feed through. The cell is lithium limited, that is a little bit of a misnomer. It is designed as a coulometrically balanced cell. So the stoichiometry of the thing is balanced between the SO<sub>2</sub> and the electrolyte with excess collector capacity from a dump-site point of view.

The cells do have safety vents in them, and have a relatively high surface area, active surface area.

(Figure 2-16)

Thirteen of these are mounted in a package that is approximately 13-1/4 inches long, and flange mounting occurs at the brackets on both ends. The brackets are attached to an arm which is supported off pivot point so that the entire device is suspended by those brackets and must withstand all the environments in all three directions.

The cells are stacked, as you can see, 13 of them. All the diodes and thermistors – there are two monitoring thermistors in there – are mounted on a flexible printed circuitboard that is manufactured to NASA's specification.

The shunt diodes are procured to a Marshall Space Flight Center specification for very, very low reverse current drain rates, because they have to stay on there 5 years. And we certainly cannot lose too much capacity from them.

The case is aluminum. It is of single-unit construction and is machined from a single block of aluminum. Connectors are in both ends. One is an instrument connector; the other is the power connector.

The battery in its current configuration does not have a fuse built into the battery. For shipping and general handling purposes, a special cap has been designed to be left with the battery

and mounted to the battery on one of the connectors. That does fuse the output leads or the power leads on the battery.

In its actual mounting location in the probe, it would not be fused. The primary considerations in that design choice right now is with respect to reliability. However, that is being reconsidered currently. We may, in fact, put a fuse in the actual unit.

(Figure 2-17)

To date, the electrical performance that we have demonstrated utilizing five cells stacked, series connected stacks. The mission has a rather sophisticated temperature profile also.

During the cruise portion of the mission, the minimum temperature is  $-5^{\circ}\text{C}$ . The five-cell stacks delivered 7.26 ampere-hours at the minimum temperature profile, or to the minimum temperature profile, which actually on entry drops down to  $-14^{\circ}\text{C}$  and then comes back up.

At a nominal or average temperature profile for the mission, the cell stacks delivered 7.73 ampere-hours, and at the maximum temperature the cell stacks delivered 7.79 ampere-hours.

The cells basically are not thermally insulated from the environment, and the thermal analysis of this module configuration says that the battery and the cells will track very closely the external environment that the probe is seeing. So, these tests were conducted without a great deal of thermal insulation around them, which generally adds to their overall capacity.

*Minimum Pyropulse Voltages.* – At the end of mission, which is an additional 7-ampere 30-millisecond pulse on the battery, would leave you with battery voltages as shown, 33, 32, and 31 volts, based on the different mission temperature profiles.

*Voltage Delay.* – Voltage delay requirements are 100 microseconds. Generally, there were problems in meeting that. There were systems design changes to include or add a preconditioning load before entry, and before the entry load profile begins to take place to clean the cell up.

The results of that testing indicated that a 1-ampere load for about 5 seconds would clean that, any passivation that was on the cells, up, and eliminate any problems with meeting that voltage delay requirement.

(Figure 2-18)

*Storage.* – There has been a little bit of accelerated storage test work done relative to the hermetic seals. However, 450 cells are going under  $0^{\circ}\text{C}$  storage environment, which is a real-time storage environment. Because of a stretchout of the program by about 2 years, we will have about 4 to 4-1/2 years of real-time data on this cell hardware.

The cells are evaluating the effects of the bypass diodes on storage as well as effects of orientation or the zero-g in the environment, so there are about three different configurations that are going into that test. The cells are being completed this month and will go on storage this month.

The other thing relative to storage, a protective cap has been designed for the glass-to-metal seal. There was at accelerated temperature, some corrosion of the glass-to-metal seal, or the glass in the glass-to-metal seal witnessed, and the protective cap is included on the hardware to basically take away the effects of orientation, which appear to be the primary difference in any corrosion rates that we have seen. In high-temperature inverted storage cell test, it has done an effective job. The cap has done an effective job in correcting it.

*Reliability.* – We did make a preliminary prediction of 0.99 probability of completing the mission, or the 6.65 ampere-hours. Basically, the way we accomplished that was with the excess capacity in the fact that a single cell could be lost at the 6.65 ampere-hour point, and the module would still be above the minimum voltage requirements in the program.

(Figure 2-19)

The first module is completed. It was completed this month. The actual weight of the unit was 2.2 kilograms. And we are in the process of completing five additional modules that will be subjected to the mechanical environments required.

Cells from phase 1 of the program have passed random and sinusoidal vibration and deceleration, both as individual tests and as sequential tests. And non-Galileo cell hardware of a similar construction has passed the radiation requirements.

Now I would like to make a few comments based on the experiences that we have run into so far in the development of this battery.

(Figure 2-20)

We believe from a safety point of view that the battery designs should be vented to design – and the original Galileo program did spec a sealed module to withstand the venting of individual cells. That was eventually changed, and the present module configuration is vented. We believe from a safety point of view that is necessary.

Isolate diodes should be used if parallel configurations are required. I think that is pretty standard at this point in time. That is part of the system as far as the way our program is put together.

The batteries should be fused. Cell designs, we believe, should be lithium limited, or at least coulometrically balanced in lithium and sulfur dioxide ratios.

We believe the people who will be eventually handling and operating these cells do need clear training and understanding of what they have in their hands. The battery module or concept should be incorporated in high-energy requirements. And by that I mean we do not believe that batteries should be built containing excessive amounts of cell hardware, large cell quantities in a single battery configuration. They should be split up into smaller, more handleable packaging-type configurations.

(Figure 2-21)

And lastly, from a reliability point of view, we feel that there is possibly some additional work that can be done in optimizing the voltage and capacity requirements to ensure that you can withstand a single cell failing within a battery, still meeting the minimum voltage requirements.

If you specify and order a four-cell battery, it is going to be very, very difficult to make 0.99 reliability predictions based on the analysis we have run so far. Single point failure can be eliminated, and it is almost a must in the high-reliability configuration.

The impact of that, of course, or the question that comes from that is relative to the losses in storage that might be incurred with the bypass diodes, which are currently undergoing tests to determine – by the way, those leakage currents for those specific diodes are in the nanoampere range.

*Performance.* – Cell manufacturing tolerances must be tightly controlled. We found some of the standard raw materials coming for our cell hardware are not adequate to meet the kind of tolerances that we are looking at for some of these applications.

Battery conditioning should be considered if there is a severe voltage delay requirement in the microsecond range. We do have long-term storage.

And again, if a long-term storage requirement is involved, control in temperature environment is very, very important in guaranteeing that you meet your storage requirements.

## DISCUSSION

MAHY: You never did tell us what the end use discharge current was.

BLAGDON: Actual load profile ranges from 0.5 milliampere on a module for 150 days on the front end, and winds up with full instrumentation on it about 3.27 amperes. End of life occurs under 3.27-ampere load.

MAHY: There is continuous use in a way over the whole 5.4 years?

BLAGDON: No. Basically, it is turned on 150 days prior to entry. During the other 4 years, it is under storage, or just inactive.

TATARIA: You said your cells are hermetically sealed. How are you taking hermetic sealing, the outside leak rate or the helium leak rate?

BLAGDON: We use the helium leak rate and a very high sampling plan on a hardware that we are currently building, the cell hardware that we are currently building to ensure that we have that. We also do 100 percent sort of all the glass-to-metal seals.

TATARIA: You did the helium leak rate?

BLAGDON: On the finished cell? No, our normal procedures require a 48-hour heat soak and then visual examination.

We are looking at some other alternatives to determine if there is any additional weight loss at that time. Currently it is a heat soak, visual and weight measurements on the cells after they are manufactured.

TATARIA: Thank you.

WATSON: Would you care to comment on the cause of the glass seal corrosion that you discussed, and how your protective cap prevents that from occurring?

BLAGDON: Basically, I don't know whether the actual causes of the glass seal corrosion are specifically known and understood today. The protective cap simply uses an O-ring pressure-type seal on the inside to not allow the electrolyte in full contact, in the inverted position, and in full contact with the cells.

It is not a second hermetic seal. It is not intended to be. The purpose is simply to take away the effects of orientation in turning the cell upside down and to reduce the amount of ionic activity that can be taking place there at that surface.

And it is accelerated, or high-temperature inverted storage tests of that cap indicate that it is doing a very nice job. It does not stop all corrosion, by the way, at the high temperature, but it is doing a very nice job.

SEITZ: I believe it was mentioned this morning that an alternate system is being considered for Galileo. Is that true?

BLAGDON: I don't think so. I don't recall that being mentioned. I guess you would have to talk to Hughes if you want to find out about that. I don't think so.





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MODULE DESIGN REQUIREMENTS

ELECTRICAL CHARACTERISTICS

- . 7.2 AHR. MINIMUM CAPACITY
- . 28.05 TO 39.0 VOLTS
- . CAPACITY WITHIN 5% WHEN DISCHARGED TO 28.05 V
- . VOLTAGE DELAY <100 MICROSECONDS
- . SINGLE POINT FAILURE PROTECTION VIA BY-PASS DIODES
- . PYRO TAP FOR 14-24 VOLTS

STORAGE

- . 5.4 YR. LIFE
- . 2.5% PER YEAR MAXIMUM CAPACITY LOSS

RELIABILITY

- . 0.99 FOR COMPLETING THE MISSION

Figure 2-13



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MODULE DESIGN REQUIREMENTS (CONT'D)

MODULE

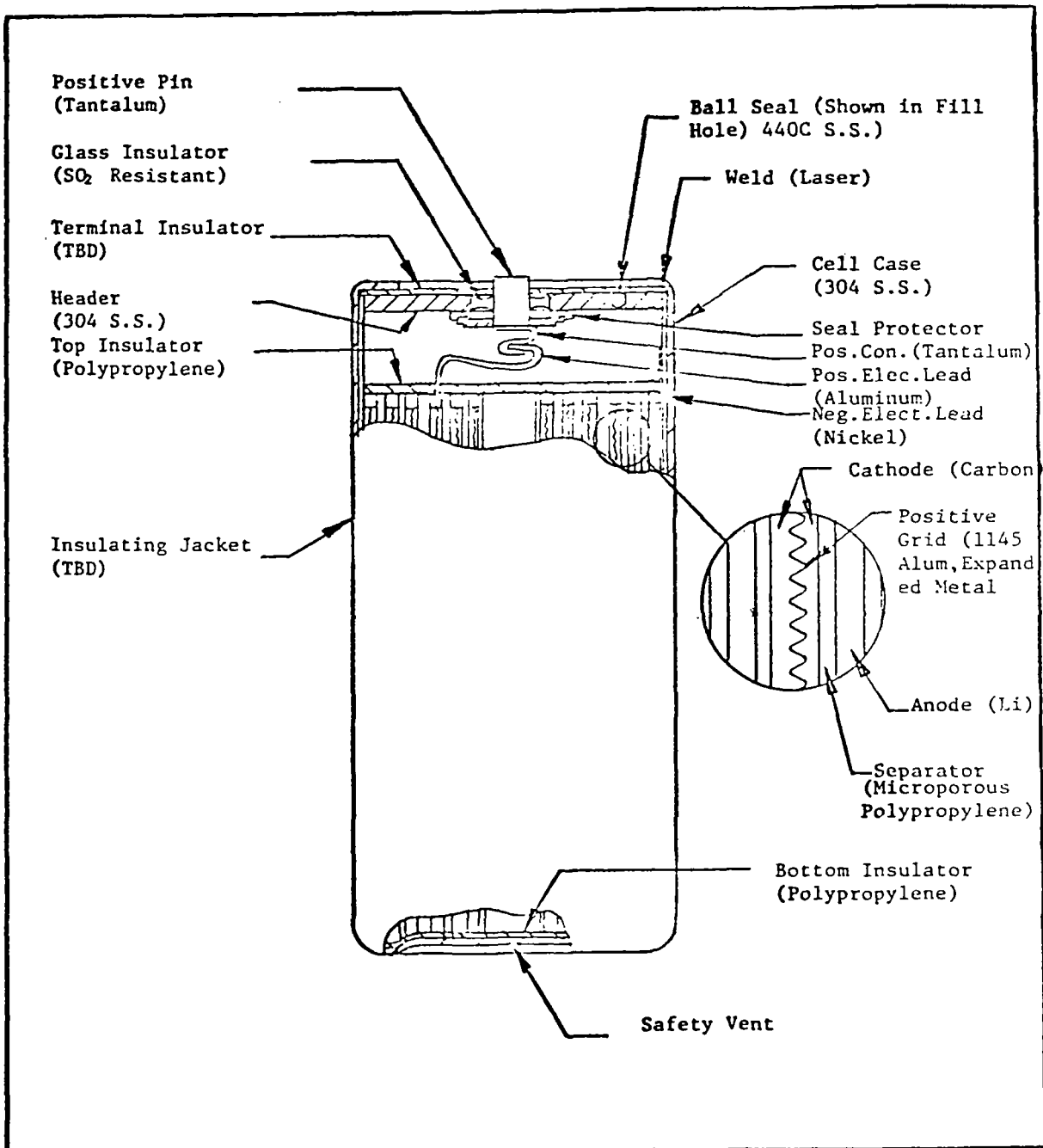
- CASE - RIGID VENTED
  - MAXIMUM DEFLECTION - 0.050 INCHES
  - FINISH 0.1

MASS - 2.5 Kg MAX.

ENVIRONMENTS

- . VIBRATION - SINE AND RANDOM VIBRATION
- . DECELERATION, 410 G's
- . 150 G's LATERAL, 30 RANDOM VIBRATION
- . SPIN 10-15 RPM, 2.5 - 5 RPM
- . RADIATION 200 KILORADS Co<sup>60</sup>
- . PRESSURE, 16 BARS QUAL; 13 BARS ACCEPTANCE

Figure 2-14



FOHM FM-100

PARTIAL CROSS SECTION OF HONEYWELL  
BASELINE CELL

Figure 2-15

# GALILEO PROGRAM

## MODULE CASE & CELL ASSEMBLY

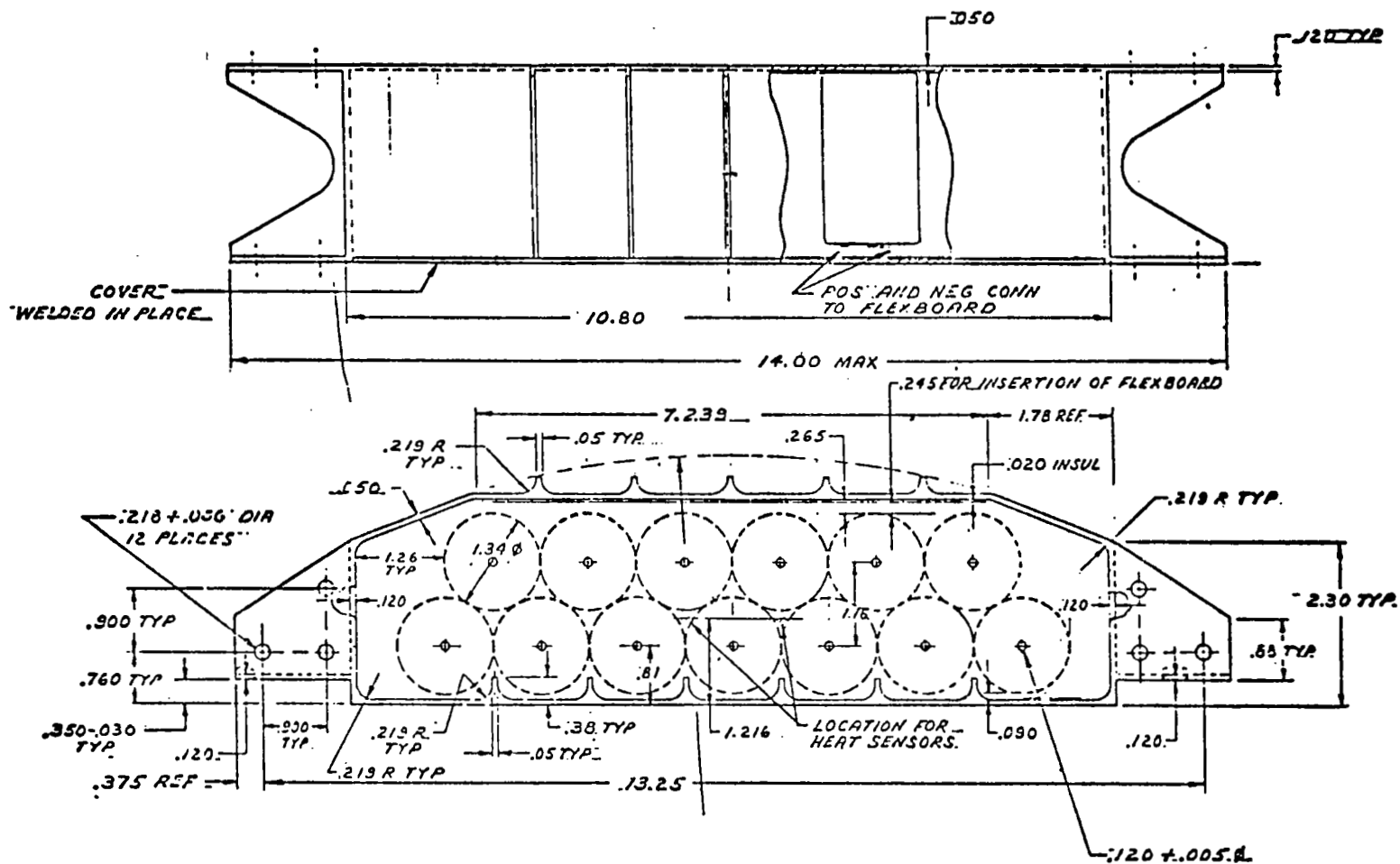


Figure 2-16



ELECTRICAL PERFORMANCE

- DEMONSTRATED CAPACITY TO 28,05 VOLTS BASED ON DISCHARGES OF 5 CELL STACKS:

<u>MISSION TEMP. PROFILE</u>	<u>CAPACITY (AHRs)</u>
MINIMUM	7.26
NOMINAL	7.73
MAXIMUM	7.79

- MINIMUM PYRO-PULSE VOLTAGE AT 6.65 AHRs (END OF MISSION):

<u>MISSION TEMP. PROFILE</u>	<u>VOLTAGE (VOLTS)</u>
MINIMUM	31.3
NOMINAL	32.0
MAXIMUM	33.0

- VOLTAGE DELAY - MET BY APPLYING A CONDITIONING LOAD WHICH REQUIRED AN ELECTRICAL SYSTEM CHANGE.

Figure 2-17



STORAGE -

- 450 CELLS TO BE STORED AT 0 °C CONFIRMING THE EFFECTS OF ORIENTATION AND BY PASS DIODE LEAKAGE CURRENT, ON TEST Nov. 1979.
- PROTECTIVE CAP OVER CELL GTM SEAL HAS MINIMIZED EFFECTS OF ORIENTATION (OR 0 G ENVIRONMENT) BASED ON 70°C INVERTED STORAGE TEST RESULTS.

RELIABILITY

- 0.99 PROBABILITY OF COMPLETING MISSION (6.65 AHRs.) HAS BEEN PREDICTED.

Figure 2-18



MODULE

- FIRST PROTOTYPE MODULE COMPLETE 7 Nov. 1979
- ACTUAL WEIGHT OF FIRST MODULE - 2.22 KILOGRAMS.
- FIVE ADDITIONAL MODULES IN PROCESS TO BE ENVIRONMENTALLY TESTED.

ENVIRONMENTS

- GALILEO CELLS (PHASE I) HAVE PASSED THE FOLLOWING SPECIFICATION ENVIRONMENTS:
  - RANDOM VIBRATION
  - SINUSOIDAL VIBRATION
  - DECELERATION
- NON-GALILEO CELLS (SIMILAR CONSTRUCTION) HAVE PASSED THE RADIATION REQUIREMENTS.

Figure 2-19



SAFETY

- BATTERY DESIGNS SHOULD BE VENTED
- ISOLATION DIODES SHOULD BE USED IF PARALLEL CONFIGURATIONS ARE REQUIRED.
- BATTERIES SHOULD BE FUSED.
- CELL DESIGNS SHOULD BE LITHIUM LIMITED.
- DEFINE OPERATION HANDLING AND TRAINING PROCEDURES.
- BATTERY MODULAR CONCEPTS SHOULD BE INCORPORATED FOR HIGH ENERGY REQUIREMENTS.

Figure 2- 20



### RELIABILITY

- OPTIMIZED BATTERY VOLTAGE/CAPACITIES TO WITHSTAND SINGLE CELL FAILURE.
- SINGLE POINT FAILURE CAN BE PRECLUDED WITH BY PASS DIODES.

### PERFORMANCE

- CELL MANUFACTURING TOLERANCES MUST BE TIGHTLY CONTROLLED.
- BATTERY CONDITIONING SHOULD BE CONSIDERED IF VOLTAGE DELAY IS CRITICAL.

### STORAGE

- CONTROLLED (LOW TEMPERATURE) ENVIRONMENTS ARE CRITICAL IF LONG TERM STORAGE IS REQUIRED.

Figure 2-21





## SULFUR STUDIES ON LITHIUM SULFUR DIOXIDE BATTERIES

A. Dey  
Mallory

Lithium SO<sub>2</sub> batteries are being manufactured in substantial numbers now by various companies and have been sold for several years now.

So there are a lot of users who use these batteries in various ways and try to extract as much as possible in terms of energy. Of course, when one does that, he occasionally runs into various problems. That is a subject that we studied for the last year or so.

The work started initially after we hired Thrombani of NASA. He was trying to use SO<sub>2</sub> D-size batteries at -30 degrees on 2-ampere force discharge, and he found some of the cells caught fire, and so forth, under these kinds of conditions. It was forced-discharge problem that occurred.

Well, when we started to study the problem, we decided that we wanted to look at it as comprehensively as possible, look at the chemistry of the system, try to learn more about the chemistry, and solve chemically as well as by other engineering means. So I will start with some of the work that we have done using DTA off lithium SO<sub>2</sub> battery chemicals.

(Figure 2-22)

The first figure shows DTA of lithium and SO<sub>2</sub> by themselves. Lithium is the anode active material, and SO<sub>2</sub> is the dipolarizer. Of course, we want to know how stable they are.

As you see, this is the heating curve here. This endotherm corresponds to melting of the lithium, and then we continue the heating to 320 degrees. In some experiments, we have increased that to 350 degrees. As you note, there is no exothermic reaction between the two very reactive materials. These are the materials which give you the energy of the battery.

This is a cooling curve where you see again that the lithium is freezing off, and again there is no reaction. That demonstrates the protective nature of the film which is the product of these two product of the cell reaction which is lithium dithionite, a solid crystalline material which coats the lithium as soon as these two are mixed. That coating is sufficiently stable so that even under such extreme conditions of heating, nothing happens. So lithium and SO<sub>2</sub> is very stable.

Next, we did the DTA of lithium and acetonitrile which is the organic solvent compound of the electrolyte. The DTA is shown in the next figure.

(Figure 2-23)

The figure shows the lithium and acetonitrile. As you see, it is very, very reactive, and it reacts even at room temperature. In fact, here, the initiating temperature is roughly 58 degrees. If you have very little lithium, you may see them react with heat evolution even at room temperature. Of course, the amount of heat generated is quite significant to cause hazard.

So, these are the two components the most responsible for all the behavior, all the unsafe behavior that we heard and we saw ourselves.

One of the things I think I should point out is that exotherms initiate at a certain temperature when you heat it up. That is the good parameter which determines the stability of the system. So, we use that parameter to develop alternative electrolytes. The lower the temperature of this exotherm initiation of this reactive reaction, the more unsafe the situation is. We would like this to occur at the highest temperature possible in an actual cell.

In the next figure, we show the DTA of the lithium, and the electrolyte.

(Figure 2-24)

The electrolyte consists of acetonitrile,  $\text{SO}_2$ , and lithium bromide, 70 percent of  $\text{SO}_2$ .

You notice again the heating, the initiation of the exotherm occurs at 170 degrees. It has been increased from 50 degrees or so, which you saw in lithium acetonitrile to 170 degrees.

This exotherm is due to the lithium and the acetonitrile. Just as in the presence of  $\text{SO}_2$  that temperature is increased, so the lithium  $\text{SO}_2$  battery will be able to sustain this kind of temperature, but no more. If you go beyond that, you will have a problem.

We have looked into the possibility of developing alternate electrolytes into which the exotherm initiation temperature is going to be. So, it is actually higher than what we find with lithium acetonitrile by themselves. You have noticed that the  $\text{SO}_2$  electrolyte contains  $\text{SO}_2$ . The presence of  $\text{SO}_2$  itself has done a tremendous improvement, 70 percent  $\text{SO}_2$ .

We are interested in finding out what is the lowest concentration of  $\text{SO}_2$  needed for lithium acetonitrile reaction to be suppressed. That we did by measuring the exotherm initiation temperatures of the lithium acetonitrile, those two complements, as a function of  $\text{SO}_2$  concentration. That is shown in the next figure.

(Figure 2-25)

Here are the exotherm initiation temperatures in degrees Centigrade. These are temperatures at which the exothermic reaction begins between lithium and acetonitrile. And we are adding  $\text{SO}_2$  in that solution. Here is the percentage of  $\text{SO}_2$ . When there is no  $\text{SO}_2$ , the exotherm is initiated as you see, roughly 50 degrees, or thereabouts, a very unsafe situation.

So, if you have a cell where all the  $\text{SO}_2$  is consumed, obviously you can expect that cell to behave in an unsafe manner because of the lithium energy problem. But, as you add  $\text{SO}_2$ , note that even at high percent  $\text{SO}_2$  in the cell gives you quite a bit of protection. The cell can stand quite high temperatures before it can generate exothermic heat, causing all kinds of problems.

Of course, we have completed the experiments of in transial moisture. As you see, these points, adding 1 percent moisture. It does not seem to make that much difference between addition of 1-percent moisture and no addition at all, because moisture there also has some protective action. At least it does not have a deleterious action in that sense in these kinds of concentrations.

We did the experiments with lithium powders, and there you see you need quite a bit, almost 25 percent or so, to get protection. Lithium powder, of course, will have a very high surface area, and there, if you do not have sufficient amount of  $\text{SO}_2$ , you may see exothermic initiation at an earlier stage.

So these studies tell us that one must have design cells so that during their use and abuse there should be sufficient  $\text{SO}_2$ , at least 10 percent or so present in the cell which will protect the lithium that is left over, or lithium powder, or any other lithium products generated during the cell use and abuse.

(Figure 2-26)

Now this figure shows similar kinds of data. Instead of  $\text{SO}_2$ , we have used a second organic solvent with acetonitrile, so again we show the exotherm initiation temperature as a function of concentration of a second organic solving, which is very protective. Probably carbonate is in one instance, and acetic hydride in another. Both of these solvents, when added to acetonitrile, provide protection to lithium as evidenced by the increase in exothermic initiation temperatures. These are the temperatures at which lithium acetonitrile will react exothermically.

Again, you notice the 5 percent, or 5 to 10 percent, of this second solvent is sufficient to give protection to lithium, and hence potentially can provide the same for a cell.

We have tested a whole variety of organic solvents as additives and developed six different organic electrolytes which have conductivities similar to the conductivity of the standard electrolyte containing acetonitrile and lithium bromide.

Of these six, I believe two of them did not have any acetonitrile at all. Since the conductivities are very comparable, we have good reason to believe the performance of these cells probably will also be comparable.

We are now in the process of testing these in actual cells for storage and for performance at low temperature as well as for safety, and I hope that we shall be able to report on that soon.

Now one can look at the lithium  $\text{SO}_2$  battery as a whole as if it were an alternative system. It has three basic reactive components: lithium,  $\text{SO}_2$ , and acetonitrile. So, from design of safe cell,

one can then look into this alternative diagram and can come up with certain approaches to make safer batteries.

(Figure 2-27)

In this figure we show an alternative phased diagram to explain this. We have the  $\text{SO}_2$  here, lithium here, and acetonitrile here. So, in a battery when it is made, the composition of these three materials will fall along these lines when the battery is made. These are all the possible stoichiometric conditions that you can think of that will fall in this line.

Now one can, by design, make the batteries so that the composition falls somewhere around here. If it is somewhere around here to begin with, when you discharge the battery, one consumes both  $\text{SO}_2$  and lithium in a very, very predictable manner based on  $\text{SO}_2$ .

Now, that has been established very well. The reaction is also very efficient, 100 percent efficient. As you discharge the cell, the composition inside the cell of these three materials changes in a manner such as this. Therefore, at the end of the discharge, you end up somewhere around here.

Now, when you end up here, this is a condition in which you do not have any lithium left. All the lithium is gone. You have plenty of  $\text{SO}_2$  left, and you have plenty of acetonitrile. This is then a lithium-limited design, as you have heard mentioned earlier, a design according to what we have talked about, a safer situation.

On the other hand, if you are here, then as we discharge the cell, you move in this direction, you end up with a situation where you do have some lithium left, and you may or may not have  $\text{SO}_2$  left, depending on where you are. In fact, here you have no  $\text{SO}_2$  left, and therefore you would expect the unsafe behavior ensuing because of the action between lithium and acetonitrile, as we have been illustrating.

So this is then a design which has excess lithium. This, of course, assumes that the efficiency of discharge of  $\text{SO}_2$  is 100 percent.

Now, as you know,  $\text{SO}_2$  is discharged at carbon cathodes. Depending on the activity of the carbon cathodes, you may or will not use all of the  $\text{SO}_2$ . The efficiency of utilization of  $\text{SO}_2$  may vary depending on the quality of the cathode or the amount of carbon in the cathode and so forth. So, that is another parameter that one has to consider for a safe design of  $\text{SO}_2$  battery.

Now, from all of this we can say that we do know quite a bit about the system. It is highly predictable because of what we have found, and therefore we can design the cell to take all kinds of abuse and use conditions.

To give you just two examples of the forced discharge that I mentioned in the beginning.

(Figure 2-28)

In this figure, I show in voltage and temperature profile, a D cell which is forced discharge at -30 degrees at 2 amperes.

This is a cell which contains excess lithium by design. You will notice here, this is the voltage, that is the temperature, and this is the number of hours, at -30 degrees at 2 amperes.

Notice initially you have a cell voltage of up to 1 volt. There is gradually a decrease and reaches zero volts. Now, if you had a reference electrode in this cell, you would find the cathode, the carbon cathode. These voltages are characteristics of the carbon cathode only. Lithium voltage remains constant. Lithium potential remains constant. It is the cathode which goes through this.

So, we know that above zero volt, all you are having here is basically reduction of  $\text{SO}_2$  primarily. Then, you reach 0 volt. Below zero volt, what you have here is also quite predictable. You are having deposition of lithium on your carbon cathode and on your aluminum exotherm.

Dr. Taylor in our lab demonstrated that, in fact, what you have is a lithium-aluminum alloy formation on the cathode in this area when the cell voltage is negative.

Also, notice that during this place when the cell is polarizing, of course, you are generating the energy that is not delivered, utilized in generative heat. So, you heat up the cell during the polarization phase. But, beyond zero volt, basically what you have is the deposition of lithium on your carbon cathode aluminum grid and dissolution of lithium on the anode, two reactions very reversible. Therefore, you have cooling basically, because you don't generate any heat. So, you are piling up a lot of this lithium-aluminum alloy and lithium dendroids during this phase.

Then, you reach a point, a very sharp reversal, and this is due to the fact that you have consumed all the lithium on the anode. There is no more lithium left; therefore, you polarize yourself severely, and that is the time when there is sufficient heat to cause this lithium material to get fired. We have a very rapid temperature buildup, temperature rise. Of course, this is the time when you have cell venting, sometimes violent venting and sometimes even fire.

So, because of all this activity when the cell is below zero volt, this occurs because of the excess lithium.

Now, if you design a cell so that the amount of lithium, the polarization of the lithium electrode is going to occur here instead of here, you just reduce the amount of lithium on your anode, and you make the cell go through this deep reversal at this point right here.

When that happens, there is not enough active lithium present to give you any problem. All you can see is venting or not venting at all.

We have tested many, many D cells with the lithium-limited designs at 2 amperes and -30 degrees and demonstrated this to be the case.

The next figure shows a typical voltage profile of such a balance, but a lithium limited cell. Assumption again is the same cathode in both cases.

(Figure 2-29)

Here is the voltage profile. You have about 2 volts for a while, and then it gradually declines. You see the voltage goes to deep reversal right at the point when the cell sees 0 volt. There is no chance for the formation of this active material I mentioned. You see that cells keep up at this point, and during the deep reversal you are wasting a lot of energy. That energy must show up somewhere. It is showing up, but it is not sufficient to give you any problem.

The cell either vents and, in fact, in most instances there is no venting at all. So, then by design, one can make these cells undergo all kinds of abuse, including very severe discharge, without any problem.

Another thing you must remember is that this characteristic, the number of hours that the cell is going to give you above 2 volts under a specific load, depends on the carbon cathode, a very important parameter. That is an area again where we have a tremendous improvement, although the cells do not vent at all.

A third possibility, also, perhaps I should mention, is that -- although I mentioned about the lithium-limited design and that, of course, has advantage not only from the forced discharge standpoint, but also from the point of view of disposal -- to establish that if you have lithium-limited design, you do not have formation of cyanide, and so forth, which certainly is an advantage.

(Figure 2-30)

But I must emphasize that all of these are dependent on current density of the total current. A cell, which is designed for 2 amperes and which can take that kind of abuse, if you increase the current to 5 or 10 amperes, this, of course will not be true. So the cells have to be designed for a particular current operation.

## DISCUSSION

BIS: I was a little bit confused when you did the electrolyte and the lithium, when you conduct the exotherm at about 200°C. Then you went ahead and did lithium, acetonitrile, and SO<sub>2</sub>; you showed a curve that got up to about 400°C.

DEY: No, 400 degrees. That is with the lithium SO<sub>2</sub>. 400°C, I am sure. It cannot be. Can you show the figure? I think you are talking about the one with the addition of SO<sub>2</sub>.

BIS: Right.

DEY: That's figure 2-24.

BIS: Now, you have got roughly 25 percent SO<sub>2</sub> in there, right?

DEY: Yes.

BIS: Now, your electrolyte is 70 percent SO<sub>2</sub>, is it not?

DEY: Yes.

BIS: What would your normal electrolyte composition on there be, assuming you eliminate the lithium bromide?

DEY: That was 70 percent. These are separate experiments. It is a good point. We did see some variation in that initiation temperature, depending on the specimens that you used, lithium specimens.

The experiments that we used earlier, we probably had some more active lithium specimens that may not have as much filler to begin with.

BIS: There is no lithium bromide in this, right?

DEY: No. That is a good point, too. Lithium bromide does catalyze some of these reactions, exothermic reactions.

BIS: That could lower the temperature?

DEY: *I think that is right.*

BIS: My second question is, basically have you done any chemistry, basic chemistry on these cells as a function of discharge rate storage? In other words, identification of species within the cells themselves?

DEY: We have done quite a bit, and we are continuing to do quite a bit of it. We expect to publish some of this soon. It is still in the works.

WATSON: Dr. Dey, in the lithium limited cell, you obviously don't utilize all the lithium at the end of your useful life. You are using the lithium as a current collector, so there is a certain percentage left over.

Do you have any feel for how much lithium is required before you enter the hazardous region?

DEY: If you do not have any current collector at all, then, of course, you have to have a finite amount. Now, what is the exact amount, I don't remember, what is the exact amount in terms of ampere-hour. But, there is a certain amount, and that will depend also on the design; how the electrodes are made, how it is connected, and to what it is connected. Because what

basically happens when you use the lithium up, you may not use it uniformly, depending on your cell design. If you don't use it uniformly, you may cut off a certain portion of lithium at a point very near the tab or near the connection. In which case, of course, you end up with a lot of lithium present.

So, care has to be exercised to how you design your anodes, how you connect it, and how uniform the reaction is to the spiral.

WATSON: One other thing. Why does it break near the tab?

DEY: Why? It will break if you don't design the cell properly. You may have reaction near the tab more than further away from it. That is strictly on cell design. This is very important.

ANGRES: I get the impression you tried to get away from acetonitrile.

DEY: Yes. And for obvious reasons, which is that it is a reactive component. It has some beneficial effect in terms of performance, but we are trying to see whether we can, in fact, get away from it or develop an electrolyte which can moderate its reactivity.

ZOLLA: Instead of a mechanism whereby you rely on the design according to the rate to safeguard you against this reverse voltage failure, would you not prefer to see a flat line design as seen in the previous paper whereby it is intended to break, and one does not have to worry about whether, in fact, one is sticking to the original design or just one parameter, one radius?

DEY: What design is that?

ZOLLA: The previous curve you saw shows the reverse voltage, as you entered reverse voltage, a flat line characteristic, which is independent of forced discharge rates.

I was just asking if you would not prefer to see that kind of characteristic in your cells.

DEY: Are you mentioning about the accounting battery where we are talking about?

ZOLLA: I know it is a different cell, but the same possibilities are there.

DEY: I wish that design were discussed in some detail, so I can make an assessment.

ZOLLA: I wish I could tell you all about it.



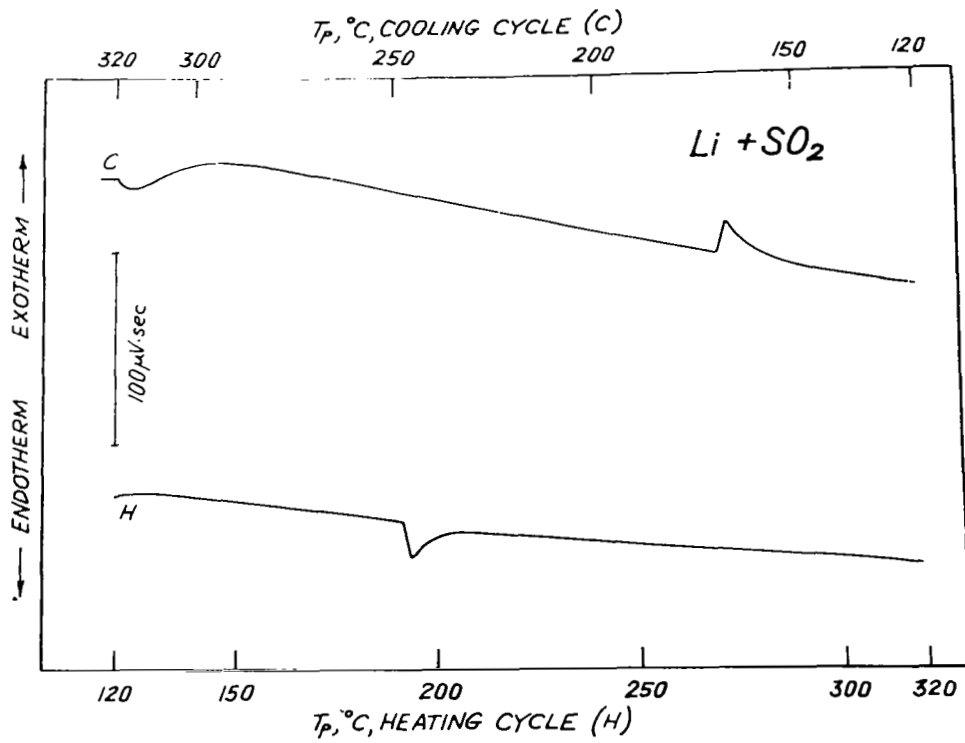


Figure 2-22

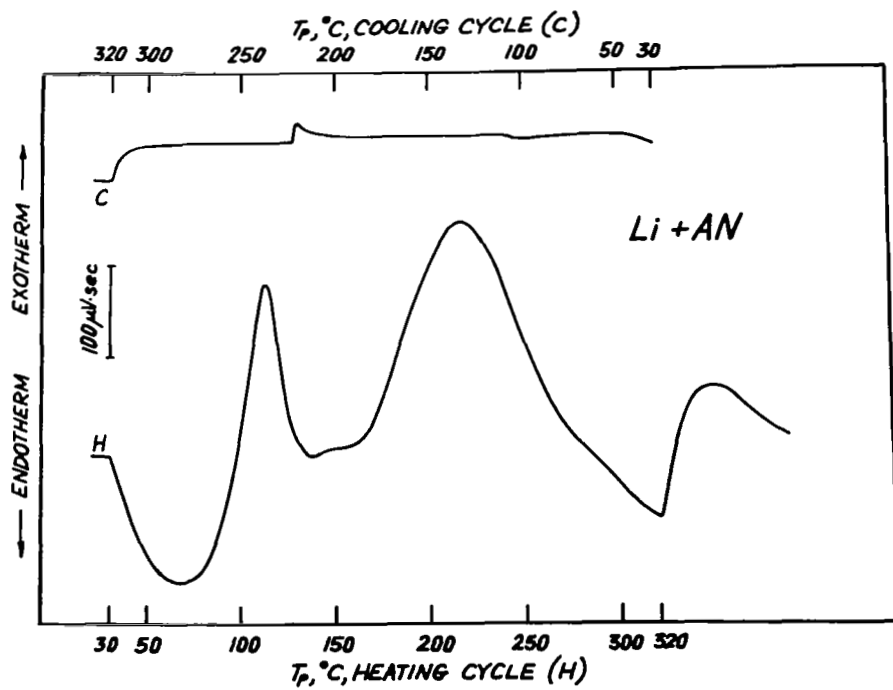


Figure 2-23

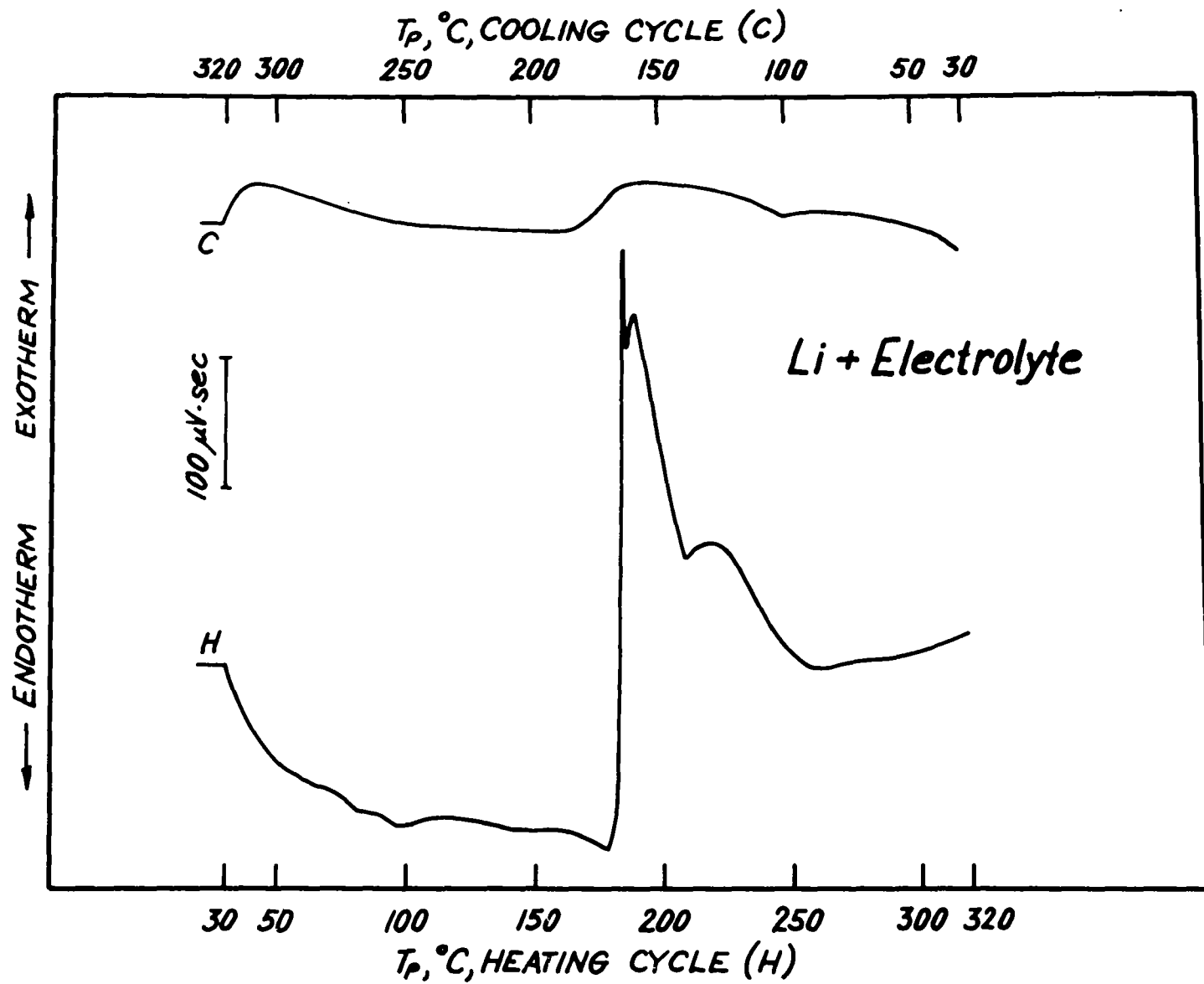


Figure 2-24

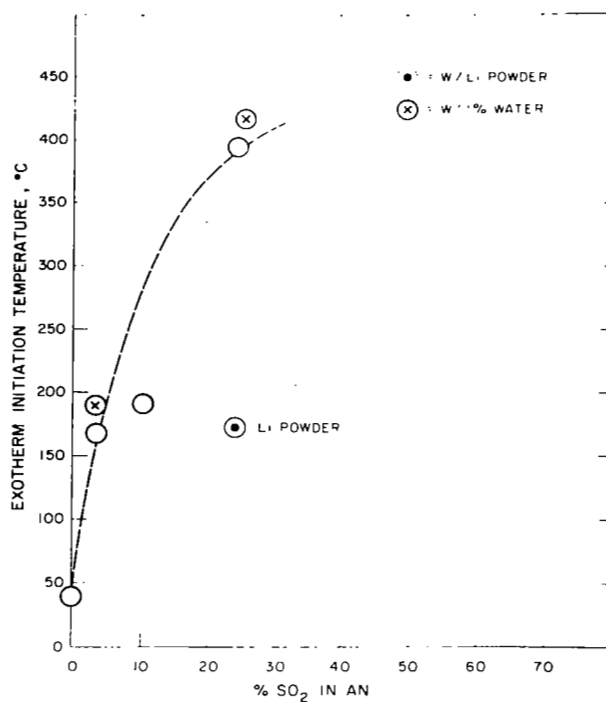


Figure 2-25

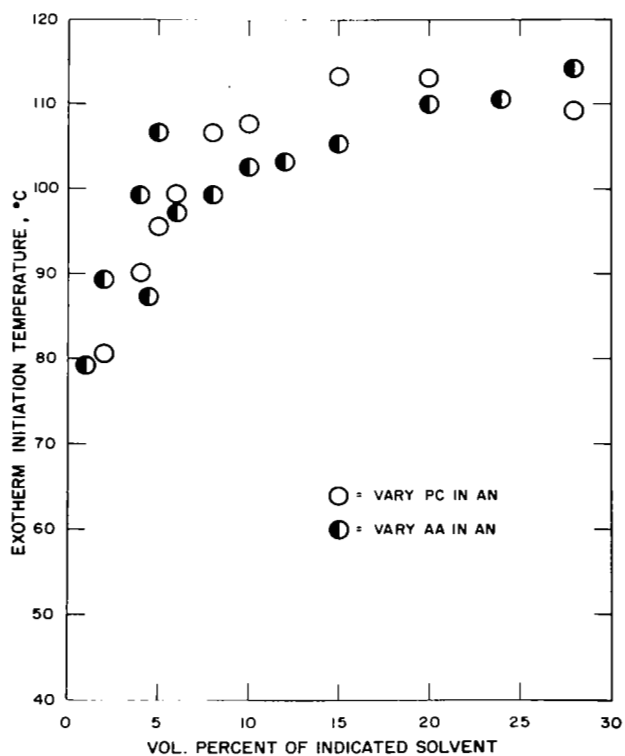


Figure 2-26

# Li/SO<sub>2</sub> DISCHARGE TRAJECTORIES

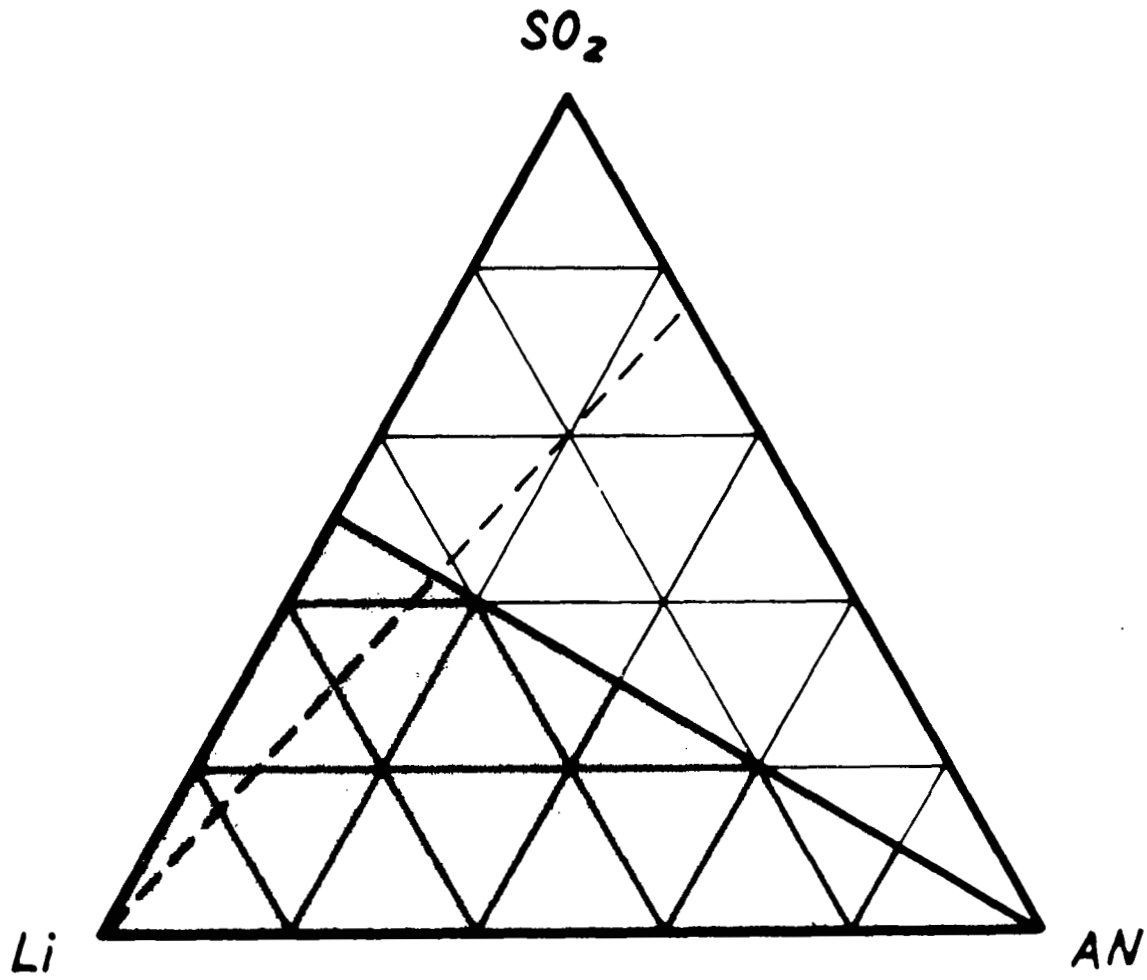


Figure 2-27

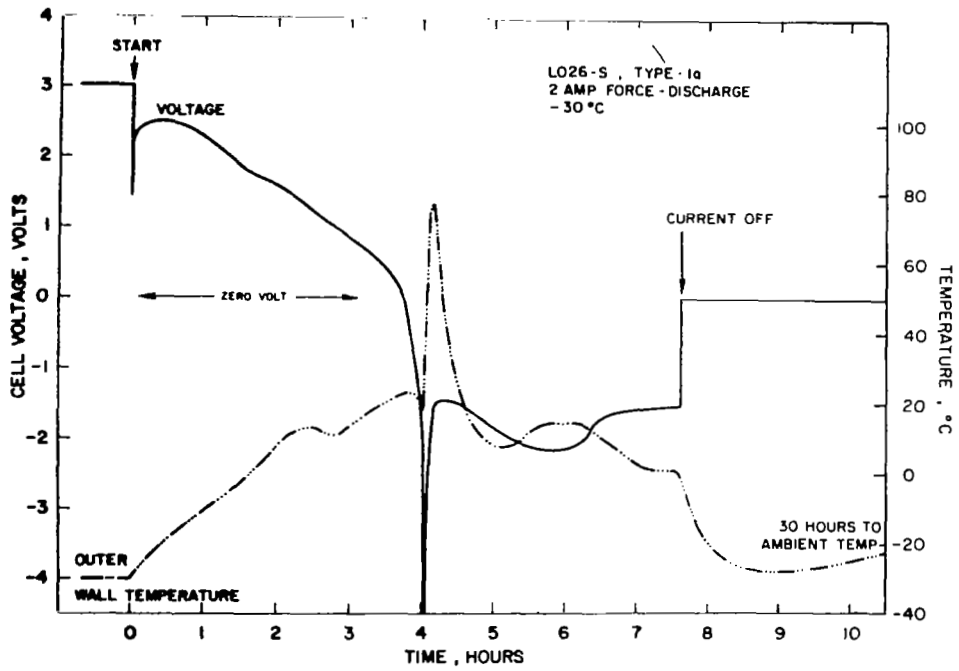


Figure 2-28

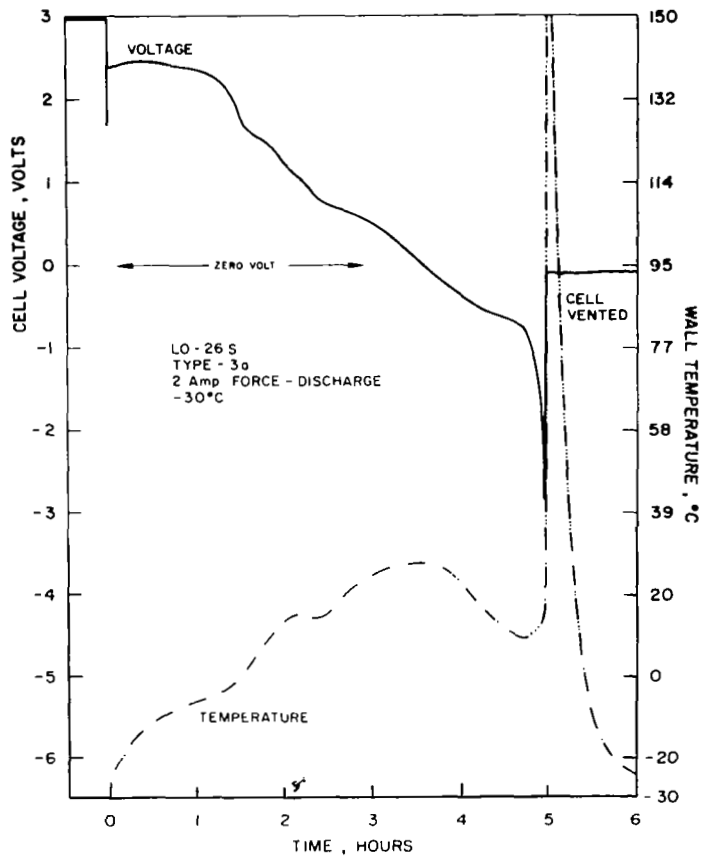


Figure 2-29

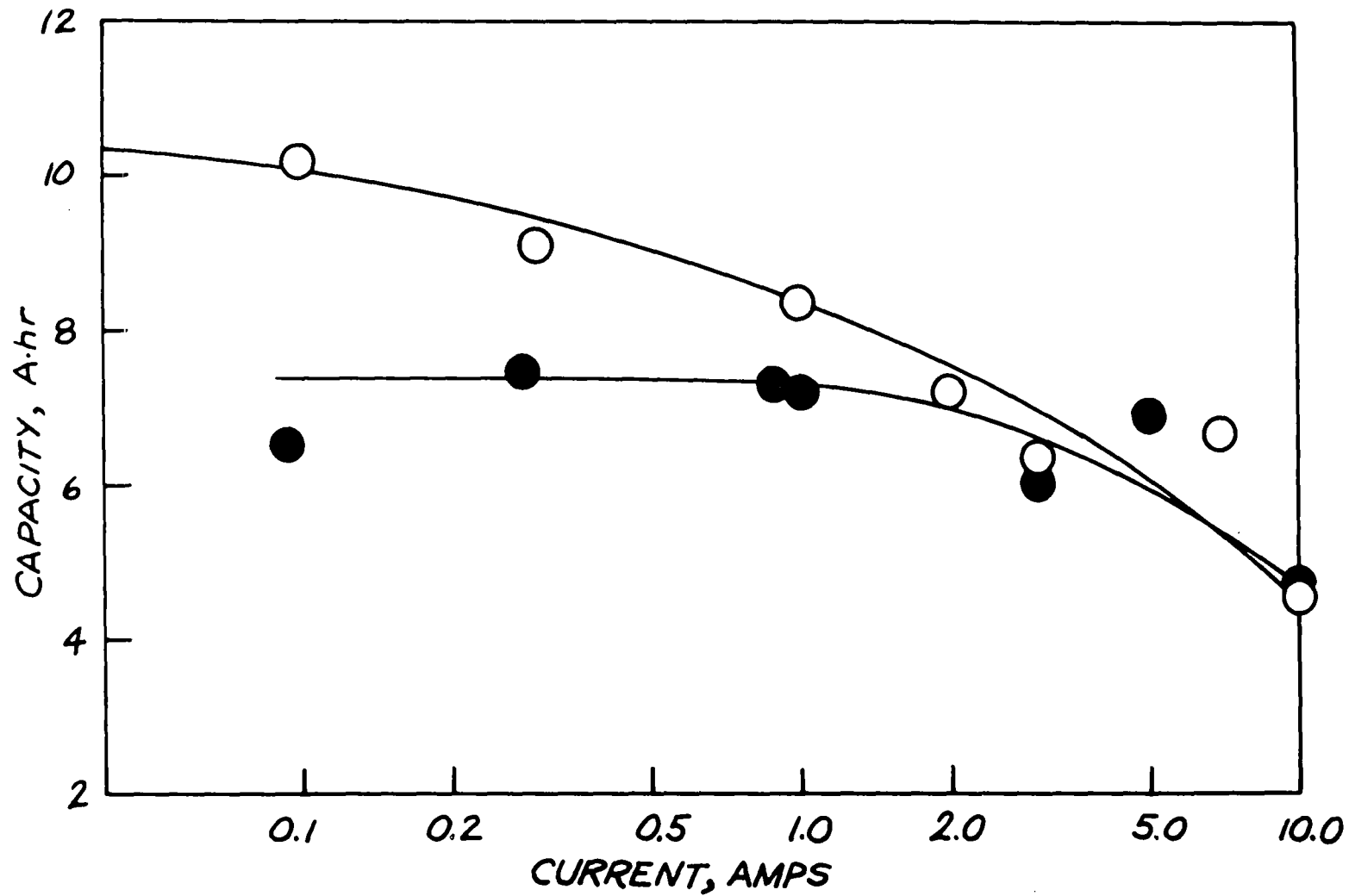


Figure 2-30

## ELECTRICAL, THERMAL AND ABUSIVE TESTS ON LITHIUM THIONYL CHLORIDE CELLS

R. Somoano for H. Frank  
JPL

I would like to discuss some of the electrical, thermal and abusive tests carried out on lithium thionyl chloride cells at JPL.

This work has been done by Harvey Frank. I am personally not associated with this program and do not know a lot about these materials. Nevertheless, I will encourage you to ask questions about any of the things I describe today. Although I probably cannot answer them, I will see that you get specific answers to those questions.

(Figure 2-31)

The next vugraph shows roughly what I will be describing. I will give you a description of the thionyl chloride-type cells, discuss some of the electrical characterizations and some of the outer limits testing, and summarize the conclusions.

(Figure 2-32)

This work actually arose out of a NASA workshop on lithium batteries that was held here at Goddard last year. The purpose of this workshop was essentially to try to prioritize the efforts on lithium batteries, and at that time it was suggested that JPL carry out single work level we are describing today.

(Figure 2-33)

The type of cell was procured from the ALTUS Company, lithium thionyl chloride cell.

There is a sample of that down there where you cannot see it. Nevertheless, it has got the diameter of my column; about 60 cells were tested, they are disc-shaped much like the ones you saw earlier, just smaller size.

The rated capacity is about 6 ampere-hours, and the rest of the characteristics you can see here.

(Figure 2-34)

The next vugraph discusses some of the electrical characterization tests done on some of these materials. The objective here is to determine the voltages equivalent to the current in time in a state of charge, particularly used in the method of Shepherd. That is, to try to fit this current voltage data to this type of equation.

Indeed, the data fits these type of equations to a fair degree of accuracy. In here, you can see the actual Shepherd constants. This was done by using the constant current discharge curves.

This type of information is useful for design performance prediction.

(Figure 2-35)

This shows a plot of energy density versus power density. You can see here that you can get about 300-watt-hours per kilogram only at very low power densities with these materials. This corresponds to the order of about 30-hour rate here. However, this type of data is useful to compare with other types of cells.

There is the LeClanche cell right here. You can see the effects of temperature, 0, 21, and 40°C.

(Figure 2-36)

This shows some of the raw data that was obtained in the thermal characterization. We have voltage plotted here as well as the heat rate in watts versus time. This is the discharge curve right here. You get about 1 ampere, 21°C.

You see the heat rate in watts, how it is fairly constant. But, near the end of discharge it increases quite rapidly.

If one takes the mid-point, for example, about 30 cells. And you look at the data shown on the next vugraph.

(Figure 2-37)

Particularly, this is the heat rate plotted versus current and amperes, 21°C. The white points are the experimental data; the dark ones are the theoretical data. Based on the thermal neutral voltage of 3.34 volts, one notices that the experimental heat rates are greater than theoretical values, which suggests that some type of chemical side reaction is occurring. In particular, maybe something other than the ordinary breakdown of thionyl chloride to SO<sub>2</sub> sulfur and lithium chloride.

The other thing to notice is at the very low rates there is actually an endothermic reaction. Heat is actually absorbed down here.

(Figure 2-38)

This summarizes some of the out-of-limit tests. This is forced reversal. The actual test conditions are shown right here.



Five cells were tested at the various constant currents at room temperature, and these are 6-ampere-hour rated capacities. The results are summarized here.

No explosions, etc.; reverse voltages range from zero to -1 volt.

In this condition large negative voltage excursions were sometimes noted, and this can provide some type of problems on voltage regulation.

Venting can occur at currents greater than 0.2 amperes or about a C/30 rate. When they do vent, they do so very shortly after the onset of reversal.

(Figure 2-39)

This is some more out-of-limits tests at which they look at high rate discharge effects. This is the type of loads that we used. By way of comparison, one at 0.4-ohm load corresponds to like C/0.7 rate. This was done at room temperature again. No explosions. Surface temperatures reached about 100°C maximum during these tests. Again venting can occur whenever the rates get greater than C/0.7.

(Figure 2-40)

This really summarizes the results obtained with lithium thionyl chloride batteries from ALTUS. Shepherd constants have been determined from the EI equations. We have seen about 300 watt-hours per kilogram at very low rates.

We mentioned that experimental heat rates are larger than the theoretical rates. For rates greater than C/6, no explosions during reversal and high rate of discharge.

Again, venting is possible during reversals. A report on this work will be prepared and be available from JPL during December.

## DISCUSSION

WILLIS: Can you describe the venting and what took place?

SOMOANO: No, I can't. I don't even see that the cells have been there, personally. I can only guess that they have been up around the seals. But I have thought about that.

WILLIS: That confirms our experience. Sometimes they vent, you don't even know it.

SOMOANO: I don't know how they detect it. There is not an obvious vent port.

MAHY: All I want you to do is put your reverse voltage discharge slide back up again. I did not get to read it all.

(Figure 2-38)

Now, I want to ask the question. How far into reversal did you carry these tests? 100 percent in every case?

SOMOANO: As far as I know, yes.

CLOYD: First of all, you had 60 cells. Were they all manufactured in the same lot? And second of all, if they were in the same lot, did you find large cell-to-cell variation in these things?

Of the few that I have seen, some results have shown that there is a lot-to-lot variation with ALTUS in some areas. Some within lot variations that are tremendous.

SOMOANO: I don't know if they were from the same lot. To the best of my knowledge, they have not seen a lot of cell-to-cell variation, but I can check on that for you. But, when we talked about the material, this was not brought up. Yet I questioned it at one time. So, I don't think that there was cell-to-cell variation.

SLIWA: When these cells do vent, what are the gases that are vented, and how much?

SOMOANO: I don't know. I don't think they measure the composition of the gas or how much. That is my feeling from the test they are doing.



## AGENDA

- INTRODUCTION
- DESCRIPTION OF CELL
- ELECTRICAL CHARACTERIZATION
- THERMAL CHARACTERIZATION
- OUT OF LIMITS TESTING

Figure 2-31



## INTRODUCTION

- SPECIAL NASA LITHIUM BATTERY WORKSHOP HELD AT NASA GODDARD IN AUG 1978
- ATTENDED BY BATTERY SPECIALISTS FROM NASA CENTERS
- PRIORITIZED EFFORTS ON LITHIUM BATTERIES FOR NASA FOR FY 79
- JPL WAS REQUESTED TO CARRY OUT WORK DESCRIBED HEREIN

Figure 2-32



## DESCRIPTION OF CELLS

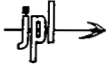
- TYPE - Li-SOCl<sub>2</sub>
- MANUFACTURER - ALTUS CO, PALO ALTO, CA
- MODEL NO. - AL-250
- NO. CELLS TESTED - 60
- CONFIGURATION - DISC-SHAPED
- DIMENSIONS - DIA = 6.35 cm, HT = 0.95 cm
- NOMINAL RATED CAPACITY - 6 Ah
- WT RANGE - 72-74 gms
- IMPEDANCES - RANGE: 3-15 Ω, AVG: 8 Ω
- OTHER - STAINLESS STEEL CASE (POS), CENTER POST (NEG), CERAMIC-TO-METAL SEAL

Figure 2-33

## ELECTRICAL CHARACTERIZATION SHEPHERD CONSTANTS

- GENERAL EQN:  $E = E_s - K \left( \frac{Q}{Q - it} \right) i - Ni$
- FOR AL-250 CELL:  $E = 3.5 - 0.108 \left( \frac{8.1}{8.1 - it} \right) i - 0.032i$

Figure 2-34



## ELECTRICAL CHARACTERIZATION ENERGY DENSITY VS POWER DENSITY FOR AL-250 CELLS

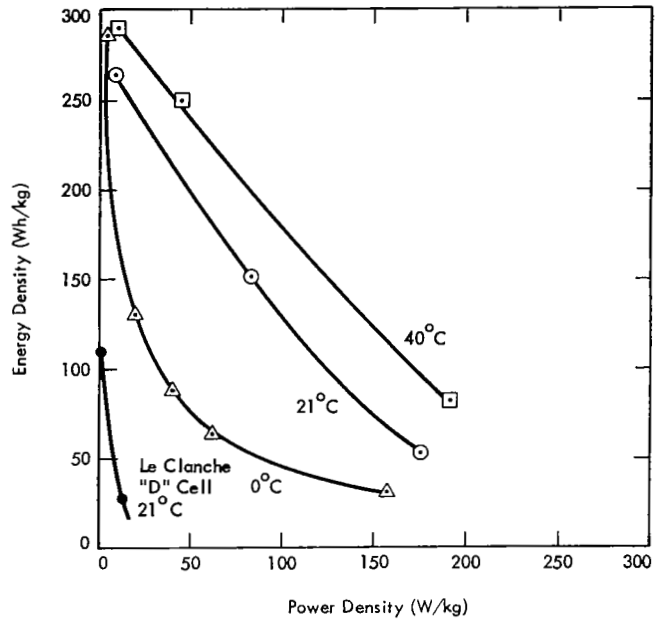
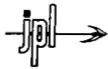


Figure 2-35



## THERMAL CHARACTERIZATION TYPICAL RESULTS OF CALORIMETRIC TESTS ON AL-250 CELLS

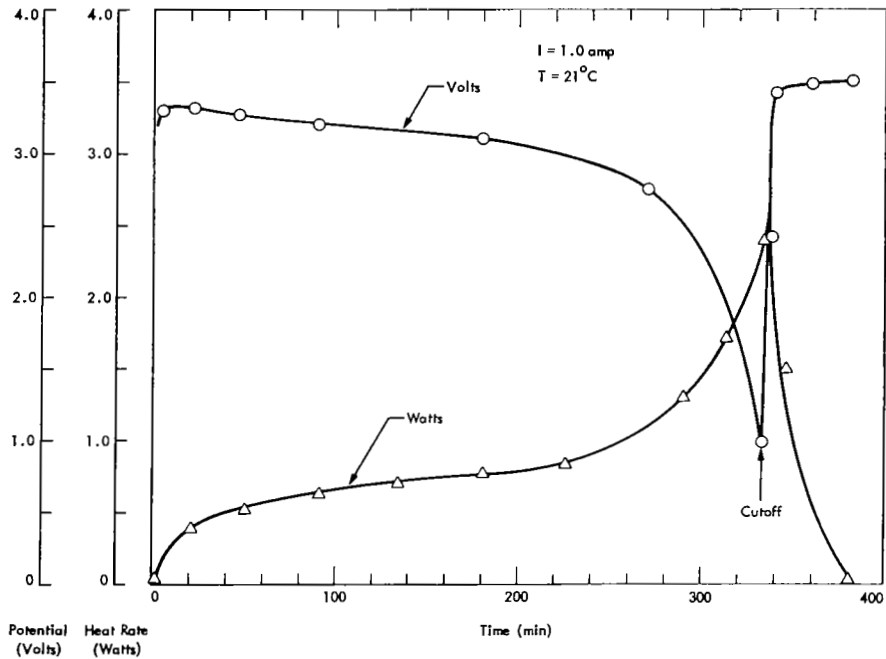
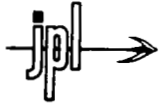


Figure 2-36



# THERMAL CHARACTERIZATION

## COMPARISON OF ACTUAL WITH THEORETICAL HEAT RATES AT MID-POINT OF DISCHARGE OF AL-250 CELLS

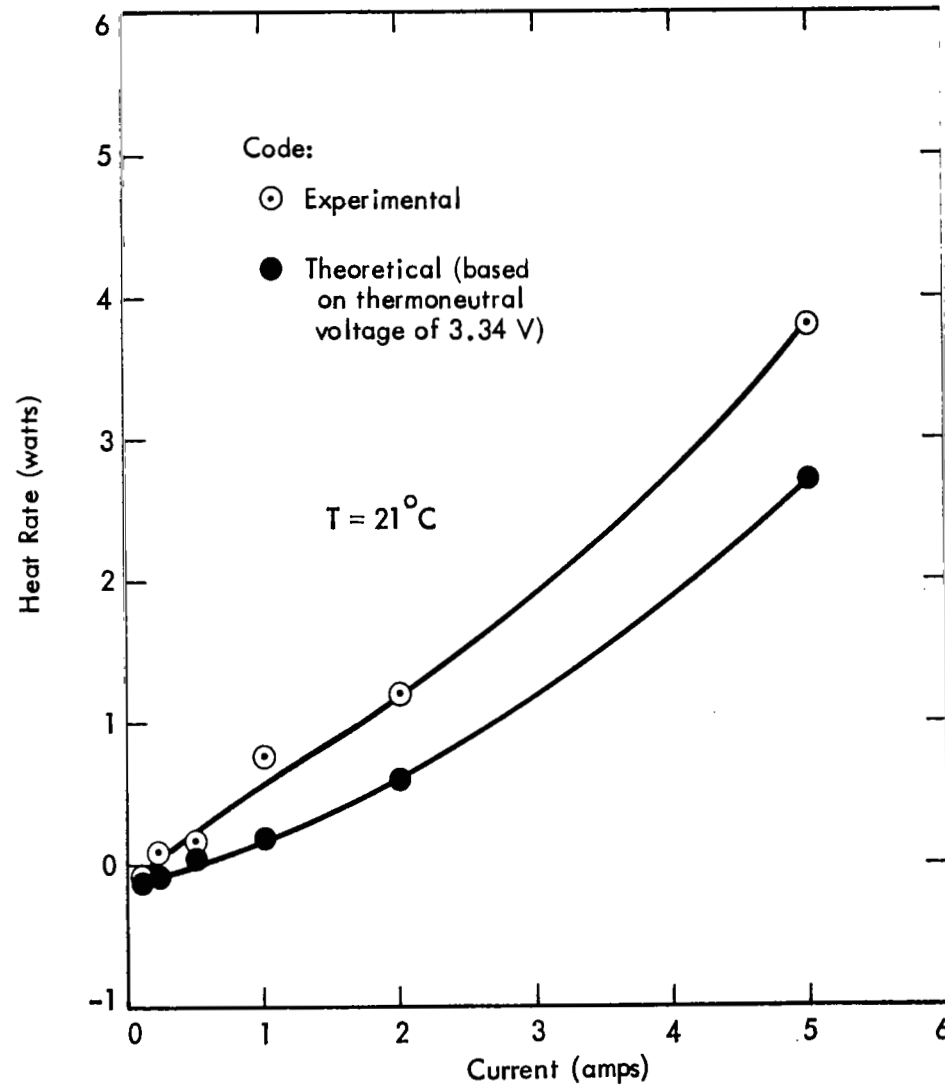


Figure 2-37



## OUT-OF-LIMITS TESTS

### FORCED REVERSAL OF AL-250 CELLS

- **TEST CONDITION:**
  - DISCHARGED, THEN REVERSED, 5 EACH CELLS AT CONSTANT CURRENTS OF 2, 1, 0.5, 0.2, AND 0.1 AMPS, RESPECTIVELY, AT ROOM TEMPERATURE FOR 100% OF RATED CAPACITY (6 Ah)
- **RESULTS:**
  - NO EXPLOSIONS
  - REVERSAL VOLTAGES USUALLY RANGED FROM 0 TO -1 VOLTS\*
  - VENTING CAN OCCUR AT CURRENTS  $> .2$  AMPS OR "C/30"
  - IF CELLS VENT, THEY DO SO SHORTLY AFTER ONSET OF REVERSAL

\*OCCASIONALLY SOME EXHIBITED LARGE NEGATIVE VOLTAGE EXCURSIONS

Figure 2-38



## OUT-OF-LIMITS TESTS

### HIGH RATE DISCHARGE OF AL-250 CELLS

- **TEST CONDITION:**
  - DISCHARGED 5 EACH CELLS ACROSS LOADS OF 0.5, 0.4, 0.3, 0.2, AND 0.1 OHMS, RESPECTIVELY, AT ROOM TEMPERATURE
- **RESULTS:**
  - NO EXPLOSIONS
  - MAXIMUM SURFACE TEMPERATURES NEAR 100°C
  - VENTING CAN OCCUR ACROSS LOADS  $< 0.4$  OHMS AND CORRESPONDING RATES  $> "C/0.7"$

Figure 2-39



## CONCLUDING REMARKS (BASED ON RESULTS OF AL-250 CELL TESTS)

- ESTABLISHED SHEPHERD CONSTANTS FOR E/I EQN
- CAN DELIVER UP TO 300 Wh/Kg AT LOW RATES
- EXPERIMENTAL HEAT RATES SOMEWHAT HIGHER THAN THEORETICAL RATES AT CURRENTS  $> "C/6"$
- NO EXPLOSIONS DURING REVERSAL AND HIGH RATE DISCHARGE
- VENTING POSSIBLE DURING REVERSAL AT CURRENTS  $> "C/30"$
- VENTING POSSIBLE DURING HIGH RATE DISCHARGE AT CURRENTS  $> "C/0.7"$
- REPORT WILL BE AVAILABLE IN DEC 79

Figure 2-40