PNL-6108
UC-94cb

/ —

RELY: A Reliability Modeling System for Analysis of Sodium-Sulfur Battery Configurations

C. J. Hostick
H. D. Huber
W. H. Doggett
J. A. Dirks

J. V. Dovey
R. B. Grinde
J. S. Littlefield
F. M. Cuta

June 1987

Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

PNL-6108

REFERENCE COPY

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor Battelle Memorial Institute, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government of any agency thereof, or Battelle Memorial Institute. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or Battelle Memorial Institute.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

RELY: A RELIABILITY MODELING SYSTEM
FOR ANALYSIS OF SODIUM-SULFUR BATTERY
CONFIGURATIONS

C. J. Hostick	J. V. Dovey
H. D. Huber	R. B. Grinde
W. H. Doggett	J. S. Littlefield
J. A. Dirks	F. M. Cuta

June 1987

Prepared for
the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Richland, Washington 99352

SUMMARY

In support of the Office of Energy Storage and Distribution of the U.S. Department of Energy (DOE), Pacific Northwest Laboratory has produced a micro-computer-based software package, called RELY, to assess the impact of sodium-sulfur cell reliability on constant current discharge battery performance. The Fortran-based software operates on IBM microcomputers and IBM-compatibles that have a minimum of 512K of internal memory. The software package has three models that provide the following: 1) a description of the failure distribution parameters used to model cell failure, 2) a Monte Carlo simulation of battery life, and 3) a detailed discharge model for a user-specified battery discharge cycle.

Cell failure is modeled as occurring randomly, using a uniform distribution for failure rates due to freeze-thaw and a Weibull distribution for failure due to wearout. The description of the failure distribution parameters assists the user in determining these parameters, and provides typical distribution parameter values based on available sodium-sulfur test data.

The Monte Carlo simulation estimates expected battery life for a variety of user-specified battery configurations. Performance requirements are entered in terms of battery capacity, and failures are modeled as producing either open or closed circuit post-failure resistances. Multiple simulations of battery life can be run to obtain a mean and standard deviation for battery life estimates.

The detailed discharge model for a user-specified discharge cycle was developed by using a current-voltage, depth-of-discharge model of sodium-sulfur cell performance. This model estimates battery discharge performance at constant discharge current in terms of its voltage and power. The model takes into consideration the number and type of failed cells that can be expected for the specified cycle, and provides the user with the option of adding switches within the battery configuration to minimize the impact of failed cells.

CONTENTS

SUMMARY	iii
1.0 INTRODUCTION	1.1
2.0 RELY USER'S GUIDE	2.1
2.1 GETTING STARTED	2.1
2.2 REFERENCE GUIDE	2.5
3.0 EXAMPLE APPLICATIONS	3.1
3.1 THE LIFE-CYCLE MODEL	3.2
3.2 DETAILED DISCHARGE MODEL	3.10
3.3 CELL FAILURE DISTRIBUTION MODEL	3.21
REFERENCES	R.1
APPENDIX A - THE WEIBULL DISTRIBUTION PARAMETERS	A.1
APPENDIX B - MODELING APPROACH	B.1
APPENDIX C - SOURCE LISTINGS	C.1
APPENDIX D - MODEL VERIFICATION	D.1
D.1 VERIFICATION OF THE LIFE CYCLE MODEL.....	D.1
D.1.1 System I	D.2
D.1.2 System II	D.4
D.2 VERIFICATION OF THE DETAILED DISCHARGE MODEL.....	D.4

FIGURES

1.1	Sodium-Sulfur Battery Reliability Model	1.2
2.1	Main Menu of RELY Software Package	2.2
2.2	Battery Representation Showing Cells, Strings, and Modules	2.6
2.3	Representation of Cell in Detailed Discharge Model	2.7
2.4	Typical Modules of Series-Parallel Connected Cells, and Parallel-Series Connected Cells	2.7
2.5	Cell Voltage as a Function of DOD	2.9
2.6	Closed Circuit Failure in Life-Cycle Model	2.9
2.7	Closed Circuit Failure in Detailed Discharge Model	2.10
2.8	Failure Switch Operation	2.12
2.9	Open Circuit Failure in Life-Cycle Model	2.14
2.10	Open Circuit Failure in Detailed Discharge Model	2.14
3.1	Suggested Use of the RELY Software Package	3.1
3.2	Input Screen for Battery Test Configuration in Life-Cycle Model	3.4
3.3	Arrangement of Cells, Strings, and Modules in Example Battery Configuration	3.5
3.4	Input Screen for Performance Requirements in Life-Cycle Model	3.6
3.5	Input Screen for Freeze-Thaw Failures in Life-Cycle Model	3.7
3.6	Input Screen for Failures Due to Wearout in Life-Cycle Model	3.8
3.7	Output Screen from Life-Cycle Model	3.11
3.8	Main Menu for Detailed Discharge Model	3.13
3.9	Input Screen to Select Editing Screens for Detailed Discharge Model	3.13
3.10	Input Screens for Editing Battery Performance Data in Detailed Discharge Model	3.14

3.11	Screen Display of Battery Configuration for Detailed Discharge Model	3.16
3.12	Output Screen from Detailed Discharge Model	3.19
3.13	Input Screen for Analysis of Results from Detailed Discharge Model	3.20
3.14	Input Screen for Graphics Output from Detailed Discharge Model	3.20
3.15	Graphics Output from Detailed Discharge Model	3.22
3.16	Partial Table of Cell Status at Time Battery Failed	3.23
3.17	Input Screen for Failure Distribution Model	3.25
3.18	Input Screen for Example Weibull Distribution (Option A)	3.25
3.19	Input Screen for Example Weibull Distribution (Option B)	3.26
3.20	Weibull Probability Density Function Illustrated by Cell Failure Distribution Model	3.28
A.1	Weibull Density Functions: $\delta = 0$, $\theta = 500$	A.2
A.2	Weibull Probability Paper	A.3
A.3	Graphical Estimation of Weibull Parameters	A.5
B.1	Block Diagram of DOS Batch File BATTERY.BAT	B.2
B.2	Block Diagram of Program RELY	B.4
B.3	Block Diagram of Subroutine SIMULAT	B.7
B.4	Generation of Weibull Random Numbers for Location $\delta=0$, Scale $\theta=500$, and Shape $\beta=2$	B.9
B.5	Block Diagram of Program BAT2A	B.10
D.1	Model Verification Battery Configuration	D.2

TABLES

A.1	Example Failure Cycles, Ranks, and Median Rank Values Used to Estimate Weibull Parameters	A.4
B.1	Summary of Supporting Subroutines	B.19
B.2	Summary of GRAFMATIC Subroutines Called by Programs RELY and BAT2A	B.22
D.1	Individual Cell Wearout Cycles	D.2

1.0 INTRODUCTION

The Energy Storage Division of the U.S. Department of Energy (DOE) is sponsoring research at Pacific Northwest Laboratory (PNL) to develop micro-computer-based software to assist battery developers in their research and development activities. This report describes the RELY software package; a reliability model for analyzing sodium-sulfur battery configurations during constant current discharge conditions.

This software is microcomputer-based and can be executed on IBM computers and IBM-compatibles that have a minimum of 512K of internal memory. A schematic of the software is shown in Figure 1.1. The software package consists of 1) a description of the failure distribution parameters used to model cell failure, 2) a Monte Carlo simulation of the battery life (in cycles), and 3) a detailed discharge model for a user-specified discharge cycle.

The Cell Failure Distribution Description is a graphical package that assists the user in understanding the parameters in the Weibull failure distribution. The graphical package also provides typical values for failure distribution parameters based on the most recent sodium-sulfur test data. The failure distribution graphics can help users determine whether the Weibull parameter estimates obtained from their bench test data are adequate.

The second part of the software package is the Life-Cycle Model which produces an estimate of the expected battery life. It models cell failures using stochastic modeling techniques; a uniform distribution is assumed for freeze-thaw failures and a Weibull distribution is used for wearout failures. Cells are modeled as either "good" or failed and battery performance requirements are stated in terms of the number of good cells required. Failed cells are modeled as having either open or closed circuit post-failure resistances. The user specifies the expected percentage of each post-failure resistance for both types of failures. Using Monte Carlo simulation techniques, multiple simulations of battery life can be run to obtain a mean and standard deviation for the battery life estimates.

The Detailed Discharge model is the third component of the software package; it provides a detailed discharge analysis of a user-specified battery

FIGURE 1.1. Sodium-Sulfur Battery Reliability Model

discharge cycle. The model was formulated using a current-voltage, depth-of-discharge model of sodium sulfur cell performance (DOE 1977). The model estimates battery discharge performance at constant discharge current in terms of voltage and power. Following the completion of the battery cycle life simulation, the Detailed Discharge Model can be used to test cycles near the end of the estimated battery life. In this manner, the battery life estimate can be verified using more exact battery performance measures (i.e., the ability of the battery to meet power requirements as opposed to a good cell count). The model accounts for the failed cells that can be expected for the specified cycle, and provides the user with the option of adding switches within the battery configuration to minimize the impact of the failed cells.

Battery configurations of up to 8,000 cells (up to 20 cells/string, 20 strings/module, and 20 modules/battery) can be modeled. Larger configurations can be modeled by grouping multiple cells into modules, and entering module data when cell data is requested. For example, large load leveling systems of 800,000 cells could be represented by grouping cells into modules of 100, and entering the resulting module characteristics as cell data into the model.

A user's guide for the RELY software is provided in Chapter 2.0. Chapter 3.0 contains example applications illustrating the input and output screens for the three modeling components of the software package. A method for estimating Weibull distribution parameters from bench test data is provided in Appendix A. The modeling approach for the software package is described in Appendix B, the source code is listed in Appendix C, and model verification calculations are shown in Appendix D.

2.0 RELY USER'S GUIDE

This chapter serves as a brief introduction and reference guide for the RELY software package. Since the model is menu-driven and largely self-explanatory, the user is urged to run the model as soon as a working copy of the diskette is made. Section 2.1 describes how to copy the diskette. Section 2.2 is an alphabetical reference guide which explains the major concepts and terminology encountered. Ideally, this reference guide should be used while the model is being run, so that the user obtains a "hands-on" knowledge of the terminology.

The RELY software package was developed using Microsoft Fortran version 3.3 (Microsoft, Inc. 1985) for IBM-PC or compatible computers. The package displays results on the screen and/or writes to disk files. In addition, graphs of the results can be displayed on the screen; these graphs were developed using the GRAFMATIC graphics library (Microcompatibles 1983). The models of the software package are linked together with the Disk Operating System (DOS) (Microsoft, Inc. 1983) batch file "BATTERY."

The menus guide the user through the process of entering and analyzing a battery system. Figure 2.1 shows the main menu of the RELY software package. This menu provides the primary interface to the user in analyzing a battery system.

2.1 GETTING STARTED

This section describes the preliminary steps for running the RELY software package.

HARDWARE REQUIREMENTS

An IBM PC or compatible computer with at least 512 K of RAM and one floppy disk drive is needed to run the RELY model (a hard disk or second floppy drive is required for large applications). A color/graphics adapter is required to display graphs.

```

*****
*
*                               MAIN MENU
*
*      ENTER
*
*      A - INPUT BATTERY TEST CONFIGURATION, CELL
*            CHARACTERISTICS AND PERFORMANCE
*            REQUIREMENTS
*
*      B - INPUT FAILURE RATES
*
*      C - RUN LIFE-CYCLE MODEL
*
*      D - RUN DETAILED DISCHARGE MODEL
*
*      E - DESCRIPTION OF FAILURE DISTRIBUTION MODEL
*
*      F - EXIT PROGRAM
*
*      ENTER LETTER FOR CHOICE:
*
*****

```

FIGURE 2.1. Main Menu of RELY Software Package

A copy of Disk Operating System (DOS) version 2.0 or higher is also necessary.

MAKING A WORKING COPY OF THE RELY MODEL

For smaller battery configurations, the following disk setup procedure is used.

Floppy Disk Users

1. Format a new disk with the /S option.
2. Be sure the DOS file COMMAND.COM is on the new disk.
3. Copy the DOS file ANSI.SYS to the new disk.
4. Copy all files from the RELY distribution disk to the newly formatted disk with the COPY *.* command. Do not use the DISKCOPY command or you will destroy the progress made in steps 1-3.

5. You now have a working copy of the RELY disk. Place the original disk in a safe place. Before using the battery model, re-boot the system to make sure that ANSI.SYS is loaded.

The above disk setup procedure is adequate for smaller battery configurations. However, large systems may create files that exceed the disk's capacity. In these cases, you can use a second disk as a data disk for the files generated by the model. Follow the additional steps below to create a data disk.

Creating a Data Disk

1. Format a new disk. The /S option is not required.
2. Copy the BATTERY.BAT file from your working RELY disk to this new disk.
3. Edit the BATTERY.BAT file on the new disk. Insert "A:" in front of the commands "RELY" and "BAT2A" in this batch file.
4. Erase the BATTERY.BAT file on your working RELY disk (optional).
5. Insert the working RELY disk in drive A and your new data disk in drive B.
6. Make B the default drive.
7. Type "BATTERY" <Return> to run the model.

An alternative to the above procedure is to follow steps 1 and 2, and edit the BATTERY.BAT file to insert "PATH=A:" immediately after the "ECHO OFF" command. Then follow steps 4-7 as above.

Hard Disk Users

1. Create a new directory, such as RELY.
2. Insert the original RELY disk in drive A and enter the newly created directory. The prompt should now be similar to "C RELY>."

3. Issue the following DOS commands:
COPY A:*.EXE <RETURN>
COPY A:*.BAT <RETURN>
4. Make sure that there is a path to DOS and that the command
DEVICE=ANSI.SYS is in your CONFIG.SYS file.
5. You have now installed RELY on your hard disk. Place the
original diskette in a safe place. Before using the battery
model, re-boot the system to make sure that ANSI.SYS is loaded.

STARTING THE BATTERY MODEL

From the appropriate drive/directory prompt, type "BATTERY" <RETURN>. The model is menu-driven and designed to be self-explanatory, so step-by-step instructions are not provided. For further information and help with a particular concept or term, consult the reference guide in Section 2.2.

When the Main Menu appears (similar to Figure 2.1), Options A, B, and C must be selected in sequential order to run the Life-Cycle Model. Option D can then be selected to run the Detailed Discharge Model. Option E can be selected at any time to introduce the user to the Weibull distribution.

NOTE: If the menus of the program do not come onto the screen from the top to the bottom, but rather scroll up from the bottom of the screen, check to be sure that the device driver ANSI.SYS is loaded.

2.2 REFERENCE GUIDE

This section provides an alphabetical list of the terms used in the RELY software package.

BAT2A.OUT

Output file created by the DETAILED DISCHARGE MODEL which contains results of the discharge analysis.

BAT2A.TMP

File created by the LIFE-CYCLE MODEL which contains information about the battery configuration and individual cells. This file is used by the DETAILED DISCHARGE MODEL.

BAT2A.\$DF

File created by the DETAILED DISCHARGE MODEL (Option 4 on main menu) which contains user-specified test conditions, cell parameters, and cell internal resistances. If this file is present when the Detailed Discharge Model is started, these values are loaded and replace the default values.

BATTERY

Energy storage device consisting of individual CELLS. CELLS are connected in series to form STRINGS. STRINGS are connected in parallel to form MODULES and MODULES are connected in series to form a BATTERY. See Figure 2.2. BATTERY configurations of up to 8,000 cells (up to 20 cells/string, 20 strings/module, and 20 modules/battery) can be modeled.

BATTERY CONFIGURATION

The number of CELLS comprising a STRING, STRINGS comprising a MODULE, and MODULES comprising a BATTERY.

FIGURE 2.2. Battery Representation Showing Cells, Strings, and Modules

BATTERY PERFORMANCE REQUIREMENTS

In the Life-Cycle Model the BATTERY performance requirements are specified as the minimum numbers of operating 1) CELLS required for STRING operation, 2) STRINGS required for MODULE operation, and 3) MODULES required for BATTERY operation.

CELL (also see BATTERY)

In the Life-Cycle Model a cell is the smallest entity considered. A cell is classified as either good or bad, without reference to its capacity or voltage.

In the Detailed Discharge Model, a cell is modeled as an open circuit voltage with an internal resistance. The Detailed Discharge Model assumes that charging a cell to less than 5% DEPTH OF DISCHARGE is impractical or impossible since the internal resistance rises so quickly for greater levels of charge. Thus, at 5% DEPTH OF DISCHARGE the cell is able to discharge, but is not able to charge any further. This is represented by the diode in Figure 2.3.

FIGURE 2.3. Representation of Cell in Detailed Discharge Model

CELL-AGING FAILURE

See WEAROUT FAILURE.

CELL CONNECTION

The method by which cells are to be connected. Figure 2.4 shows the two connection alternatives.

FIGURE 2.4. Typical Modules of Series-Parallel Connected Cells (left) and Parallel-Series Connected Cells (right)

CELL INTERNAL RESISTANCE

The output impedance of a cell. The user inputs this parameter in the Detailed Discharge Model as a function of the cell's state of discharge, in 10% discharge increments. By default it is a constant 35 mohms until changed by the user.

CELL PARAMETERS

Characteristics of an individual cell which are necessary to model a battery system. These are determined by the user from bench-test data.

CELL VOLTAGE (also see CELL and FULLY CHARGED CELL CAPACITY)

The open circuit voltage of a cell. This quantity varies according to the Depth of Discharge (DOD). DOE is defined as one minus the THEORETICAL CAPACITY. Figure 2.5 explains the parameters needed in the Detailed Discharge Model. The FULLY CHARGED CELL CAPACITY is equal to 95% of the THEORETICAL CELL CAPACITY when the default value for the LOWER ELECTROLYTE FAILURE VOLTAGE (1.78 volts) is used. Changing the LOWER ELECTROLYTE FAILURE VOLTAGE will result in a DOD greater or less than 100% at the time of OVER-DISCHARGE FAILURE. Thus, the FULLY CHARGED CELL CAPACITY can be greater or less than 95% of the THEORETICAL CELL CAPACITY. However, in no case will the cell be at a DOD less than 5%.

CLOSED CIRCUIT FAILURE

FAILURE MODE in which a CELL acts as a closed (short) circuit after it fails.

In the Life-Cycle Model, a closed circuit failure results in zero resistance through the failed cell (effectively deletes the cell from the battery). See Figure 2.6.

In the Detailed Discharge Model, the open circuit voltage is V_0 and the internal resistance is R_0 when the cell is operating. When a cell suffers a closed circuit failure, the internal resistance is set to the CLOSED CIRCUIT FAILURE RESISTANCE value (R_f) when the cell is operating. The open circuit

FIGURE 2.5. Cell Voltage as a Function of DOD

FIGURE 2.6. Closed Circuit Failure in Life-Cycle Model

cell voltage drops to zero (V_f). The CLOSED CIRCUIT FAILURE RESISTANCE parameter should be obtained from the user's bench-test data on the cell. See Figure 2.7.

FIGURE 2.7. Closed Circuit Failure in Detailed Discharge Model

CLOSED CIRCUIT FAILURE RESISTANCE

A CELL PARAMETER equal to the typical resistance of a cell that has suffered a CLOSED CIRCUIT FAILURE.

CYCLE TO ANALYZE

The particular discharge cycle which the user selects to simulate in the Detailed Discharge Model. Appears in the TEST CONDITIONS menu.

DEPTH OF DISCHARGE (DOD)

The percentage of a cell's capacity which has been used thus far. Equal to one minus the remaining amp-hours (as a fraction of the cell theoretical capacity).

DETAILED DISCHARGE MODEL

The RELY sub-model which analyzes a specific cycle of the battery's lifetime. Detailed voltage-current-resistance information is obtained as a function of discharge time.

DISCHARGE CURRENT

User-specified TEST CONDITION: the constant current (amps) output by the battery during the test.

DURATION OF TEST

User-specified total time (hours) for which the battery is to be discharged. Appears in the TEST CONDITIONS menu.

FAILURE DISTRIBUTION MODEL

The RELY sub-model which introduces the user to the WEIBULL DISTRIBUTION. There are two parts to this sub-model. Based on user-specified Weibull parameters, the first part of the model generates the actual WEIBULL DISTRIBUTION density function and the second part simulates the density function based on 100 to 1,000 cell failures.

FAILURE MODE

Type of failure suffered by a cell, either closed or open circuit.

FAILURE SWITCH

When a cell fails in the Detailed Discharge Model, it effectively becomes a resistor. Without failure switches, the resistance is equal to either the CLOSED CIRCUIT or OPEN CIRCUIT FAILURE RESISTANCE. If failure switches are used, however, the cell is removed from the circuit as shown in Figure 2.8. Only one failure switch type may be selected by the user, and it protects against all FAILURE MODES.

FREEZE-THAW FAILURE

When cells are allowed to cool after charge-discharge cycle, and later are re-heated to operating temperature, this is called a FREEZE-THAW. The components of the cell undergo thermal stresses, and may fail during reheating.

FIGURE 2.8. Failure Switch Operation

FREEZE-THAW FAILURE RATE

The probability that an individual cell will fail during a single FREEZE-THAW.

FULLY CHARGED OPEN CIRCUIT CELL VOLTAGE

See CELL VOLTAGE.

FULLY CHARGED CELL CAPACITY

A CELL PARAMETER equal to the working capacity of the cell (in amp-hours). When the default value for the LOWER ELECTROLYTE FAILURE VOLTAGE (1.78 volts) is used, the FULLY CHARGED CELL CAPACITY is equal to 95% of the THEORETICAL

CELL CAPACITY. If the electrolyte is assumed to fail at a higher voltage than the default, the FULLY CHARGED CELL CAPACITY will be less than 95% of the THEORETICAL CELL CAPACITY. Conversely, if the electrolyte is assumed to fail at a lower voltage than the default, the FULLY CHARGED CELL CAPACITY will be greater than 95% of the THEORETICAL CELL CAPACITY. This value is calculated in the Detailed Discharge Model.

LIFE-CYCLE MODEL

The RELY sub-model which estimates a battery's useful life based on the BATTERY CONFIGURATION, BATTERY PERFORMANCE REQUIREMENTS, and failure rates and modes. Voltages, resistances, and capacities are not considered in this sub-model. The Life-Cycle Model must be executed prior to the execution of the Detailed Discharge Model.

LOWER ELECTROLYTE FAILURE VOLTAGE

See CELL VOLTAGE.

MODULE

See BATTERY.

OPEN CIRCUIT FAILURE

FAILURE MODE in which a cell acts as an open circuit after it fails.

In the Life-Cycle Model, an open circuit failure causes the entire string to fail. See Figure 2.9.

In the Detailed Discharge Model, the open circuit voltage is V_0 and the internal resistance is R_0 when the cell is operating. When a cell suffers an open circuit failure, the internal resistance is set to the OPEN CIRCUIT FAILURE RESISTANCE (R_f). The open circuit cell voltage drops to zero (V_f). The OPEN CIRCUIT FAILURE RESISTANCE parameter should be obtained from the user's bench-test data on the cell. See Figure 2.10.

FIGURE 2.9. Open Circuit Failure in Life-Cycle Model

FIGURE 2.10. Open Circuit Failure in Detailed Discharge Model

OPEN CIRCUIT FAILURE RESISTANCE

A CELL PARAMETER equal to the typical resistance of a cell that has suffered an OPEN CIRCUIT FAILURE.

OVER DISCHARGE FAILURE

The FAILURE MODE of a cell if it fails due to over-discharging (also called under-voltage electrolyte failure). Specified as a CELL PARAMETER.

OVER-DISCHARGED CELL

A cell which has been discharged completely (i.e., there is no remaining charge). When this happens, the cell fails. See CELL VOLTAGE.

OVER-VOLTAGE FAILED CELL

A cell which has received a voltage greater than the UPPER ELECTROLYTE FAILURE VOLTAGE. When this happens, the cell fails.

OVER-VOLTAGE FAILURE

A CELL PARAMETER which is the FAILURE MODE of a cell if it fails due to an over-voltage.

POST-FAILURE RESISTANCE

In the Life-Cycle Model, another term for the FAILURE MODE.

In the Detailed Discharge Model, open and closed circuit failure modes are treated individually. See OPEN CIRCUIT FAILURE and CLOSED CIRCUIT FAILURE.

RELY.OUT

Output file created by the Life-Cycle Model which contains results of the simulation. Created only if the user selects "F" when asked if results should be displayed on the screen or written to a disk file.

STRING

See BATTERY.

TEST CONDITIONS

Conditions which the user sets for a particular test in the Detailed Discharge Model. This is where "what-if" questions can be answered for various power outputs, cell connections, and failure switches.

THEORETICAL CELL CAPACITY

The user-specified CELL PARAMETER which is the capacity (in amp-hours) of a cell as it moves from 0 to 100% Na_2S_3 .

TIME INCREMENT

The time increment for the DETAILED DISCHARGE calculations. Since all parameters are constant for this discrete interval, small intervals will give more accurate results. Appears in TEST CONDITIONS menu.

UNDER-VOLTAGE FAILURE

See OVER-DISCHARGE FAILURE.

UPPER ELECTROLYTE FAILURE VOLTAGE

A CELL PARAMETER equal to the maximum voltage a cell can withstand before electrolyte failure.

WEAROUT FAILURE (also called CELL-AGING FAILURE)

Failure to a cell caused by a natural, random wearout (as opposed to a FREEZE-THAW FAILURE). These types of failures are assumed to follow a WEIBULL DISTRIBUTION.

WEIBULL DISTRIBUTION

The statistical distribution which models WEAROUT FAILURES. The Weibull distribution is often used to model natural, random failures in reliability studies.

WEIBULL LOCATION PARAMETER

The minimum possible life of a cell. See Appendix A.

WEIBULL SCALE PARAMETER

The characteristic life of a cell. See Appendix A.

WEIBULL SHAPE PARAMETER

The parameter which controls the shape of the distribution. The failure rate decreases, increases, or remains constant over time if this value is less than one, greater than one, or equal to one, respectively. See Appendix A.

3.0 EXAMPLE APPLICATIONS

The suggested sequence for using the RELY package is shown in Figure 3.1. The purpose of the Life-Cycle Model is to approximate battery life based on specified cell parameters and failure rates. This estimate can be verified by the use of the Detailed Discharge Model. In this manner, an estimate of battery life can be obtained without a time-consuming detailed performance simulation of each discharge cycle.

FIGURE 3.1. Suggested Use of the RELY Software Package

Before running the Life-Cycle Model and after determining battery cell parameters, the user specifies the battery configuration, minimum performance requirements, and failure rates. Failure rates can be determined from bench-test data using the approach presented in Appendix A and the failure distribution example menu selection. Failure rates are required for both freeze-thaw cell failures and cell failures due to wearout.

The Life-Cycle Model is then executed to determine an estimate of battery life. To verify the estimate of battery life, the Detailed Discharge Model can be used to simulate specific cycles near the end of expected battery life. For example, if the Life-Cycle Model estimates battery life to be 1,000 cycles, the Detailed Discharge Model could be used to simulate cycle 1,000 to determine if detailed performance requirements were being met. If not, the general performance requirements specified in the Life-Cycle Model need to be more restrictive. If performance requirements are easily being met at the end of the estimated cycle life, the Life-Cycle Model's performance requirements may be too restrictive. This process is repeated until the Life-Cycle Model accurately predicts battery life.

An example application of the Life-Cycle Model illustrating its input and output screens is presented in Section 3.1. An example use of the Detailed Discharge Model illustrating its input and output screens is presented in Section 3.2. The Cell Failure Distribution Model is presented in Section 3.3.

3.1 THE LIFE-CYCLE MODEL

The Life-Cycle Model performs independent Monte Carlo simulations of battery discharge cycles for user-defined battery configurations. In each simulation, the model predicts stochastic cell failures for two independent types of failure modes: freeze-thaw and cell wearout. Each simulation continues until the number of working cells, strings, and modules in the battery configuration falls below minimum user-defined failure criteria (i.e., until the battery fails).

Freeze-thaw conditions are simulated whenever the battery is allowed to cool and then reheat. The model generates uniformly distributed pseudorandom numbers to determine whether or not a cell has failed due to freeze-thaw. Both

the freeze-thaw failure rate and the number of cycles between each cooling and reheating of the battery are specified by the user.

Wearout failure refers to cells randomly failing. The model generates Weibull-distributed pseudorandom numbers to predict the cycle in which a cell will fail due to wearout.

If a cell fails before the end of a simulation run (i.e., before the battery fails), its failure mode, the cycle in which the failure occurred, and the location of the failed cell are stored in internal arrays. The cell failure information from the last simulation run is written to a disk file for subsequent use by the Detailed Discharge Model when the user selects the Detailed Discharge option on the main menu.

Statistics are obtained from the independent Monte Carlo simulations to provide estimates of the means and standard deviations of the number of cycles before the battery fails, the number of freeze-thaw failures, and the number of wearout failures. You are given the option to display the statistics on the computer screen or request that they be written to a disk file at the end of the simulation runs.

The input and output screens for the Life-Cycle Model obtained by selecting Options A, B, and C in the Main Menu are described below.

Main Menu Option A

When you select option A in the Main Menu, the program displays the input screen for the Life-Cycle Model labeled "Battery Test Configuration" (Figure 3.2). This screen prompts you to enter values for three input parameters for defining the battery configuration to be tested:

1. Number of cells in each string
2. Number of parallel strings in each module.
3. Number of modules in a series.

The arrangement of the cells, strings, and modules in the example battery configuration is shown in Figure 3.3. RELY allows up to 20 cells per string, 20 strings per module, and 20 modules per battery. When you are satisfied with the definition of the battery test configuration, enter Y or y for "yes" when queried on whether the input values on this screen are correct, and press

```

*****
*          BATTERY TEST CONFIGURATION          *
*
*   THE BATTERY CONFIGURATION IS ENTERED BY   *
*   SPECIFYING THE NUMBER OF CELLS IN SERIES PER *
*   STRING, THE NUMBER OF STRINGS IN PARALLEL PER *
*   MODULE, AND THE NUMBER OF MODULES IN SERIES *
*
*   ENTER NUMBER OF CELLS PER STRING:  15      *
*
*   ENTER NUMBER OF STRINGS IN PARALLEL:  4    *
*
*   ENTER NUMBER OF MODULES IN SERIES:  8     *
*
*   ARE THESE VALUES CORRECT?  (Y/N):  Y     *
*****

```

FIGURE 3.2. Input Screen for Battery Test Configuration in Life-Cycle Model

<RETURN>. The program will then display the next input screen for the Life-Cycle Model labeled "Performance Requirements".

The input screen labeled "Performance Requirements" is shown in Figure 3.4. This screen asks you to specify the battery's minimum performance requirements in terms of string, module, and battery requirements. These requirements indicate the number of sub-units that must be operating for the larger unit to remain in operation. For example, if cell failures reduce the number of operating cells below the string requirement, the string is no longer operable. The input performance parameters are as follows:

1. Minimum number of good cells required in each operating string
2. Minimum number of good strings required in each operating module
3. Minimum number of good modules required for minimum battery capacity.

When you are satisfied with the definition of the battery performance requirements, enter Y or y for "yes" when queried on whether the input values on this screen are correct, and press <RETURN>. The program will then return you to the Main Menu for selection of Option B.

Main Menu Option B

When you select Option B in the Main Menu, the program displays the input screen for the Life-Cycle Model labeled "Freeze-Thaw Failures". The screen is

FIGURE 3.3. Arrangement of Cells, Strings, and Modules in Example Battery Configuration

```

*****
*                                     *
*          PERFORMANCE REQUIREMENTS          *
*                                     *
* BATTERY PERFORMANCE IS SPECIFIED BY THE USER IN *
* TERMS OF STRING, MODULE AND BATTERY REQUIREMENTS. *
* THESE REQUIREMENTS INDICATE THE NUMBER OF SUB-UNITS *
* THAT MUST BE EFFECTIVELY OPERATING FOR THE LARGER *
* UNIT TO REMAIN IN OPERATION. FOR EXAMPLE, IF CELL *
* FAILURES REDUCE THE NUMBER OF OPERATING CELLS BELOW *
* THE STRING REQUIREMENT THE STRING IS NO LONGER *
* OPERABLE. *
* *
* ENTER THE MINIMUM NUMBER OF GOOD CELLS *
* REQUIRED PER OPERATING STRING: 12 *
* *
* ENTER THE MINIMUM NUMBER OF GOOD STRINGS *
* REQUIRED PER OPERATING MODULE: 3 *
* *
* ENTER THE MINIMUM NUMBER OF GOOD MODULES *
* REQUIRED FOR MINIMUM BATTERY CAPACITY: 6 *
* *
* ARE THESE VALUES CORRECT? (Y/N): Y *
*****

```

FIGURE 3.4. Input Screen for Performance Requirements in Life-Cycle Model

shown in Figure 3.5. This screen prompts you to enter values used for predicting freeze-thaw failures of sodium-sulfur cells and to specify the percentage of each type of post-failure resistance for cells that fail due to freeze-thaw. These types of failures result from stress cracking in the beta alumina electrolyte when the battery is allowed to cool and is then reheated. A certain percentage of the cells can be expected to fail during each freeze-thaw occurrence to which the battery is subjected. The first charge-discharge cycle is assumed to be a freeze-thaw.

The input parameters required to predict freeze-thaw failures and specify the percentage of each type of post-failure resistance of the failed cells are as follows:

1. Expected number of battery charge-discharge cycles between each freeze-thaw occurrence to which the battery is subjected.
2. Freeze-thaw failure rate, expressed as the probability of an individual cell failing during a freeze-thaw.

```

*****
*                                     *
*                               FREEZE-THAW FAILURES                               *
*                                     *
*   FREEZE-THAW FAILURES OCCUR WHEN THE BATTERY IS                             *
*   ALLOWED TO COOL AND IS THEN REHEATED.  A CERTAIN                           *
*   PERCENTAGE OF THE CELL POPULATION CAN BE EXPECTED                           *
*   TO FAIL PREMATURELY DURING EACH FREEZE-THAW.                               *
*                                     *
*   ENTER NO. OF CYCLES BETWEEN FREEZE-THAWS (XXXXX):  50                       *
*                                     *
*   ENTER FREEZE-THAW CELL FAILURE RATE (0.XXXX):  0.03                         *
*                                     *
*   ENTER PERCENTAGE OF POST FAILURE RESISTANCES THAT ARE                       *
*   OPEN CIRCUIT (XXX.XX):  0                                                    *
*                                     *
*   PERCENTAGE OF POST FAILURE RESISTANCES THAT ARE                             *
*   CLOSED CIRCUIT (100. - OPEN CIRCUIT PERCENTAGE):                             *
*   100.00                                                                       *
*                                     *
*   ARE THESE VALUES CORRECT?  (Y/N):  Y                                       *
*****

```

FIGURE 3.5. Input Screen for Freeze-Thaw Failures in Life-Cycle Model

3. Percentage of post failure resistances due to freeze-thaw that are open circuit; the percentage of post failure resistances due to freeze-thaw that are closed circuit are calculated as 100% minus the open circuit failure percentage.

Remember, that in the Life-Cycle Model when there is an open circuit failure, the cell is assumed to have an infinite post failure resistance and the entire string fails. Thus, in the Life-Cycle Model only the percentage of cells that would fail and effectively remove a string from service should be labeled as open circuit failures. In addition, when a cell fails, its initial post failure resistance may be much lower than it will be many cycles later. Thus, to get the most accurate estimate of battery life, the percentage of open and closed circuit failures used in the Life-Cycle Model should represent the expected failure distribution at the end of the battery life for this type of failure. Finally, if the failure switches are going to be used in the Detailed Discharge Model, the post failure resistance in the Life-Cycle Model should be set to 100% for the type of failure switch (either closed or open).

When you are satisfied with the values you have entered for characterizing freeze-thaw failures, enter Y or y for "yes" when queried on whether the input values on this screen are correct, and press <RETURN>. The program will then display the next input screen for the Life-Cycle Model labeled "Failures Due to Wearout".

The input screen labeled "Failures Due to Wearout" is shown in Figure 3.6. This screen prompts you to enter values for predicting cell failures due to cells reaching their natural end of life (wearout) and to specify the type of post-failure resistance for cells that fail due to wearout. Cell wearout failures result from degradation due to normal charge-discharge cycling of the battery. The Weibull distribution is used to model stochastic cell failures due to wearout. The input parameters on this screen are as follows:

```

*****
*                               *
*           FAILURE DUE TO WEAROUT           *
*                               *
* FAILURE DUE TO WEAROUT REFERS TO CELLS REACHING *
* THEIR NATURAL END-OF-LIFE. IT IS ASSUMED THAT *
* THESE FAILURES ARE WEIBULL DISTRIBUTED. *
*                               *
* ENTER WEIBULL LOCATION PARAMETER (XXXX): 0 *
*                               *
* ENTER WEIBULL SCALE PARAMETER (XXXXX.XX): 1500. *
*                               *
* ENTER WEIBULL SHAPE PARAMETER (XX.XX): 1.0 *
*                               *
* ENTER PERCENTAGE OF POST FAILURE RESISTANCES *
* THAT ARE OPEN CIRCUIT (XXX.XX): 0 *
*                               *
* PERCENTAGE OF POST FAILURE RESISTANCES THAT ARE *
* CLOSED CIRCUIT (100. - OPEN CIRCUIT PERCENTAGE): *
*                               *
* ARE THESE VALUES CORRECT? (Y/N): Y *
*****

```

FIGURE 3.6. Input Screen for Failures Due to Wearout in Life-Cycle Model

1. Weibull location parameter
2. Weibull scale parameter
3. Weibull shape parameter
4. Percentage of post failure resistances due to wearout that are open circuit; the percentage of post failure resistances due to wearout that are closed circuit are calculated as 100% minus the open circuit failure percentage.

Remember, that in the Life-Cycle Model when there is an open circuit failure, the cell is assumed to have an infinite post failure resistance and the entire string fails. Thus, in the Life-Cycle Model only the percentage of cells that would fail and effectively remove a string from service should be labeled as open circuit failures. In addition, when a cell fails, its initial post failure resistance may be much lower than it will be many cycles later. Thus, to get the most accurate estimate of battery life, the percentage of open and closed circuit failures used in the Life-Cycle Model should represent the expected failure distribution at the end of the battery life for this type of failure. Finally, if the failure switches are going to be used in the Detailed Discharge Model, the post failure resistance in the Life-Cycle Model should be set to 100% for the type of failure switch (either closed or open).

Definitions of the Weibull input parameters are given in the description of the Cell Failure Distribution Model in Section 3.3 and in Appendix A. When you are satisfied with the values you have entered for characterizing cell wearout failures, enter Y or y for "yes" when queried on whether the input values on this screen are correct, and press <RETURN>. The program will then return you to the Main Menu for selection of Option C.

Main Menu Option C

Option C in the Main Menu is selected to execute the Life-Cycle Model once all input parameters have been defined using Options A and B. When you select Option C, you are first asked to specify the number of independent Monte Carlo simulation runs you want the Life-Cycle Model to perform. Next, you are asked if the value you have entered for the number of simulation runs is correct. Finally, you are asked if the simulation output should be sent to a file or the

screen, indicated by entering F or S, respectively. After you have entered one of these values, press <RETURN> to execute the Life-Cycle Model.

If you entered F, the program will write the simulation output to the file RELY.OUT. If you entered S, the program will write the simulation output to the screen. Following the simulation output, you are asked if you want to execute the Life-Cycle Model again with the same input data, but using a different set of pseudorandom numbers. When you are finished with the Life-Cycle Model, enter N or n for "no" when asked if you want to repeat this process for the same initial data and press <RETURN>. The program will then return you to the Main Menu for selection of Option D.

Output Screen

If you selected to display the simulation output on the screen, the output screen shown in Figure 3.7 is displayed. If you opted to write the output to the file RELY.OUT, you can view the contents of the file after you are finished with the program and have selected Option F to return to the computer operating system.

The output from the Life-Cycle Model shown in Figure 3.7 first echoes the values you entered for the input parameters in Options A and B. Next, the output shows the number of charge-discharge cycles before the battery failed, the open, closed, and total freeze-thaw cell failures, and the open, closed, and total wearout cell failures in each Monte Carlo simulation. This is followed by statistical estimates of the means and sample standard deviations of these items. Finally, tabular histograms that are 50 cycles wide show the open, closed, and total freeze-thaw cell failures, and the open, closed, and total wearout cell failures in each histogram cell.

3.2 DETAILED DISCHARGE MODEL

The Detailed Discharge Model simulates a sodium-sulfur battery discharge cycle for the battery configuration, cell parameters, and test conditions input by the user. The stochastic cell failures and number of charge-discharge cycles the battery can perform before it fails are obtained from the last simulation run performed by the Life-Cycle Model. Any discharge cycle from the

```

*****
*                                     RUN MODEL                               *
*                                     *                                     *
* SPECIFY THE NUMBER OF SIMULATION RUNS: 5                                *
* IS THIS VALUE CORRECT? (Y/N): Y                                         *
* DELIVER OUTPUT TO FILE OR TO SCREEN? (F/S): S                           *
*                                     *                                     *
*                               ESTIMATE OF BATTERY LIFE                     *
*                                     *                                     *
* BATTERY CONFIGURATION TESTED:                                           *
*   CELLS PER STRING = 15                                                  *
*   STRINGS PER MODULE = 4                                                 *
*   MODULES PER BATTERY = 8                                                *
* FAILURE CRITERIA:                                                       *
*   MINIMUM ACCEPTABLE NUMBER OF CELLS PER STRING = 12                   *
*   MINIMUM ACCEPTABLE NUMBER OF STRINGS PER MODULE = 3                   *
*   MINIMUM ACCEPTABLE NUMBER OF MODULES PER BATTERY = 6                 *
* FAILURE RATES:                                                           *
*   NO. OF CYCLES BETWEEN FREEZE-THAWS = 50                               *
*   FREEZE-THAW CELL FAILURE RATE PER CYCLE = 0.0300                     *
* FAILURE DUE TO WEAROUT:                                                  *
*   WEIBULL PARAMETERS - LOCATION = 0                                     *
*                           SCALE = 1500.00                               *
*                           SHAPE = 1.00                                  *
* POST FAILURE RESISTANCE PARAMETERS:                                       *
*   FREEZE-THAW FAILURES OPEN CIRCUIT PERCENTAGE = .00                  *
*   FREEZE-THAW FAILURE CLOSED CIRCUIT PERCENTAGE = 100.00              *
*   WEAROUT FAILURE OPEN CIRCUIT PERCENTAGE = .00                       *
*   WEAROUT FAILURE CLOSED CIRCUIT PERCENTAGE = 100.00                  *
* CYCLE LIFE AND FAILURE TOTALS:                                           *
*                                     *                                     *
*                                     NUMBER OF FAILURES                    *
*                                     FREEZE-THAW                          WEAROUT
*                                     OPEN  CLOSED  TOTAL  OPEN  CLOSED  TOTAL
*      RUN  CYCLE LIFE
*      1    128      0     41     41      0     34     34
*      2    200      0     54     54      0     47     47
*      3    106      0     52     52      0     36     36
*      4    112      0     36     36      0     44     44
*      5    122      0     39     39      0     36     36
* AVERAGE = 133.6 .0  44.4  44.4 .0  39.4  39.4
* STD. DEV. = 38.1 .0   8.1   8.1 .0   5.7   5.7
*
* FAILURE DISTRIBUTIONS:
*                                     *                                     *
*                                     AVERAGE NUMBER OF FAILURES          *
*                                     FREEZE-THAW                          WEAROUTS
*                                     OPEN  CLOSED  OPEN  CLOSED
*      RANGE
*      0- 50 CYCLES      .00  13.00      .00  14.60
*      51- 100 CYCLES    .00  15.40      .00  15.60
*      101- 150 CYCLES   .00  11.80      .00   6.60
*      151- 200 CYCLES   .00   2.00      .00   2.20
*      201- 250 CYCLES   .00   2.20      .00   0.40
*****

```

FIGURE 3.7. Output Screen from Life-Cycle Model

first cycle to the last cycle before the battery failed in the last simulation run of the Life-Cycle Model can be simulated.

The Detailed Discharge Model calculates the output voltage in user-defined time increments from an individual cell based upon the current, internal resistance, and depth-of-discharge of the cell. This information is combined with the configuration of cells, strings of cells, and modules specified for the battery to calculate the current flows, resistances, and output voltages across the strings, modules, and battery for each time increment. The calculations account for the failed cells (cumulative number, location and failure modes) predicted for the user-specified discharge cycle by the last simulation run performed by the Life-Cycle Model. The discharge simulation continues until the discharge duration specified for the battery is exceeded or until the battery can no longer deliver the constant discharge current specified in the test conditions.

The simulation results are both tabularly displayed on the computer screen and written to a disk file called BAT2A.OUT. The results can also be displayed graphically on the computer screen. Nine system performance measures are output as a function of discharge duration at the user-defined time increments to summarize the battery's performance: total voltage, average module voltage, battery power, average voltage of working cells, minimum voltage of working cells, average capacity of working cells, average resistance of all cells, the number of under-voltage electrolyte cell failures, and the number of over-voltage electrolyte cell failures.

The input and output screens for the Detailed Discharge Model obtained by selecting Option D in the Main Menu are described below.

Main Menu Option D

Option D in the Main Menu is selected to execute the Detailed Discharge model after Options A, B, and C have been selected to execute the Life-Cycle Model. When you select Option D, the program displays the Main Menu for the Detailed Discharge Model shown in Figure 3.8.

If you select Option 1 in the Main Menu, the program displays the input screen shown in Figure 3.9. This screen allows you to select three editing

```

*****
*           DETAILED DISCHARGE MODEL           *
*                                                                 *
*           MAIN MENU                                           *
*                                                                 *
*       1.  EDIT Performance Data                             *
*       2.  VIEW Battery Configuration                       *
*       3.  RUN Simulation                                    *
*       4.  SAVE Performance Data                             *
*       5.  EXIT to Life-Cycle Model                         *
*       6.  EXIT to DOS                                       *
*                                                                 *
*       Enter Selection >1                                     *
*****

```

FIGURE 3.8. Main Menu for Detailed Discharge Model

```

*****
*                                                                 *
*           SELECT INPUT SCREEN                                *
*                                                                 *
*       1.  Test Conditions                                    *
*       2.  Cell Parameters                                    *
*       3.  Edit Cell Internal Resistance                     *
*       4.  Return to Main Menu                               *
*                                                                 *
*       Enter Selection >1                                     *
*****

```

FIGURE 3.9. Input Screen to Select Editing Screens for Detailed Discharge Model

screens to view/change the input data to be used for the Detailed Discharge Model in simulating the discharge performance of the battery. The three editing screens are shown in Figure 3.10.

The first two editing screens (the second screen is in two parts) display the parameter values for the battery test conditions and cell characteristics. The parameters defining the test conditions and cell characteristics were described in Section 2.2. The third editing screen displays a table of values showing the internal resistance of a operational cell as a function of its theoretical capacity (as defined in Section 2.2). The first resistance value listed in the table is for 95% of theoretical capacity. The Detailed

```

*****
*                                     *
*                               TEST CONDITIONS                               *
*                               Input Screen 1                               *
*                                     *
*                               Cycle to Analyze      100                     *
*                               Duration of Test      6.0000   Hours          *
*                               Time Increment        .2500   Hours          *
* Cell Connection:  1 = Series-Par.  2 = Parallel-Ser.      1                 *
* Failure Switches: 0 = None.  1 = Closed.  2 = Open      0                 *
*                               Constant Discharge Current  45.0000   Amps    *
*                                     *
*                               MENU                                           *
*                               1. Modify These Values                        *
*                               2. Edit Cell Parameters                      *
*                               3. Edit Cell Internal Resistances           *
*                               4. Return to Main Menu                      *
*                               Enter Selection >                           *
*****

*****
*                                     *
*                               CELL PARAMETERS                               *
*                               First Half of Input Screen 2                *
*                                     *
* Fully-Charged Open Circuit Cell Voltage      2.0760   Volts              *
* Upper Electrolyte Failure Voltage            10.0000   Volts              *
* Lower Electrolyte Failure Voltage            1.7800   Volts              *
* Theoretical Cell Capacity                    50.0000   Amp-Hours          *
* Fully-Charged Cell Capacity                  47.5000   Amp-Hours          *
* Freeze-Thaw Failure Open Circuit Resistance   .2000   Ohms                *
* Freeze-Thaw Failure Closed Circuit Resistance .0700   Ohms                *
* Wearout Failure Open Circuit Resistance       .2000   Ohms                *
* Wearout Failure Closed Circuit Resistance     .0700   Ohms                *
*                                     *
*                               MENU                                           *
*                               1. Modify These Values                        *
*                               2. Edit Second Half of Cell Parameters       *
*                               3. Edit Test Conditions                     *
*                               4. Edit Cell Internal Resistances           *
*                               5. Return to Main Menu                      *
*                               Enter Selection >                           *
*****

```

FIGURE 3.10. Input Screens for Editing Battery Performance Data in Detailed Discharge Model

```

*****
*
*               CELL PARAMETERS
*           Second Half of Input Screen 2
*
*   Over-Voltage Failure Resistance Parameters:
*   Over-Voltage Failure Open Circuit Percentage    30.00    Percent
*   Over-Voltage Failure Closed Circuit Percentage  70.00    Percent
*   Over-Voltage Failure Open Circuit Resistance    .2000    Ohms
*   Over-Voltage Failure Closed Circuit Resistance  .0700    Ohms
*   Over-Discharge Failure Resistance Parameters:
*   Over-Discharge Failure Open Circuit Percentage  30.00    Percent
*   Over-Discharge Failure Closed Circuit Percentage 70.00    Percent
*   Over-Discharge Failure Open Circuit Resistance  .2000    Ohms
*   Over-Discharge Failure Closed Circuit Resistance .0700    Ohms
*
*               MENU
*   1. Modify These Values
*   2. Edit First Half of Cell Parameters
*   3. Edit Test Conditions
*   4. Edit Cell Internal Resistances
*   5. Return to Main Menu
*   Enter Selection >
*****

*****
*
*               CELL INTERNAL RESISTANCE
*
*   Theoretical    Resistance
*   Capacity (%)    (Ohms)
*   -----
*   95              .0350
*   90              .0350
*   80              .0350
*   70              .0350
*   60              .0350
*   50              .0350
*   40              .0350
*   30              .0350
*   20              .0350
*   10              .0350
*
*               MENU
*   1. Modify These Values
*   2. Edit Test Conditions
*   3. Edit Cell Parameters
*   4. Return to Main Menu
*   Enter Selection >
*****

```

FIGURE 3.10. (contd)

Discharge Model assumes that charging a cell above this value is impractical or impossible since the internal resistance rises so quickly for greater levels of charge. For cell capacities between 95 and 10% of theoretical the model interpolates between the values listed in the table. For capacities less than 10% of theoretical the 10% value is used.

The menus displayed on each of the editing screens allow you to either change the parameter values, switch to another editing screen, or return to the Main Menu shown in Figure 3.8. If you elect to change the parameter values displayed on an editing screen, the program positions the cursor to the first parameter value displayed on the editing screen. You can either enter a new value for the parameter and press <RETURN>, or simply press <RETURN> if you don't want to change the current parameter value. The program then displays the resulting parameter value and moves the cursor down to the next parameter value, and so forth.

If you select Option 2 in the Main Menu, the program displays the battery configuration screen shown in Figure 3.11. The parameter values defining the battery configuration were previously input by selecting option A for the Life-Cycle Model in the Main Menu shown in Figure 2.1. Except for changing the cell connections from series-parallel to parallel-series, the battery configuration can only be changed by returning to the Life-Cycle Model (Option 5 in Figure 3.8) and re-executing that model. When the parallel-series cell connection option is selected in the Detailed Discharge Model the Life-Cycle Model results may no longer provide a reasonable estimate of battery life. This could occur if there had been open circuit failures in the Life-Cycle Model because they

```
*****
*          BATTERY CONFIGURATION          *
*                                          *
*      Number of Modules           8      *
*      Number of Strings           4      *
*      Number of Cells             15     *
*      Hit Return to Continue         *
*****
```

FIGURE 3.11. Screen Display of Battery Configuration
for Detailed Discharge Model

remove the entire string whereas they remove only the effected cell in a parallel-series configuration. To more accurately model a parallel-series arrangement in the Life-Cycle Model set the string length to 1.

The parameter values initially shown for the test conditions, cell characteristics, and cell internal resistances when you execute the software package for the first time are default values set internally in the program by FORTRAN DATA statements. If you select Option 4 in the Main Menu after you have changed the parameter values, the program saves the new values by writing them to a disk file named BAT2A.\$DF. Thereafter, whenever you run the Detailed Discharge Model, regardless of whether you have returned to the DOS operating system, the program first reads the parameter values from the BAT2A.\$DF disk file. You can still change these parameter values if you wish by using the three editing screens shown in Figure 3.10 before running the simulation of the battery's discharge (Option 3 in Figure 3.8).

The Detailed Discharge Model allows the user to specify two post failure resistances (closed and open circuit failures), and the probability of each, for both over- and under-voltage failures. Typically over-discharge failure resistances can range from only slightly higher than normal resistance (not a severe over-discharge) to a resistance greater than an order of magnitude higher (severe over-discharge). While there is not detailed information available on the distribution of the post failure resistances the distribution can be modeled by the user as bi-modal. Since these resistances tend to change over time the user should specify the resistances and probabilities such that the distribution of open and closed circuit failure resistances reflect the final resistance profile at battery failure. If slightly different resistances are used for each type of failure, this will help in identifying type of failure in the table of cells when analyzing the Detailed Discharge Model results.

Recall that you can analyze any discharge cycle from the first cycle to the last cycle before the battery failed in the last simulation run of the Life-Cycle Model. Using the sample output from the last simulation run of the Life-Cycle Model shown in Figure 3.7, any discharge cycle from 1 to 122 can be

analyzed. For the purpose of illustrating the sample output from the Detailed Discharge Model, the 100th discharge cycle was selected, as shown by the first input screen in Figure 3.10.

When you are satisfied with the parameter values displayed on the three editing screens, select Option 3 in the Main Menu shown in Figure 3.8 to run the simulation of the battery's discharge.

Output Screens

Once you have selected to run the simulation, the program will display the flashing message "Calculating Battery Discharge at Time = X.XXX" on the screen. When the simulation is finished, the program will display the output screen shown in Figure 3.12. The results shown on this screen were generated by running the Detailed Discharge Model with the input data sets shown in Figures 3.10 and 3.11. The same information displayed on this screen is also written to a disk file BAT2A.OUT. You can view the contents of this file after you are finished with the program and have returned to the computer operating system.

The output screen first echoes the parameter values you selected for defining the battery configuration, test conditions, and cell characteristics. Next, the output screen displays a table of nine system performance measures calculated at the user-defined time increments during the battery's discharge to summarize the battery's performance. These are:

1. Total battery voltage
2. Average module voltage
3. Battery output power in kilowatts
4. Average voltage of working cells
5. Minimum voltage of working cells
6. Average capacity of working cells in amp-hours
7. Average resistance of all cells in ohms
8. Number of under-voltage electrolyte cell failures
9. Number of over-voltage electrolyte cell failures.

The simulation stops when the user-specified discharge duration is exceeded or when the battery is fully discharged.

Following the simulation output, the program displays the Analysis Menu shown in Figure 3.13. This menu allows you to display graphs of the simulation results (Option 1), display a table showing the status of the cells (Option 2), or return to the Main Menu for the Detailed Discharge Model (Option 3) shown in Figure 3.8.

```
*****
*               ANALYSIS OF RESULTS               *
*                                                     *
*          1. GRAPHICAL Analysis                    *
*          2. TABLE of Cells                       *
*          3. RETURN to Main Menu                   *
*          Enter Selection >1                       *
*****
```

FIGURE 3.13. Input Screen for Analysis of Results
from Detailed Discharge Model

If you select Option 1, the program displays the Graphics Menu shown in Figure 3.14. This menu allows you to display graphs of the following system performance measures versus discharge time:

1. Total battery voltage
2. Average module voltage
3. Battery power.

```
*****
*               GRAPHICAL ANALYSIS                 *
*                                                     *
*          1. Total Voltage vs Time                 *
*          2. Average Module Voltage vs Time        *
*          3. Total Power vs Time                   *
*          4. Return to Previous Menu               *
*          Enter Selection >                        *
*****
```

FIGURE 3.14. Input Screen for Graphics Output
from Detailed Discharge Model

The three graphs resulting from the simulation of the example data set used in Figures 3.10 and 3.11 are shown in Figure 3.15.

If you select Option 2 in Figure 3.13, the program displays a table of the status of the cells at the time the battery failed or exceeded the user-specified discharge duration. Figure 3.16 shows a partial table of the status of the cells when the battery failed after discharging 4.0 hours during the 100th discharge cycle. The cells labeled "bad" represent all failures due to freeze-thaw or wearout that occurred prior to or on the 100th discharge cycle. These failures were passed from the last simulation run of the Life-Cycle Model. The cells labeled "good" that have a failed resistance value (0.2 or 0.07 ohms in this example) for the final cell resistance represent cells that failed during battery discharge in the 100th discharge cycle due to over-discharging.

If you select Option 3 in Figure 3.13, the program returns you to the Main Menu for the Detailed Discharge Model shown in Figure 3.8. At this point, you can change the battery performance data if you wish and rerun the Detailed Discharge Model or return to the Main Menu for the software package shown in Figure 2.1.

3.3 CELL FAILURE DISTRIBUTION MODEL

This section describes the graphical package that can assist the user in understanding the statistical distribution which models the stochastic failure behavior of individual sodium-sulfur cells reaching their end of life due to cell wearout. The Weibull probability distribution was selected for this purpose because of its close correlation with test results on the reliability of sodium-sulfur cells and its flexibility in representing a wide range of failure patterns.

The Cell Failure Distribution Model provides two options for generating and displaying a graph of the Weibull probability density function from a set of three Weibull input parameters: location, scale, and shape. Option A

FIGURE 3.15. Graphics Output from Detailed Discharge Model

```

*****
*                                     *
*                                     *
*                                     *
*                                     *
*      MODULE      STRING      CELL      RELY      DETAILED      *
*      *          *          *          CELL      DISCHARGE      *
*      *          *          *          STATUS    MODEL          *
*      *          *          *          *        FINAL CELL      *
*      *          *          *          *        RESISTANCE     *
*      *          *          *          *        *              *
*      1          1          1          BAD        .70000E-01    *
*      1          1          2          GOOD       .35000E-01    *
*      1          1          3          GOOD       .35000E-01    *
*      1          1          4          BAD        .70000E-01    *
*      1          1          5          GOOD       .35000E-01    *
*      1          1          6          GOOD       .35000E-01    *
*      1          1          7          GOOD       .35000E-01    *
*      1          1          8          GOOD       .35000E-01    *
*      1          1          9          GOOD       .35000E-01    *
*      1          1          10         BAD        .70000E-01    *
*      1          1          11         GOOD       .35000E-01    *
*      1          1          12         GOOD       .35000E-01    *
*      1          1          13         GOOD       .35000E-01    *
*      1          1          14         GOOD       .35000E-01    *
*      1          1          15         GOOD       .35000E-01    *
*      .          .          .          .          .            *
*      .          .          .          .          .            *
*      .          .          .          .          .            *
*      8          3          12         BAD        .70000E-01    *
*      8          3          13         GOOD       .70000E-01    *
*      8          3          14         GOOD       .70000E-01    *
*      8          3          15         GOOD       .20000        *
*      8          4          1          GOOD       .70000E-01    *
*      8          4          2          GOOD       .70000E-01    *
*      8          4          3          GOOD       .70000E-01    *
*      8          4          4          GOOD       .70000E-01    *
*      8          4          5          GOOD       .70000E-01    *
*      8          4          6          GOOD       .70000E-01    *
*      8          4          7          GOOD       .70000E-01    *
*      8          4          8          GOOD       .70000E-01    *
*      8          4          9          GOOD       .70000E-01    *
*      8          4          10         GOOD       .70000E-01    *
*      8          4          11         GOOD       .70000E-01    *
*      8          4          12         GOOD       .70000E-01    *
*      8          4          13         GOOD       .70000E-01    *
*      8          4          14         GOOD       .20000        *
*      8          4          15         GOOD       .20000        *
*****

```

FIGURE 3.16. Partial Table of Cell Status at Time Battery Failed

tabulates 100 equally-spaced points using the Weibull probability density function to generate the display of the density function. The density function is given as follows:

$$f(x) = \frac{\beta}{\theta} \left(\frac{x - \delta}{\theta} \right)^{\beta-1} \exp \left[- \left(\frac{x - \delta}{\theta} \right)^{\beta} \right] \quad x \geq \delta = \text{otherwise}$$

where δ = the location parameter ($\delta \geq 0$ in the Battery Reliability Model)

θ = the scale parameter ($\theta > 0$)

β = the shape parameter ($\beta > 0$).

The mean of the Weibull distribution can be shown to be

$$E(x) = \delta + \theta \Gamma \left(1 + \frac{1}{\beta} \right)$$

where Γ is the Gamma function.

The tabulated data are connected by straight-line segments to generate the display of the Weibull probability density function.

Option B generates a pseudorandom sample of 100 to 1,000 (user-specified) observations from the Weibull distribution. The method is described in Appendix A. These data are grouped into a frequency histogram using 12 equally-spaced histogram cells. The number of observations in each cell is divided by the cell width and total sample size to obtain the height of each histogram cell. The height of each histogram cell is plotted on the ordinate against the midpoint of the cell on the abscissa. The points are then connected by straight line segments to approximate the Weibull probability density function used to model cell lifetimes.

Summaries of the Weibull parameters are given below. More detailed descriptions of the Weibull parameters and of a graphical procedure for estimating the Weibull parameters from test data are given in Appendix A.

Main Menu Option E

If you select Option E in the Main Menu, the program displays the input screen for the Cell Failure Distribution Model labeled "Example Weibull Distribution Model." The screen is shown in Figure 3.17. This screen prompts you to select Option A or B for generating and displaying the Weibull probability density function.

```
*****
*                               *
*      FAILURE DISTRIBUTION MODEL      *
*                               *
*      ENTER                               *
*                               *
*      A - ACTUAL WEIBULL DISTRIBUTION DENSITY *
*            FUNCTION BASED ON USER INPUT WEIBULL *
*            PARAMETERS                               *
*                               *
*      B - DENSITY FUNCTION OF RANDOM CELL FAILURES *
*            BASED ON USER INPUT WEIBULL PARAMETERS *
*                               *
*      ENTER LETTER FOR CHOICE:  A                *
*****
```

FIGURE 3.17. Input Screen for Failure Distribution Model

If you select Option A, the program displays the input screen shown in Figure 3.18. This screen prompts you to enter values for the three input parameters (location, scale, and shape) needed to define a Weibull distribution.

```
*****
*                               *
*      EXAMPLE WEIBULL DISTRIBUTION      *
*                               *
*      FOLLOWING IS THE ACTUAL WEIBULL DISTRIBUTION *
*      DENSITY FUNCTION BASED ON THE SPECIFIED *
*      WEIBULL PARAMETERS.                               *
*                               *
*      ENTER LOCATION PARAMETER:  0.                *
*                               *
*      ENTER SCALE PARAMETER:  1500.                *
*                               *
*      ENTER SHAPE PARAMETER:  1.                  *
*                               *
*      ARE THESE VALUES THAT YOU WANT? (Y/N):  Y    *
*****
```

FIGURE 3.18. Input Screen for Example Weibull Distribution (Option A)

If you select Option B, the program displays the input screen shown in Figure 3.19. This screen prompts you to enter values for the three Weibull input parameters (location, scale, and shape) and the number of pseudorandom observations you want to sample for the Weibull distribution.

```

*****
*           EXAMPLE WEIBULL DISTRIBUTION           *
*
*   THE FOLLOWING DISTRIBUTION SIMULATES            *
*   RANDOM CELL FAILURES BASED ON THE              *
*   SPECIFIED WEIBULL PARAMETERS.                  *
*
*   ENTER LOCATION PARAMETER: 0.                   *
*
*   ENTER SCALE PARAMETER:  1500.                   *
*
*   ENTER SHAPE PARAMETER:  1.                      *
*
*   ENTER NUMBER OF RANDOM CELL FAILURES           *
*   (FROM 100 TO 1000):  1000                      *
*
*   ARE THESE VALUES THAT YOU WANT? (Y/N):  Y     *
*****

```

FIGURE 3.19. Input Screen for Example Weibull Distribution (Option B)

The three Weibull input parameters (location, scale, and shape) are summarized below:

1. The location parameter δ , also known as the threshold parameter, represents the number of battery charge-discharge cycles before which no cell failures can occur due to wearout. It establishes the starting point of the left end of the distribution. A typical value to select for the location parameter in modeling sodium-sulfur cell-aging failures is 0.
2. The scale parameter θ , also known as the characteristic life, controls the amount of skewness, or spread from left to right, in the distribution. The probability of cell failure prior to $(\theta + \delta)$ is equal to 0.632. Thus, for any Weibull distribution, $(\theta + \delta)$ divides the area under the probability density function into 0.632 and 0.368

for all values of the shape parameter β . A typical value to select for the scale parameter θ in modeling sodium-sulfur cell-aging failures is 1,500.

3. The shape parameter β controls the shape of the distribution. Values less than 1 indicate a decreasing cell failure rate as the number of charge-discharge cycles increases, a value of 1 indicates a constant cell failure rate, and values greater than 1 indicate an increasing cell failure rate as the number of charge-discharge cycles increases. As β increases, the mean of the Weibull distribution approaches $(\theta + \delta)$ and the variance approaches zero. The Weibull distribution with $\beta = 1$ represents the exponential distribution and with $\beta \geq 3.0$ approximates the normal distribution. A typical value to select for the shape parameter in modeling sodium-sulfur cell-aging failures is 1.0.

When you are satisfied with the values you have entered for the Weibull input parameters, enter Y or y for "yes" when queried on whether the input values are correct, and press <RETURN> to execute the Cell Failure Distribution Model. After a delay of several seconds, a graph showing the Weibull density function will be displayed on the computer screen. An example of the graph generated by selecting Option A is shown in Figure 3.20. This graph corresponds to the input values selected for the location, scale, and shape parameters in the input screen shown in Figure 3.18.

After the Weibull graph is displayed, you will be asked if you want to display another sample Weibull density function. This option gives you the ability to perform rapid sensitivity studies on the Weibull failure distribution by experimenting with different parameter values and observing the effect on the resulting graphs displays of the Weibull density function. When you no longer want to look at sample Weibull density functions, enter N or n for "no" when queried on whether you want to repeat the process, and press <RETURN>. The program will then return you to RELY's Main Menu.

FIGURE 3.20. Weibull Probability Density Function Illustrated by Cell Failure Distribution Model (Option A)

REFERENCES

- Microsoft, Inc. 1983. Documentation for the Disk Operating System Version 2.0. Microsoft, Inc., Bellevue, Washington.
- Microcompatibles. 1983. GRAFMATIC Documentation of GRAFMATIC Graphics Library. Microcompatibles, Silver Spring, Maryland.
- Kapur, K. C., and L. R. Lamberson. 1977. Reliability in Engineering Design. John Wiley and Sons, Inc., New York.
- King, J. R. 1971. Probability Charts for Decision Making. Industrial Press, Inc., New York.
- Microsoft, Inc. 1985. Documentation for Microsoft FORTRAN Compiler Version 3.31. Microsoft, Inc., Bellevue, Washington.
- U.S. Department of Energy, (DOE). 1977. Phenomenological Cell Modeling: A Tool for Planning and Analyzing Battery Testing at the BEST Facility. DOE Report 60025-1, U.S. Department of Energy, Washington, D.C.

APPENDIX A

THE WEIBULL DISTRIBUTION PARAMETERS

APPENDIX A

THE WEIBULL DISTRIBUTION PARAMETERS

The purpose of this appendix is to provide the user with a brief introduction to the Weibull distribution and to demonstrate how Weibull parameters can be estimated from test data. Wearout failures in the RELY software package are modeled using this statistical distribution. The Weibull distribution is often used in reliability analyses to model natural failures of devices.

The three parameters of the Weibull distribution are the location parameter δ , the scale parameter θ , and the shape parameter β . The location parameter is simply the minimum possible life. A typical value used in battery and electrical system analysis is zero. The only effect δ has on the Weibull distribution is the shifting of the distribution along the x-axis.

Due to the nature of the Weibull distribution, 63.2% of all failures occur between the minimum life value δ and the scale parameter value θ . This is true regardless of the parameter values. The average life is linearly related to θ hence the term scale parameter.

The shape parameter β determines the shape of the distribution. For large values of β , the shape of the distribution resembles that of the normal distribution. Furthermore, the value of β determines whether the rate of failure decreases, increases, or remains constant over time. If $\beta < 1$, the failure rate decreases over time, while if $\beta > 1$, the failure rate increases. If $\beta = 1$, the failure rate is constant over time, as with the exponential distribution. Figure A.1 displays example Weibull density functions. For all three plots, $\delta = 0$ and $\theta = 500$. Beta is varied from 0.5 to 1.0 to 4.0. The differences caused by varying the β values point out both an advantage and a warning in using the Weibull distribution. It is an extremely flexible distribution and thus it is widely used in reliability applications. However, because of its flexibility, the estimation of parameters must be as accurate as possible.

FIGURE A.1. Weibull Density Functions: $\delta = 0$, $\theta = 500$

This section describes how to graphically estimate Weibull distribution parameters from bench-test data. The graphical method is chosen for its simplicity and ease of application. More precise estimates can be developed using statistical estimation procedures if the user desires. Graphical estimation is done on Weibull probability paper. A blank sheet of this paper is shown in Figure A.2. The cumulative probability of failure is plotted against the observed failure cycles. The horizontal and vertical scales of Weibull probability paper are not linear, but are transformed such that if perfectly Weibull-distributed data are plotted, a straight line results. Thus, graphical techniques can be used to: 1) determine if the data can reasonably be represented by a Weibull distribution, and 2) estimate the parameters of a Weibull distribution.

An example will be used to illustrate the graphical techniques. It is assumed in the example that the minimum possible life θ is zero, which is the

FIGURE A.2. Weibull Probability Paper

typical value for sodium-sulfur cell analysis. If, for some reason, the minimum possible life is not zero, a simple transformation to the original data can be made. For guidance in handling this situation, and for greater technical detail, the reader should consult Kapur and Lamberson (1977) and/or King (1971).

Assume that a sample of $n = 5$ cells are charged and discharged until failure. The cells fail on cycles 67, 120, 130, 220, and 290. King (1971) recommends an absolute minimum of five data points from which to estimate parameters for practical cases. Once the failure cycles are obtained, they are arranged in ascending order (67, 120, 130, 220, 290) and a rank (denoted by j) is associated with each failure cycle. In this case, the rank of $j = 1$ is assigned to 67, $j = 2$ to 120, and so on until $j = 5$ is associated with 290. The assignment of ranks is essential for the determination of parameters by this method.

The ranks ($j = 1, 2, 3, 4, 5$) are used to compute the median rank value, which is an approximation to the fraction of cells failing prior to the j^{th} observation. The formula for the median rank value is $(j - 0.3)/(n + 0.4)$, where j is the rank and n is the sample size (5 in this case). For example, for $j = 2$, which corresponds to the second lowest failure cycle (120), the median rank value is $(2 - 0.3)/(5 + 0.4) = 0.314$. Thus, it is estimated that 31% of all cells would fail prior to cycle 120. The observations, their ranks, and their median rank values are shown in Table A.1.

Once the median rank values have been calculated, they are plotted against the corresponding failure cycles on Weibull probability paper as in Figure A.3. The line of best fit is then drawn through these points. The shape parameter β is estimated as the slope of this line. This results in an estimate of $\beta = 1.6$ because the line "rises" 1.6 inches for every 1 inch it "runs." The scale parameter θ is found by projecting a horizontal line from the 63.2% point on the vertical axis to the fitted line, and then projecting this line to the horizontal axis. The point at which this line intersects the axis is the

TABLE A.1. Example Failure Cycles, Ranks, and Median Rank Values Used to Estimate Weibull Parameters

<u>Failure Cycle</u>	<u>Rank (j)</u>	<u>Median Rank Value</u>
67	1	0.129
120	2	0.314
130	3	0.500
220	4	0.685
290	5	0.870

FIGURE A.3. Graphical Estimation of Weibull Parameters

estimate of theta. In this case, $\theta = 190$ cycles. It is assumed that the location parameter delta is zero, and the good fit of the straight line confirms this assumption.

If the bench-test data do not seem to follow a reasonably straight line when plotted on Weibull probability paper, it is best to consult the references. It may still be possible to use the Weibull distribution to model failures, perhaps with a non-zero location parameter. The Weibull distribution was chosen to model wearout failures in RELY because of its wide applicability to natural failures of devices. The references should also be consulted if more detailed statistical information is needed.

A step-by-step summary of graphical estimation of Weibull parameters is given below.

1. Order the failure cycles (n = sample size) in ascending order.
2. Assign ranks (values of j) to each of the n failure cycles. For the earliest failure, $j = 1$. For the latest, $j = n$.
3. Compute the median rank value for each observation, using $(j - 0.3)/(n + 0.4)$.
4. Plot the median rank values expressed in percent (vertical axis) versus the failure cycles (horizontal axis) on Weibull probability paper.
5. Fit the "best" line to the points, either visually or by least squares regression.
6. If the line fits the data reasonably well, estimate the parameters:
 β = slope of the fitted line and θ = cycle which corresponds to a cumulative failure probability of 63.2%
7. If the data do not seem to follow a reasonably straight line, review the data for accuracy and consult the references.

After estimating values for the Weibull parameters, they can be input to the Cell Failure Distribution Model and other models of the software package. If test data are not available, preliminary estimates of the parameters are necessary.

APPENDIX B

MODELING APPROACH

APPENDIX B

MODELING APPROACH

The software package stored on the diskette in the jacket of this report consists of the following three files:

1. Disk Operating System (DOS) batch file BATTERY.BAT
2. Fortran-executable program file RELY.EXE
3. Fortran-executable program file BAT2A.EXE.

Figure B.1 shows a block diagram of the overall structure of the DOS batch file BATTERY.BAT. This file executes two Fortran-executable programs, RELY and BAT2A, to run the three simulation models: the Life-Cycle Model, the Detailed Discharge Model, and the Cell Failure Distribution Model.

RELY receives input from the user which defines the battery configuration and performance requirements, failure distribution parameters, and freeze-thaw conditions. The primary purpose of RELY is to estimate the expected battery life (in cycles). No detailed voltage, resistance, or power characteristics are considered in RELY. Cells fail only from freeze-thaw conditions or normal wearout conditions. An excellent application of RELY is to explore various battery geometries to determine their expected useful lives. From these results, the designer can begin to place requirements on the configuration of the battery and the reliability of a given cell.

Whereas RELY estimates the useful lifetime (in cycles) of the battery without considering the detailed conditions of each charge-discharge cycle, BAT2A simulates a particular cycle of the battery's life. Information about working and failed cells and the types of failures are passed from RELY to BAT2A. In addition, BAT2A solicits input from the user about certain cell and battery characteristics, such as cell capacity, voltage, and resistance. BAT2A simulates the user-specified discharge cycle of the battery for a specified test period. When the battery can no longer maintain the current required, the test ends. Graphs can be displayed showing total voltage, average module voltage, and battery power as functions of discharge time.

FIGURE B.1. Block Diagram of DOS Batch File BATTERY.BAT

With BAT2A, the user can obtain detailed information about the battery's performance for any desired cycle. Theoretically, it would be possible to have one model simulate battery life and perform detailed calculations for each cycle. However, this approach would result in extremely long execution times. Since it is desirable to be able to run the simulation on an IBM-PC or compatible microcomputer, the two-model approach is an excellent compromise. RELY can be used to determine several "good" configurations, and BAT2A can be employed to analyze each configuration in detail.

Program RELY is executed first. The block diagram of program RELY is shown in Figure B.2. The principal functions performed by RELY are to:

1. Display the Main Menu to the user
2. Display the input screens to the Life-Cycle model and the Cell Failure Distribution model
3. Call the major subroutine SIMULAT, as indicated by the dashed lines shown in Figure B.1, to simulate the Life-Cycle model
4. Execute the Cell Failure Distribution model.

The block diagram of subroutine SIMULAT is shown in Figure B.3. Subroutine SIMULAT performs multiple, independent Monte Carlo simulations to estimate the expected battery cycle life. Cell failures due to freeze-thaw and wearout are modeled as randomly occurring phenomena based upon the uniform and Weibull distributions, respectively. Cell failures are modeled as producing a user-specified percentage of open and/or closed circuit post-failure resistance. The simulation continues until the number of working cells, strings, and modules in the user-specified battery configuration falls below minimum user-specified failure criteria, i.e., the battery fails. The stochastic cell failures and battery cycle life predicted in the last simulation run of the Life-Cycle Model are then written to a disk file BAT2A.TMP for subsequent use by program BAT2A when menu Option D is selected.

The manner in which random numbers are used by subroutine SIMULAT in the Life-Cycle simulation is explained below. Cells are "frozen" and then "thawed" at regular frequencies, as specified by the user. In addition, the user enters the probability of a cell failing during a freeze-thaw cycle. Suppose this

FIGURE B.2. Block Diagram of Program RELY

FIGURE B.2. (contd)

FIGURE B.2. (contd)

probability is 0.05. If the current cycle being simulated is a freeze-thaw cycle, a uniformly distributed number between 0 and 1 is generated by a call to subroutine RANF. If this random number is less than or equal to the probability of failure during a freeze-thaw, the cell fails. For example, suppose the random number generated is 0.769. Since $0.769 > 0.05$, the cell survives the freeze-thaw. If, however, the random number is 0.0128, the cell fails.

Wearout failures are modeled differently than freeze-thaw failures. The cycle during which a cell wears out is assumed to be distributed as a Weibull random variable. The Weibull distribution is often used in reliability engineering to model failures. With changes in the parameters (discussed in Appendix A), it takes on various characteristics. This discussion is provided as a brief synopsis of how Weibull random numbers are generated.

Every probability distribution is associated with a particular cumulative distribution. The cumulative distribution gives the probability (between 0 and 1) that a generated random number, say X , will be less than or equal to a specified value, say A . In general, the cumulative distribution can be written as a function of X . This function, by its definition, always results in a value between 0 and 1. In this sense, X is the "input," and U , the number between 0

FIGURE B.3. Block Diagram of Subroutine SIMULAT

and 1, is the "output." When generating random numbers, the process is reversed, such that U is the input and X is the output. Mathematically, this is known as the inverse transform method of generating random numbers from a particular distribution.

Figure B.4 graphically displays how this procedure is carried out. The graph is the cumulative Weibull distribution with parameters: location $\delta = 0$, scale $\theta = 500$, and shape $\beta = 2$. First, a uniform number between 0 and 1 is generated by a call to subroutine RANF. This number is labeled U on the graph, and equal to 0.60 in Figure B.4. Then, in a graphical sense, the point on the horizontal axis that corresponds with U is determined. This value is approximately 480 in Figure B.4. This number is a random sample from a Weibull distribution with the specified parameters. The FORTRAN subroutine FAILURE generates these random numbers using mathematical formulas underlying the

FIGURE B.4. Generation of Weibull Random Numbers for Location $\delta = 0$, Scale $\theta = 500$, and Shape $\beta = 2$

graph. The random numbers generated are the cycles during which the cells of the battery will wear out, if they do not fail during a prior freeze-thaw. Thus, in this case, the particular cell will wear out during cycle 480.

Program RELY includes a block of code comprising the Cell Failure Distribution Model. This model gives the user the option to become acquainted with the general shape of the Weibull density function before running the Life-Cycle Model. The Cell Failure Distribution Model allows the user two options to generate and display a graph of the Weibull probability density function on the computer screen. With each option, the user inputs values for the location, scale, and shape parameters of the Weibull distribution. Option A tabulates 100 equally-spaced points using the Weibull probability density function to generate the plot data. Option B calls subroutine FAILURE from 100 to 1,000 times (user-input) to generate a pseudorandom sample of observations from the Weibull distribution to generate the plot data. The plot data are then used to display a graph of the corresponding Weibull probability density function.

By changing the input values for the Weibull parameters, the user can immediately observe the effect on the shape of the Weibull density function. This can assist the user in determining the adequacy of Weibull parameter estimates obtained from bench-test data to model cell wearout failures before running the Life-Cycle Model.

The selection of menu Options D or F in program RELY terminates execution of RELY and returns control to the DOS batch file BATTERY.BAT. As shown in Figure B.1, the batch file checks to determine which of the two options was selected to terminate RELY. If Option F was selected, the batch file exits to the operating system. If Option D was selected, the batch file executes program BAT2A.

Program BAT2A simulates the Detailed Discharge Model. The block diagram for program BAT2A is shown in Figure B.5. Program BAT2A estimates battery discharge performance based on constant current discharge in terms of its voltage and power. The calculations are based on a current-voltage depth-of-discharge model of sodium-sulfur cell performance for a user-specified discharge cycle. The model accounts for the impact that the cumulative number and types of failed cells will have upon battery performance in the user-specified discharge

FIGURE B.5. Block Diagram of Program BAT2A

FIGURE B.5. (contd)

FIGURE B.5. (contd)

FIGURE B.5. (contd)

FIGURE B.5. (contd)

FIGURE B.5. (contd)

FIGURE B.5. (contd)

FIGURE B.5. (contd)

cycle. The cell failure information is obtained from the disk file BAT2A.TMP that was generated from the last simulation run performed by the Life-Cycle Model in subroutine SIMULAT. Program BAT2A provides the user with the option of adding switches within the battery configuration to minimize the impact of the failed cells.

Following execution of program BAT2A, the batch file re-executes program RELY. This displays the main menu again and offers the user the option to

continue with more simulations of the three models or to select option F to terminate program RELY. If option F is selected, the batch file terminates and exits to the operating system.

The smaller, supporting subroutines called by programs RELY and BAT2A and subroutine SIMULAT are summarized in Table B.1. Six of these subroutines are used to enhance the screen displays, such as causing the computer to beep, causing the display to flash, reversing the foreground/background color schemes to highlight the screen, clearing the screen, erasing parts of the screen, and positioning the cursor. These subroutines are: BEEPER, BLINK, CLRSCN, MOVE, RESTORE, and REVERSE. The other nineteen subroutines listed in Table B.1 are used to initialize cell arrays, generate Weibull pseudorandom numbers, and perform Fortran I/O functions. Table B.2 summarizes the subroutines from the GRAFMATIC graphics library that are called by programs RELY and BAT2A to produce two-dimensional plots on the computer screen.

TABLE B.1. Summary of Supporting Subroutines

<u>Subroutine</u>	<u>Description</u>	<u>Calling Routine</u>
BEEPER	Issues a beep when the simulation of the Detailed Discharge Model is done.	BAT2A
BLINK	Uses the extended screen and keyboard control features described in Chapter 2 of the DOS Technical Reference (Microsoft, Inc. 1983) to cause the screen display to blink.	BAT2A
CLRSCN	Uses the extended screen and keyboard control features to clear the screen.	RELY, BAT2A
FAILURE	Generates a Weibull-distributed pseudorandom number used to predict the battery charge-discharge cycle in which a cell will fail due to wearout.	RELY, SIMULAT
GAMMA	Calculates the Gamma function of $(1. + X)$ for $0 \leq x \leq 1$. This function subroutine is used to calculate the theoretical mean of the Weibull distribution.	RELY
INTEGER	Checks whether the user has input an integer value for parameters that require an integer input.	RELY
GRPHMENU	Displays the graphical analysis menu in the Detailed Discharge Model.	BAT2A
INITIAL	Numbers the cells consecutively over all strings and modules and sets a status flag using the four-dimensional cell array CELLDAT to indicate that the cell is working at the beginning of the Life-Cycle Model simulation.	RELY
MAINMENU	Displays the main menu for the Detailed Discharge Model	BAT2A
MOVE	Uses the extended screen and keyboard control features to move the cursor to any screen position specified by its row and column screen coordinates.	BAT2A
OUTPG1	Echoes input data to the Life-Cycle Model back to the screen or to a user-specified disk file.	SIMULAT

TABLE B.1. (contd)

<u>Subroutine</u>	<u>Description</u>	<u>Calling Routine</u>
PERCENT	Checks whether the user has input a decimal fraction for the cell freeze-thaw failure rate.	
PG2HEAD	Writes the page headings for the second page of simulation output from the Life-Cycle Model to the screen or a user-specified disk file.	SIMULAT
PG3HEAD	Writes the page headings for the third page of simulation output from the Life-Cycle Model to the screen or a user-specified disk file.	SIMULAT
PG3LN1	Writes the final lines of simulation output from the Life-Cycle Model showing the failure frequency distribution of cell freeze-thaw and wearout failures by cycle ranges.	SIMULAT
RANF	Returns a pseudonym number uniformly distributed between 0 and 1.	RELY, SIMULAT, BAT2A
RANGE	Checks whether the user has input a reasonable value, i.e., between 0 and an acceptable maximum value. If reasonable data are not input, subroutine RANGE prompts the user for a new input value and continues to do so until the user inputs a value that is valid within the operational limits of the program.	RELY
RESCHCK	Called when a cell fails. Subroutine RESCHCK sets the corresponding entry of the CELLDAT array equal to either plus or minus the current cycle, depending on whether the failed cell has an open or closed circuit failure mode. In addition, if the cell has an open circuit failure mode, subroutine RESCHCK sets a flag for the current string containing the cell to indicate that the string has failed.	SIMULAT
RESTORE	Uses the extended screen and keyboard control features to restore the normal light foreground and dark background color schemes used in the screen displays.	RELY, BAT2A

TABLE B.1. (contd)

<u>Subroutine</u>	<u>Description</u>	<u>Calling Routine</u>
REVERSE	Uses the extended screen and keyboard control features to reverse the normal foreground/background color scheme used in the screen displays from a dark background and light foreground (displayed letters) to a light background and dark foreground to highlight the screen display.	RELY, BAT2A
RSLTMENU	Displays a menu giving the user the choice between graphical analysis, listing a table of cells, and returning to the main menu in the Detailed Discharge Model.	BAT2A
SCRNMENU	Displays the screen selection menu below the main menu and prompts the user to select an input screen in the Detailed Discharge Model.	BAT2A
UPCAS	Translates a lower case input consisting of one character to the equivalent upper case character.	RELY
XSCAL	Scales X-axis array for plotting Weibull probability density function.	RELY
YSCAL	Scales Y-axis array for plotting Weibull probability density function.	BAT2A

TABLE B.2. Summary of GRAFMATIC Subroutines Called by Programs RELY and BAT2A

<u>Subroutine</u>	<u>Description</u>	<u>Calling Routine</u>
QCMOV	Moves cursor to the specified column and row on the screen.	RELY
QPTABL	Provides a two-dimensional plot on the screen of an X-Y table of data. Subroutine QPTABL scales the graph, draws the axes, and plots a series of straight-line segments connecting the tabular points.	RELY, BAT2A
QPTXT	Writes text in the specified color on the screen graph starting at the specified column and row.	RELY, BAT2A
QSETUP	Defines the color and type (solid or dashed) used to plot lines and the color and symbol used to mark data on tabular plots.	RELY, BAT2A
QSMODE	Clears the screen and sets the resolution (number of columns and rows) in effect on the screen graphics.	RELY, BAT2A

APPENDIX C

SOURCE LISTINGS


```

C PROGRAM RELY
C *****
C PURPOSE: estimates life of battery
C
C LIMITATIONS AND PREREQUISITES:
C
C LOGICAL NAMES AND FILES USED:
C     2 = logical unit for output data file
C
C ROUTINES USED:
C     CLRSCN, REVERSE, RESTORE, RANGE, INTEGER, FAILURE
C     PERCNT, UPCAS, SIMULAT, GAMMA, XSCAL, YSCAL
C     QSMODE, QSETUP, QPTABL, QPTXT, QCMOV
C *****
C DEVELOPMENT INFORMATION:
C     CREATED BY : JANIS LITTLEFIELD ON : 1985
C               PHIL COOPER
C               HARLAN HUBER
C               JOHN DOVEY
C               AT : Battelle Pacific Northwest Laboratories
C                   Richland, Washington 99352
C     MACHINE/OPERATING SYSTEM: PC DOS V2.10
C     COMPILER : MICROSOFT FORTRAN77 V3.30
C     COMPILER SWITCHES : Default
C
C MODIFICATION HISTORY: none
C     MODIFIED BY : ON :
C     REASON FOR MODIFICATION:
C     DESCRIPTION OF MODIFICATION:
C
C     CONSTANTS (PARAMETER STATEMENTS):
C     PARAMETER (NSAMPL=1000, NCELLS=12)
C
C     COMMON BLOCKS:
C     IMPLICIT CHARACTER*1 (C)
C $INCLUDE: 'PARM.INC'
C $INCLUDE: 'RELY.INC'
C $INCLUDE: 'WEIBUL.INC'
C
C     PARM.INC -- size of battery
C     RELY.INC -- data info for RELY
C     WEIBUL.INC -- Weibull distribution parameters
C
C     VARIABLES:
C     CHARACTER*20 CHAR, XLABEL, YLABEL
C     CHARACTER*29 XLAB1
C     CHARACTER*38 XLAB2
C     CHARACTER*1 CHOICE
C     CHARACTER Ans*10
C     INTEGER COUNTER, N, R, TOPS, RUN, J, CYCLIF, IPOWER
C     INTEGER*2 NDOTS, LKOLOR, ISYMBL, KLRSYM, ICOL, IROW
C     INTEGER*2 MODE, IORG, NPT, ITYPE, NCHAR, KOLOR
C     REAL XARRAY(NSAMPL), YARRAY(NSAMPL), XX(NSAMPL), YY(NSAMPL)
C     REAL BAD, ROUND, R1, R2, XPSCALE, YPSCALE
C     LOGICAL SECTA, SECTB, SECTC, SECTD, SECTE
C
C     VARIABLES USED IN THE WEIBULL EXAMPLE ONLY:
C     NDOTS, LKOLOR, ISYMBL, KLRSYM
C     MODE, IORG, NPT, ITYPE, NCHAR, KOLOR, R
C     ICOL, IROW, ICOUNT, XLABEL, XLEN
C     XARRAY(1000), YARRAY(1000), XX(1000), YY(1000), BAD
C
C     VARIABLES SET BY THE USER:
C     SHAPE, SCALE, PREWAY
C     CELLREQ, STREQ, MODREQ
C     RUN, COUNTER, FDATA(4,100), LOCATE, N
C     RESIST
C
C     VARIABLES REPRESENTING THE BATTERY CONFIGURATION:
C     CELLOAT(10,10,20,1)

```

```

C MODULE, STRING, CELLS
C *****
C DATA STATEMENTS:
C DATA SECTA, SECTB, SECTC, SECTD, SECTE /5*.FALSE./
C
C *** Get current screen mode -- reset before program stops
C Call QRMODE (ModeBeg, ModeCol)
C *** Check to see if Detailed Discharge Model has just been run
C Open (3,file= 'STOP1.TMP',IOStat=IOChk)
C IF (IOChk .eq. 0) then
C     Close (3)
C     go to 500
C endif
C
C *** Write title screen
C
C CALL CLRSCN
C WRITE (*,1)'
C CALL REVERSE
C 1 FORMAT (1X,A55)
C WRITE (*,5)
C 5 FORMAT ( / )
C WRITE (*,1)'
C WRITE (*,1)' *****
C WRITE (*,1)'
C WRITE (*,1)' RELIABILITY MODELING SYSTEM FOR ANALYSIS OF
C WRITE (*,1)' SODIUM-SULFUR BATTERY CONFIGURATIONS
C WRITE (*,1)'
C WRITE (*,1)' PREPARED BY PNL FOR THE OFFICE OF ENERGY
C WRITE (*,1)' STORAGE AND DISTRIBUTION.
C WRITE (*,1)'
C WRITE (*,1)' UNITED STATES DEPARTMENT OF ENERGY
C WRITE (*,1)' PROJECT MONITOR : J.E. QUINN
C WRITE (*,1)'
C WRITE (*,1)' AUTHORS: JANIS LITTLEFIELD
C WRITE (*,1)' PHIL COOPER
C WRITE (*,1)' HARLAN HUBER
C WRITE (*,1)' JOHN DOVEY
C WRITE (*,1)' *****
C WRITE (*,1)'
C CALL RESTORE
C 2 FORMAT (1X,A55)
C WRITE (*,2)'
C WRITE (*,2)' PROGRAM ESTIMATES SODIUM-SULFUR BATTERY LIFE AND
C WRITE (*,2)' PERFORMANCE GIVEN BATTERY CONFIGURATION AND RELIA-
C WRITE (*,2)' BILITY DATA.
C WRITE (*,2)'
C WRITE (*,2)' TO BEGIN - HIT RETURN'
C READ (*,3) C
C 3 FORMAT (A1)
C 500 CONTINUE
C MODE = 2
C CALL QSMODE (MODE)
C Call ClrScn
C WRITE (*,1)'
C CALL REVERSE
C WRITE (*,5)
C WRITE (*,1)'
C WRITE (*,1)'
C WRITE (*,1)' MAIN MENU
C WRITE (*,1)' -----
C WRITE (*,1)' ENTER
C WRITE (*,1)'-----
C WRITE (*,1)' A - INPUT BATTERY TEST CONFIGURATION, CELL
C WRITE (*,1)' CHARACTERISTICS AND PERFORMANCE REQUIREMENTS
C WRITE (*,1)'
C WRITE (*,1)' B - INPUT FAILURE RATES
C WRITE (*,1)'

```

```

WRITE (*,1)' C - RUN LIFE-CYCLE MODEL
WRITE (*,1)'
WRITE (*,1)' D - RUN DETAILED DISCHARGE MODEL
WRITE (*,1)'
WRITE (*,1)' E - DESCRIPTION OF FAILURE DISTRIBUTION MODEL
WRITE (*,1)'
WRITE (*,1)' F - EXIT PROGRAM
WRITE (*,1)'
CALL RESTORE
WRITE (*,2)' '
WRITE (*,2)' '
1001 WRITE (*,1)'(A)' ENTER LETTER FOR CHOICE: '
READ (*,1)'(BN,A1)',ERR=1001) CHOICE
IF(CHOICE.EQ.'A' .OR. CHOICE .EQ. 'a')GOTO 200
IF(CHOICE.EQ.'B' .OR. CHOICE .EQ. 'b')GOTO 300
IF(CHOICE.EQ.'C' .OR. CHOICE .EQ. 'c')GOTO 400
IF(CHOICE.EQ.'D' .OR. CHOICE .EQ. 'd')GOTO 800
IF(CHOICE.EQ.'E' .OR. CHOICE .EQ. 'e')GOTO 100
IF(CHOICE.EQ.'F' .OR. CHOICE .EQ. 'f')GOTO 600
GOTO 1001
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCC MENU ITEM A: CCCC
CCCC input battery test configuration, cell CCCC
CCCC characteristics and performance requirements CCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
200 CONTINUE
SECTB = .TRUE.
CALL CLRSCN
WRITE(*,1)'
CALL REVERSE
WRITE(*,5)
WRITE (*,1)'
WRITE(*,1)'
WRITE(*,1)'
WRITE(*,1)'
BATTERY TEST CONFIGURATION
-----
WRITE(*,1)' THE BATTERY CONFIGURATION IS ENTERED BY
WRITE(*,1)' SPECIFYING THE NUMBER OF CELLS IN SERIES PER
WRITE(*,1)' STRING, THE NUMBER OF STRINGS IN PARALLEL PER
WRITE(*,1)' MODULE, AND THE NUMBER OF MODULES IN SERIES.
WRITE(*,1)'
CALL RESTORE
WRITE(*,1)' '
1007 WRITE(*,1)'(A)' ENTER NUMBER OF CELLS PER STRING: '
READ(*,1)'(A10)',ERR=1007) Ans
IF (Ans .EQ. ' ') Go To 1007
Read (Ans,2002,Err = 1007) Temp
CALL RANGE (Temp,Real(PLNSIZ),1.)
Cells = Temp
WRITE(*,1)' '
1008 WRITE(*,1)'(A)' ENTER NUMBER OF STRINGS IN PARALLEL: '
READ(*,1)'(A10)',ERR=1008) Ans
IF (Ans .EQ. ' ') Go To 1008
Read (Ans,2002,Err = 1008) Temp
CALL RANGE (Temp,Real(COLSIZ),1.)
String = Temp
WRITE(*,1)' '
1009 WRITE(*,1)'(A)' ENTER NUMBER OF MODULES IN SERIES: '
READ(*,1)'(A10)',ERR=1009) Ans
IF (Ans .EQ. ' ') Go To 1009
Read (Ans,2002,Err = 1009) Temp
CALL RANGE(Temp,Real(ROWSIZ),1.)
Module = Temp
WRITE(*,1)' '
WRITE(*,1)' '
1010 WRITE(*,1)'(A)' ARE THESE VALUES CORRECT? (Y/N): '
READ(*,1)'(A1)',ERR=1010) C
IF (.NOT.(C .EQ. 'Y' .OR. C .EQ. 'y' .OR.
1 C .EQ. 'N' .OR. C .EQ. 'n')) GO TO 1010
IF(C.EQ.'N'.OR.C.EQ.'n')GOTO 200

```

```

201 CONTINUE
CALL CLRSCN
WRITE(*,1)'
CALL REVERSE
WRITE(*,5)
WRITE(*,1)'
WRITE(*,1)'
WRITE(*,1)'
PERFORMANCE REQUIREMENTS
-----
WRITE(*,1)' BATTERY PERFORMANCE IS SPECIFIED BY THE USER IN
WRITE(*,1)' TERMS OF STRING, MODULE AND BATTERY REQUIREMENTS.
WRITE(*,1)' THESE REQUIREMENTS INDICATE THE NUMBER OF SUB-UNITS
WRITE(*,1)' THAT MUST BE EFFECTIVELY OPERATING FOR THE LARGER
WRITE(*,1)' UNIT TO REMAIN IN OPERATION. FOR EXAMPLE, IF CELL
WRITE(*,1)' FAILURES REDUCE THE NUMBER OF OPERATING CELLS BELOW
WRITE(*,1)' THE STRING REQUIREMENT THE STRING IS NO LONGER
WRITE(*,1)' OPERABLE.
WRITE(*,1)' '
CALL RESTORE
C
WRITE (*,1)' '
1011 WRITE(*,1)'(A)' ENTER THE MINIMUM NUMBER OF GOOD CELLS '
WRITE(*,1)'(A)' REQUIRED PER OPERATING STRING: '
READ(*,1)'(A10)',ERR=1011) Ans
IF (Ans .EQ. ' ') Go To 1011
Read (Ans,2002,Err = 1011) Temp
CALL RANGE (Temp,Real(CELLS),1.)
CellReq = Temp
WRITE(*,1)' '
1012 WRITE(*,1)'(A)' ENTER THE MINIMUM NUMBER OF GOOD STRINGS
WRITE(*,1)'(A)' REQUIRED PER OPERATING MODULE: '
READ(*,1)'(A10)',ERR=1012) Ans
IF (Ans .EQ. ' ') Go To 1012
Read (Ans,2002,Err = 1012) Temp
CALL RANGE (Temp,Real(STRING),1.)
StrgReq = Temp
WRITE(*,1)' '
1013 WRITE(*,1)'(A)' ENTER THE MINIMUM NUMBER OF GOOD MODULES
WRITE(*,1)'(A)' REQUIRED FOR MINIMUM BATTERY CAPACITY: '
READ(*,1)'(A10)',ERR=1013) Ans
IF (Ans .EQ. ' ') Go To 1013
Read (Ans,2002,Err = 1013) Temp
CALL RANGE (Temp,Real(MODULE),1.)
ModReq = Temp
WRITE(*,1)' '
1014 WRITE(*,1)'(A)' ARE THESE VALUES CORRECT? (Y/N): '
READ(*,1)'(BN,A1)',ERR=1014) C
IF (.NOT.(C .EQ. 'Y' .OR. C .EQ. 'y' .OR.
1 C .EQ. 'N' .OR. C .EQ. 'n')) GO TO 1014
IF (C.EQ.'N'.OR.C.EQ.'n') GO TO 201
GO TO 500
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCC MENU ITEM B: CCCC
CCCC input failure data CCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
300 CONTINUE
SECTC = .TRUE.
CALL CLRSCN
WRITE(*,1)'
CALL REVERSE
WRITE(*,5)
WRITE (*,1)'
WRITE(*,1)'
WRITE(*,1)'
FAILURE DATA
-----
WRITE(*,1)' FAILURE DATA REQUIRED INCLUDES INFORMATION
WRITE(*,1)' ON TYPES OF FAILURES, FAILURE RATES, AND POST-
WRITE(*,1)' FAILURE RESISTANCE. THIS PROGRAM HAS THE
WRITE(*,1)' CAPABILITY OF MODELING 2 TYPES OF INDEPENDENT
WRITE(*,1)' FAILURES:

```

```

WRITE(*,1)
WRITE(*,1)      * FREEZE-THAW FAILURES
WRITE(*,1)      * FAILURE DUE TO WEAROUT
WRITE(*,1)
WRITE(*,1) FOR EACH TYPE OF FAILURE, THE POST-FAILURE
WRITE(*,1) RESISTANCES ARE SPECIFIED AS A PERCENTAGE OF :
WRITE(*,1)
WRITE(*,1)      * OPEN - CIRCUIT FAILURES
WRITE(*,1)      * CLOSED-CIRCUIT FAILURES
WRITE(*,1)
CALL RESTORE
WRITE(*,2)
WRITE(*,2)
WRITE(*,2) TO CONTINUE - HIT RETURN '
READ(*,*)
301 CONTINUE
CALL CLRSCN
WRITE(*,1)
CALL REVERSE
WRITE(*,5)
WRITE(*,1)
WRITE(*,1)      FREEZE-THAW FAILURES
WRITE(*,1)
WRITE(*,1)
WRITE(*,1)
WRITE(*,1) FREEZE-THAW FAILURES OCCUR WHEN THE BATTERY IS
WRITE(*,1) ALLOWED TO COOL AND IS THEN REHEATED. A CERTAIN
WRITE(*,1) PERCENTAGE OF THE CELL POPULATION CAN BE EXPECTED
WRITE(*,1) TO FAIL DURING EACH FREEZE-THAW.
WRITE(*,1)
WRITE(*,1)
CALL RESTORE
WRITE(*,1)
WRITE(*,1)
1018 WRITE(*,1) 'ENTER NO. OF CYCLES BETWEEN FREEZE-THAWS',
1 (XXXXX):
READ(*,1) (A10),ERR=1018) Ans
IF (Ans.EQ. ' ') Go To 1018
Read (Ans,2002,Err = 1018) FTFreq
WRITE (*,1) (/ ,1X,F10.0) FTFreq
CALL RANGE (FTFreq,10000.,1.)
WRITE(*,1)
1015 WRITE(*,1) 'ENTER FREEZE-THAW CELL FAILURE RATE (0.XXXX): '
READ(*,1) (A10),ERR=1015) Ans
IF (Ans.EQ. ' ') Go To 1015
Read (Ans,2002,Err = 1015) PFMAY
WRITE (*,1) (/ ,1X,F10.4) PFMAY
Call Range (PFMAY,1.,0.)
WRITE(*,1)
1016 WRITE(*,1) 'ENTER PERCENTAGE OF POST FAILURE RESISTANCES THAT'
WRITE(*,1) (1X,A) 'ARE OPEN CIRCUIT (XXX.XX) : '
READ(*,1) (A10),ERR=1016) Ans
IF (Ans.EQ. ' ') GOTO 1016
READ (Ans,2002,Err=1016) PFOPEN
IF (PFOPEN.LT. 0. .OR. PFOPEN.GT. 100.) GO TO 1016
PFSHORT = 100. - PFOPEN
WRITE(*,1)
WRITE(*,1) 'PERCENTAGE OF POST FAILURE RESISTANCES THAT ARE'
WRITE(*,1) (1X,A) 'CLOSED CIRCUIT (100. - OPEN CIRCUIT PERCENTAGE)'
1 :
WRITE(*,1) (1X,F8.2) PFSHORT
WRITE(*,1)
WRITE(*,1)
1017 WRITE(*,1) 'ARE THESE VALUES CORRECT? (Y/N): '
READ(*,1) (BN,A1),ERR=1017) C
IF (.NOT.(C.EQ. 'Y' .OR. C.EQ. 'y' .OR.
1 C.EQ. 'N' .OR. C.EQ. 'n')) GO TO 1017
IF (C.EQ. 'N' .OR. C.EQ. 'n') GOTO 301
302 CONTINUE
303 CONTINUE

CALL CLRSCN
WRITE(*,1)
CALL REVERSE
WRITE(*,5)
WRITE(*,1)
WRITE(*,1)      FAILURE DUE TO WEAROUT
WRITE(*,1)
WRITE(*,1)
WRITE(*,1) FAILURE DUE TO WEAROUT REFERS TO CELLS REACHING
WRITE(*,1) THEIR NATURAL END-OF-LIFE. IT IS ASSUMED THAT
WRITE(*,1) THESE FAILURES ARE WEIBULL DISTRIBUTED.
WRITE(*,1)
CALL RESTORE
WRITE(*,1)
C
1019 WRITE(*,1) 'ENTER WEIBULL LOCATION PARAMETER (XXXX): '
READ(*,1) (A10),ERR=1019) Ans
IF (Ans.EQ. ' ') Go To 1019
Read (Ans,2002,Err = 1019) Temp
CALL RANGE (Temp,10000.,0.)
Locate = Temp
WRITE (*,1) (/ ,1X,I10) Locate
WRITE(*,1)
1020 WRITE(*,1) 'ENTER WEIBULL SCALE PARAMETER (XXXXX.XX): '
READ(*,1) (A10),ERR=1020) Ans
IF (Ans.EQ. ' ') Go To 1020
Read (Ans,2002,Err = 1020) Scale
CALL RANGE (Scale,100000.,0.)
WRITE (*,1) (/ ,1X,F10.2) Scale
WRITE(*,1)
1021 WRITE(*,1) 'ENTER WEIBULL SHAPE PARAMETER (XX.XX): '
READ(*,1) (A10),ERR=1021) Ans
IF (Ans.EQ. ' ') Go To 1021
Read (Ans,2002,Err = 1021) Shape
CALL RANGE (Shape,10.,0.1)
WRITE (*,1) (/ ,1X,F10.2) Shape
IF (SCALE/SHAPE.GT.15000.) THEN
WRITE(*,*) 'SHAPE PARAMETER TOO SMALL, SCALE TOO LARGE '
WRITE(*,*) 'FOR CALCULATIONS. PLEASE REENTER. '
WRITE(*,*)
GOTO 1020
ENDIF
WRITE(*,1)
1022 WRITE(*,1) 'ENTER PERCENTAGE OF POST FAILURE RESISTANCES TH'
1 ARE
WRITE(*,1) (1X,A) 'OPEN CIRCUIT (XXX.XX) : '
READ(*,1) (A10),ERR=1022) Ans
IF (Ans.EQ. ' ') GOTO 1022
READ (Ans,2002,Err=1022) PWOPEN
IF (PWOPEN.LT. 0. .OR. PWOPEN.GT. 100.) GO TO 1022
PWSHORT = 100. - PWOPEN
WRITE(*,1)
WRITE(*,1) 'PERCENTAGE OF POST FAILURE RESISTANCES THAT ARE'
WRITE(*,1) (1X,A) 'CLOSED CIRCUIT (100. - OPEN CIRCUIT PERCENTA'
1 :
WRITE(*,1) (1X,F8.2) PWSHORT
WRITE(*,1)
WRITE(*,1)
1023 WRITE(*,1) 'ARE THESE VALUES CORRECT? Y/N: '
READ(*,1) (BN,A1),ERR=1023) C
IF (.NOT.(C.EQ. 'Y' .OR. C.EQ. 'y' .OR.
1 C.EQ. 'N' .OR. C.EQ. 'n')) GO TO 1023
IF (C.EQ. 'N' .OR. C.EQ. 'n') GOTO 303
GOTO 500
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCC MENU ITEM C: CCCC
CCCC run life-cycle model CCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
400 CONTINUE
SECTD = .TRUE.

```



```

WRITE(*,1)'
WRITE(*,1)'          FAILURE DISTRIBUTION MODEL
WRITE(*,1)'
WRITE(*,1)'
WRITE(*,1)'ENTER
WRITE(*,1)'-----
WRITE(*,1)'
WRITE(*,1)' A - ACTUAL WEIBULL DISTRIBUTION DENSITY FUNCTION
WRITE(*,1)'   BASED ON USER INPUT WEIBULL PARAMETERS
WRITE(*,1)'
WRITE(*,1)' B - DENSITY FUNCTION OF RANDOM CELL FAILURES
WRITE(*,1)'   BASED ON USER INPUT WEIBULL PARAMETERS
WRITE(*,1)'
CALL RESTORE
WRITE(*,1)'
WRITE(*,1)'
222 WRITE(*,1)'(A\)' ENTER LETTER FOR CHOICE: '
READ(*,1)'(BN,A1)',ERR=222) CHOICE
IF (CHOICE.EQ. 'A' .OR. CHOICE.EQ. 'a' .OR. CHOICE.EQ. 'B'
1 .OR. CHOICE.EQ. 'b') GOTO 223
GOTO 222
223 MODE = 2
CALL QSMODE(MODE)
224 CONTINUE
CALL CLRSCN
WRITE(*,1)'
CALL REVERSE
WRITE(*,5)
WRITE(*,1)'
WRITE(*,1)'          EXAMPLE WEIBULL DISTRIBUTION
WRITE(*,1)'
WRITE(*,1)'
IF(CHOICE.EQ. 'A' .OR. CHOICE.EQ. 'a') THEN
WRITE(*,1)' FOLLOWING IS THE ACTUAL WEIBULL DISTRIBUTION DENSITY '
WRITE(*,1)' FUNCTION BASED ON THE SPECIFIED WEIBULL PARAMETERS. '
ELSE
WRITE(*,1)' THE FOLLOWING DISTRIBUTION SIMULATES RANDOM CELL '
WRITE(*,1)' FAILURES BASED ON THE SPECIFIED WEIBULL PARAMETERS. '
ENDIF
WRITE(*,1)'
CALL RESTORE
WRITE(*,1)'
WRITE(*,1)'
WRITE(*,1)'
1002 WRITE(*,1)'(A\)' ENTER LOCATION PARAMETER: '
READ(*,1)'(A10)',ERR=1002) Ans
IF (Ans.EQ. ' ') Go To 1002
Read (Ans,2002,Err = 1002) Temp
CALL RANGE (Temp,10000.,0.)
Locate = Temp
WRITE(*,1)'
WRITE(*,1)'
1003 WRITE(*,1)'(A\)' ENTER SCALE PARAMETER: '
READ(*,1)'(A10)',ERR=1003) Ans
IF (Ans.EQ. ' ') Go To 1003
Read (Ans,2002,Err = 1003) Scale
CALL RANGE (Scale,100000.,0.00001)
WRITE(*,1)'
WRITE(*,1)'
IF (LOCATE/SCALE .GT. 1.E6) THEN
WRITE(*,*) ' LOCATE/SCALE CANNOT EXCEED 1,000,000 '
WRITE(*,*) ' FOR PLOTTING. PLEASE REENTER. '
WRITE(*,*) '
GO TO 1002
ENDIF
1004 WRITE(*,1)'(A\)' ENTER SHAPE PARAMETER: '
READ(*,1)'(A10)',ERR=1004) Ans
IF (Ans.EQ. ' ') Go To 1004
Read (Ans,2002,Err = 1004) Shape
CALL RANGE (Shape,10.,0.1)
WRITE(*,1)'
WRITE(*,1)'
C
IF(SCALE/SHAPE.GT.15000.) THEN
WRITE(*,*) ' SHAPE PARAMETER TOO SMALL, SCALE TOO LARGE '
WRITE(*,*) ' FOR CALCULATIONS. PLEASE REENTER. '
WRITE(*,*) '
GOTO 1003
ENDIF
IF (CHOICE.EQ. 'A' .OR. CHOICE.EQ. 'a') THEN
NSAMP = 100
GOTO 1006
ENDIF
1005 WRITE(*,1)'(A\)' ENTER NUMBER OF RANDOM CELL FAILURES (FROM 10
10 1000): '
READ(*,1)'(A10)',ERR=1005) Ans
IF (Ans.EQ. ' ') GOTO 1005
READ (Ans,2001,ERR=1005) NSAMP
IF (NSAMP.LT. 100 .OR. NSAMP.GT. 1000) GO TO 1005
WRITE(*,1)'
WRITE(*,1)'
1006 WRITE(*,1)'(A\)' ARE THESE VALUES THAT YOU WANT? (Y/N): '
READ(*,1)'(BN,A1)',ERR=1006) C
IF (.NOT.(C.EQ. 'Y' .OR. C.EQ. 'y' .OR.
1 C.EQ. 'N' .OR. C.EQ. 'n')) GO TO 1006
IF (CHOICE.EQ. 'B' .OR. CHOICE.EQ. 'b') GOTO 10060
C
C *** Option A - Graph Weibull density function by tabulating actual
Weibull
C *** density function. Tabulate NSAMP equally spaced points between
XST and
C *** XFIN (obtained by solving F(XFIN)=0.99).
C
ICOUNT = 0
XST = LOCATE
XFIN = LOCATE + SCALE * (-ALOG(0.01))**(1./SHAPE)
C *** Calculate interval size: DELTX
DELTx = (XFIN - XST) / NSAMP
C
C *** Tabulate NSAMP points from Weibull density function
C
TEMP = SHAPE / SCALE
YFIN = 0.
DO 50 N = 1,NSAMP
X = XST + DELTX * (N-1)
TEMP1 = (X - LOCATE) / SCALE
IF (SHAPE.EQ. 1.0) THEN
C *** Weibull probability density function (pdf) reduces to an
C *** exponential density function with pdf (x) = 1/SCALE at x = LOCA
TEMP2 = 1.0
ELSE IF (SHAPE.GT. 1.0 .AND. TEMP1.EQ. 0.) THEN
C *** Weibull pdf (x) = 0 at x = LOCATE
TEMP2 = 0.
ELSE IF (SHAPE.LT. 1.0 .AND. TEMP1.EQ. 0.) THEN
C *** Weibull pdf (x) is infinity at x = LOCATE (set to 0 and don't p
C *** this point below)
TEMP2 = 0.
ELSE IF (SHAPE.NE. 1.0 .AND. TEMP1.GT. 0.) THEN
C *** Weibull pdf (x) is positive at x > LOCATE
TEMP2 = TEMP1 ** (SHAPE - 1.0)
ENDIF
TEMP3 = TEMP2 * TEMP1
XARRAY(N) = X
YARRAY(N) = TEMP * TEMP2 * EXP(-TEMP3)
IF (YARRAY(N) .GE. YFIN) YFIN = YARRAY(N)
50 CONTINUE
C
C *** Calculate theoretical mean of actual Weibull distribution

```

```

C
  ARG = 1./SHAPE
  GAM = GAMMA (ARG)
  AVE = LOCATE + SCALE * GAM
C
C*** Scale for plotting
C
  CALL YSCALE (YFIN, IPOWER, YPSCALE)
  IF (YPSCALE .NE. 1.) THEN
    DO 51 N = 1, NSAMP
      YARRAY(N) = YARRAY(N) / YPSCALE
51    CONTINUE
  ENDIF
  SUM = 0.
  NPT = NSAMP
  YST = 0.0
  GOTO 72
C
C *** Option B - Graph Weibull density function by randomly sampling
Weibull
C *** distribution and grouping into histogram cells.
C *** Initialize variables.
C
10060 ICOUNT = 0
DO 60 N = 1, NSAMP
  XX(N) = 0.0
  YY(N) = 0.0
  XARRAY(N) = 0.0
  YARRAY(N) = 0.0
60  CONTINUE
  SUM = 0.0
  XMAX = 0.0
DO 70 N = 1, NSAMP
  XX(N) = N
  CALL FAILURE(YY(N))
  IF(YY(N).GT.XMAX) XMAX = YY(N)
  SUM = SUM + YY(N)
70  CONTINUE
C *** Calculate average of sampled Weibull distribution
  AVE = SUM / NSAMP
  WDCCELL = (XMAX-LOCATE)/NCELLS
C *** Number of cell intervals to plot
  NPT = NCELLS + 1
DO 80 N = 1, NPT
  X1 = LOCATE+(N-1)*WDCCELL
  X2 = X1+WDCCELL
  XARRAY(N) = (X1+X2)/2.
DO 71 K = 1, NSAMP
  IF(YY(K).GE.X1.AND.YY(K).LT.X2) YARRAY(N)=YARRAY(N)+1
71  CONTINUE
80  CONTINUE
  FRC = 1./(NSAMP*WDCCELL)
DO 86 K = 1, NPT
  YARRAY(K) = YARRAY(K)*FRC
86  CONTINUE
C
C *** Use the value of the Weibull probability density function (pdf)
C *** at x = LOCATE as the first plot point in the array to be plotted
C
  IF (SHAPE .EQ. 1.0) THEN
C *** Weibull pdf at x = LOCATE
    YLOCATE = 1. / SCALE
  ELSE IF (SHAPE .GT. 1.0) THEN
C *** Weibull pdf at x = LOCATE
    YLOCATE = 0.
  ELSE IF (SHAPE .LT. 1.0) THEN
C *** Infinite so set to 0 and don't plot this point below
    YLOCATE = 0.
  ENDIF
C

```

```

C *** Insert this plot point as the first point in the plot arrays
C
DO 87 K = 1, NPT
  N = NPT - K + 1
  XARRAY(N+1) = XARRAY(N)
  YARRAY(N+1) = YARRAY(N)
87  CONTINUE
  NPT = NPT + 1
  XARRAY(1) = LOCATE
  YARRAY(1) = YLOCATE
  YMAX = 0.0
DO 555 N = 1, NPT
  IF(YARRAY(N).GE.YMAX) YMAX = YARRAY(N)
555 CONTINUE
C
C *** Scale for plotting
C
  CALL YSCALE (YMAX, IPOWER, YPSCALE)
  IF (YPSCALE .NE. 1.) THEN
    DO 556 N = 1, NPT
      YARRAY(N) = YARRAY(N) / YPSCALE
556  CONTINUE
  ENDIF
  XST = LOCATE
  XFIN = XMAX + WDCCELL/2.0
  YST = 0.
  YFIN = YMAX
C
C *** Subtract LOCATE from x-array before plotting and label x-axis
C *** accordingly in order to plot with Grafmatics software
C
72  DO 73 K = 1, NPT
  XARRAY(K) = XARRAY(K) - LOCATE
73  CONTINUE
  XST = XST - LOCATE
  XFIN = XFIN - LOCATE
C
C *** Scale translated X values as power of 10 if necessary in order
C *** plot with Grafmatics software
C
74  CALL XSCALE (XFIN, ICOUNT, XPSCALE)
  IF (XPSCALE .NE. 1.0) THEN
    XST = XST / XPSCALE
    DO 75 I = 1, NPT
      XARRAY(I) = XARRAY(I) / XPSCALE
75  CONTINUE
  ENDIF
C
C *** Setup and call Grafmatic graphics package for plot
C
  IF (SHAPE .LT. 1.0) THEN
C *** Skip first plot point if Weibull shape parameter < 1.0 since
C *** Weibull pdf is infinite at x = LOCATE
    NPT = NPT - 1
    DO 76 K = 1, NPT
      XARRAY(K) = XARRAY(K+1)
      YARRAY(K) = YARRAY(K+1)
76  CONTINUE
  ENDIF
  CALL CLRSCN
  IORG = 1
  XSCALE = 1.0
  NDOTS = 0
  LKOLOR = 3
  ISYMBL = -1
  KLRSYM = 1
  MODE = 6
  CALL QSMODE(MODE)
  CALL QSETUP(NDOTS, LKOLOR, ISYMBL, KLRSYM)
  MODE = 2

```

```

CALL QSMODE(MODE)
ITYPE = 1
MODE = 8
CALL QSMODE(MODE)
CALL QPTABL(10RG,XSCALE,XST,XFIN,YST,YFIN,
1  ITYPE,NPT,XARRAY,YARRAY)
C
C *** Y-axis labels
C
CALL QPTXT (28,'PROBABILITY DENSITY FUNCTION',2,1,22)
IF (YPSCALE.EQ.1.) THEN
CALL QPTXT (28,'',2,1,21)
ELSE
WRITE (YLABEL,77) IPOWER
77  FORMAT (' (X 10E',I3,') ')
CALL QPTXT (28,YLABEL,2,1,21)
ENDIF
C
C *** X-axis labels
C
IF (LOCATE.EQ.0) THEN
IF (ICOUNT.EQ.0) THEN
CALL QPTXT (28,'CYCLE LIFE',2,35,1)
ELSE
WRITE (XLABEL,78) ICOUNT
78  FORMAT ('CYCLE LIFE (X 10E',I2,')')
CALL QPTXT (28,XLABEL,2,35,1)
ENDIF
ELSE
IF (ICOUNT.EQ.0) THEN
WRITE (XLABEL,79) LOCATE
79  FORMAT ('CYCLE LIFE (' ,I5, ' + X-VALUE)')
CALL QPTXT (29,XLABEL,2,25,1)
ELSE
WRITE (XLABEL,799) LOCATE, ICOUNT
799  FORMAT ('CYCLE LIFE (' ,I5, ' + X-VALUE X 10E',I2,')')
CALL QPTXT (38,XLABEL,2,20,1)
ENDIF
ENDIF
C *** Upper right-hand corner of graph
CALL QCMOV (40,24)
WRITE(*,554) AVE
554  FORMAT(1X,' AVE. LIFE =',G13.6,' CYCLES')
10070 WRITE(*,'(A)') REPEAT? (Y/N)
READ (*,'(BN,A1)',ERR=10000) C
IF (.NOT.(C.EQ. 'Y' .OR. C.EQ. 'y' .OR.
1  C.EQ. 'N' .OR. C.EQ. 'n')) GO TO 10070
IF (C.EQ. 'Y' .OR. C.EQ. 'y') GO TO 221
MODE = 2
CALL QSMODE(MODE)
GO TO 500
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCC  MENU ITEM F:  CCCC
CCCC  exit program  CCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
600  CONTINUE
SECTE = .TRUE.
CALL CLRSCN
Call QSMODE (ModeBeg)
601  OPEN(2,FILE='STOP.TMP',STATUS='NEW',FORM='FORMATTED')
CLOSE (2)
STOP
2001  FORMAT (BN,I10,BZ)
2002  FORMAT (BN,F10.0,BZ)
END

```

```

C
C PROGRAM BAT2A
C
C *****
C PURPOSE: Runs complex model battery simulation.
C
C LIMITATIONS AND PREREQUISITES:
C must run RELY first, menu option 'D' to build parameter
C file 'BAT2A.TMP' - read by this program to perform the
C complex model.
C
C LOGICAL NAMES AND FILES USED:
C 2 = input data file 'BAT2A.TMP' from RELY program
C 3 = input data file of default test & cell parameters
C 7 = output data file 'BAT2A.OUT'
C
C ROUTINES USED:
C CLRSCN, REVERSE, RESTORE, MOVE, BLINK, RANF, BEEPER
C MAINMENU, GRPHMENU, RSLTMENU, SCRNMENU
C QRMODE, QSMODE, QSETUP, QPTABL, QPTXT
C
C *****
C DEVELOPMENT INFORMATION:
C CREATED BY : Cody J. Hostick ON : 1985 - Aug. 1986
C John V. Dovey
C Ron K. Nakaoka
C Carl H. Ishoff
C AT : Battelle Pacific Northwest Laboratories
C Richland, Washington 99352
C MACHINE/OPERATING SYSTEM: PC DOS V2.10
C COMPILER : MICROSOFT FORTRAN77 V3.31
C COMPILER SWITCHES : Default
C
C CONSTANTS (PARAMETER STATEMENTS):
C IMPLICIT CHARACTER*1 (C)
C IMPLICIT REAL*4 (D)
C PARAMETER (NOINCR = 99)
C PARAMETER (NOINRR = NOINCR + 1)
C
C COMMON BLOCKS:
C $INCLUDE:'PARM.INC'
C $INCLUDE:'BAT2A.INC'
C $INCLUDE:'WEIBUL.INC'
C COMMON /BAT2A9/ BCELL7
C COMMON /BAT210/ HIRES
C REAL BCELL7(ROWSIZ, COLSIZ, PLNSIZ)
C INTEGER*2 HIRES(ROWSIZ, COLSIZ, PLNSIZ)
C
C BAT2A.INC -- battery info for BAT2A
C PARM.INC -- size of battery
C WEIBUL.INC -- Weibul distribution parameters
C
C VARIABLES:
C CHARACTER*15 ANS, FNAME
C CHARACTER*40 CHAR
C INTEGER*2 MODE, IORG, ITYPE, NPT, NCHAR, KOLOR, ICOL, IROW
C INTEGER*2 NDOTS, LKOLOR, ISYMBL, KLRSYM
C INTEGER MODULE, STRING, CELL, Y2, Q, N, X5, X8, CYCREQ, BADCEL, W
C INTEGER CELLPF, CELLP, FSWTCH, SWITCH, ITIME, J, OVRDIS, X, MAXCYC, OVRCHG
C INTEGER TOTCEL, GOODCEL, NFOCF, NFOCCF, NWOCF, NWCCF
C REAL XARRAY(NOINRR), YARRAY(NOINRR), EMIN, CELVOL, CELRES, CELCHG
C REAL OCR(10), TCARAY(10)
C REAL TIME, R1, R2, ROUND, YLEN, QINIT, E, FCHARGE
C REAL QQTP, EMAX, ICEL, QCEL, REMAIN, SRESIST
C REAL POCOPEN, POCCLCLOS, PODOPEN, PODCLOS
C REAL FTFCCR, FTFCCR, WOFCCR, WOFCCR, OCFCCR, OCFCCR, ODFCCR, ODFCCR
C REAL XFTFCCR, XFTFCCR, XWOFCCR, XWOFCCR, XOCFCCR, XOCFCCR, XODFCCR, XODFCCR
C REAL XODFCCR, CAPMAX
C DIMENSION OUT(NOINRR, 10)
C LOGICAL GOOD, XRESIS, TIMEUP, PARLEL, STRON, SETCAP
C 1 , SETCP

```

```

C
C DATA STATEMENTS:
C DATA QINIT, E, EMIN, EMAX /50.0, 2.076, 1.78, 10.0/
C DATA T, TESTI, TESTT, CYCREQ /25, 45, 6, 0/
C DATA CELLPF, CELLP /1, 1/
C DATA QQTP, SWITCH /3, 0, 0/
C DATA FTFCCR, FTFCCR, WOFCCR, WOFCCR /0.2, 0.070, 0.2, 0.070/
C DATA POCOPEN, OCFCCR, OCFCCR /30, 0.2, 0.070/
C DATA PODOPEN, ODFCCR, ODFCCR /30, 0.2, 0.070/
C DATA OCR /0.035, 0.035, 0.035, 0.035, 0.035, 0.035, 0.035, 0.035, 0.035, 0.035/
C DATA TCARAY /95, 90, 80, 70, 60, 50, 40, 30, 20, 10/
C DATA XRESIS, PARLEL, SETCAP /.FALSE., .FALSE., .FALSE./
C DATA SETCP /.FALSE./
C
C *** Definitions of new variables in Detailed Discharge Model
C FCHARGE = fully charged cell capacity
C *** Definitions of post-failure resistance percentages in Detailed
C Discharge Model (program BAT2A)
C POCOPEN = percentage of over-charge failures that are open circ
C POCCLCLOS = percentage of over-charge failures that are closed
C circuit (100. - POCOPEN)
C PODOPEN = percentage of over-discharge failures that are open
C circuit
C PODCLOS = percentage of over-discharge failures that are closed
C circuit (100. - PODOPEN)
C *** Definitions of 8 types of failure resistances in Detailed
C Discharge Model (program BAT2A)
C FTFCCR = freeze-thaw failure open-circuit resistance
C FTFCCR = freeze-thaw failure closed-circuit resistance
C WOFCCR = wearout failure open-circuit resistance
C WOFCCR = wearout failure closed-circuit resistance
C OCFCCR = over-charge failure open-circuit resistance
C OCFCCR = over-charge failure closed-circuit resistance
C ODFCCR = over-discharge failure open-circuit resistance
C ODFCCR = over-discharge failure closed-circuit resistance
C *** Definitions of cell counters
C TOTCEL = number of total cells
C GOODCEL = number of good cells
C NFOCF = number of freeze-thaw open-circuit failures
C NFOCCF = number of freeze-thaw closed-circuit failures
C NWOCF = number of wearout open-circuit failures
C NWCCF = number of wearout closed-circuit failures
C
C *****
C * Section 1: Default Values for Input Screen *
C *****
C *** Get Current Screen Mode -- Reset before program stops
C Call QRMODE (ModeBeg, ModeCol)
C *** Read Default Input Values, if they exist on disk
C
C Open (3, file='BAT2A.SDF', IOSTAT=IOChk)
C IF (IOChk .NE. 0) Go To 509
C Read (3, *, ERR=508) CycReq
C Read (3, *, ERR=508) TestT
C Read (3, *, ERR=508) T
C Read (3, *, ERR=508) CellPF
C Read (3, *, ERR=508) Switch
C Read (3, *, ERR=508) TestI
C Read (3, *, ERR=508) Qinit
C Read (3, *, ERR=508) E
C Read (3, *, ERR=508) EMax
C Read (3, *, ERR=508) EMin
C Read (3, *, ERR=508) FTFCCR
C Read (3, *, ERR=508) FTFCCR
C Read (3, *, ERR=508) WOFCCR
C Read (3, *, ERR=508) WOFCCR
C Read (3, *, ERR=508) POCOPEN
C Read (3, *, ERR=508) OCFCCR

```



```

Read (3,*,ERR=500) OCFCCR
Read (3,*,ERR=500) PODOPEN
Read (3,*,ERR=500) ODFOCR
Read (3,*,ERR=500) ODFCCR
Read (3,*,ERR=500) (OCR(I),I=1,10)
508 Close (3)
C
509 FCHARGE = (.95 - (.45 * (EMIN-1.78)/(E-1.78))) * QINIT
POCCLOS = 100. - POCOPEN
PODCLOS = 100. - PODOPEN
do 778 i = 1, rowsiz
do 775 j = 1, colsiz
rs(i,j) = 0.0
is(i,j) = 0.0
qcell(i,j) = 0.0
do 774 k = 1, pinsiz
bcell4(i,j,k) = 0.0
bcell5(i,j,k) = .true.
774 continue
775 continue
776 continue
IF (xresis) THEN
C *** Restore original values for 8 types of post-failure resistances
C *** if they were altered below to reflect failure switches
ftfocr = xftfocr
ftfocr = xftfocr
wofocr = xwofocr
wofocr = xwofocr
ocfocr = xocfocr
ocfocr = xocfocr
odfocr = xodfocr
odfocr = xodfocr
xresis = .false.
ENDIF
timeup = .false.
OPEN (2,FILE='BAT2A.TMP',FORM='FORMATTED',STATUS='OLD')
READ (2,999) MODULE, STRING, CELL, LOCATE, SHAPE, SCALE
999 FORMAT (4I10,2F20.10)
READ (2,998) MAXCYC
IF (CycReq .GT. MaxCyc) CycReq = MaxCyc
998 FORMAT (I10)
C
*****
*
* Section 2: Input Screen
*
*****
C
C *** SUB-SECTION 2-A
C
C *** This section prints the main menu and accepts the selection
C *** by the user. Program flow is then transferred to the
C *** appropriate section.
C
1051 CALL MainMenu (IR,IC)
1050 Call Move (IR,IC)
WRITE (*,*) '
CALL Move (IR,IC)
Read(*,'(A10)',Err=1050) Ans
IF (Ans .EQ. ' ') Go To 1050
READ (Ans,2003,ERR=1050) IAns
IF ((IAns .LT. 1) .OR. (IAns .GT. 8)) GO TO 1050
C
C *** Determine where to branch, depending on user's selection
IF (IAns .EQ. 1) THEN
C *** Screen Selection Menu
GO TO 1100
ELSE IF (IAns .EQ. 2) Then
C *** View Battery Configuration
Go To 1800

```

```

ELSE IF (IAns .EQ. 3) THEN
C *** Run Simulation
GO TO 201
ELSE IF (IAns .EQ. 4) THEN
C *** Save Data Values on Disk
GO TO 1700
ELSE IF (IAns .EQ. 5) Then
C *** Exit to Life Cycle Model
GO TO 1002
ELSE
C *** Exit to DOS
Go To 1004
ENDIF
C
C *****
C
C *** SUB-SECTION 2-B Screen Selection Menu
C
C *** This section displays the screen selection menu and
C *** routes program flow to the required point, depending
C *** on the user's choice
C
1100 CALL ScrnMenu (IR,IC)
1101 Call Move (IR,IC)
WRITE (*,*) '
CALL Move (IR,IC)
Read (*,'(A13)',Err=1101) Ans
IF (Ans .EQ. ' ') Go To 1101
READ (Ans,2003,ERR=1101) IAns
IF ((IAns .LT. 1) .OR. (IAns .GT. 4)) GO TO 1101
C
IF (IAns .EQ. 1) THEN
C *** Edit Test Conditions
GO TO 1200
ELSE IF (IAns .EQ. 2) THEN
C *** Edit Cell Parameters
GO TO 1300
ELSE IF (IAns .EQ. 3) THEN
C *** Edit Cell Internal Resistance Values
Go To 202
ELSE
C *** Main Menu
GO TO 1051
ENDIF
C
C
C *****
C
C *** VIEW Battery Configuration -- Display Battery Size on Screen
C
1800 Call ClrScr
Write (*,5001) 'BATTERY CONFIGURATION'
Write (*,*) '
Write (*,5002) 'Number of Modules per Battery',Module
Write (*,5002) ' Number of Strings per Module',String
Write (*,5002) ' Number of Cells per String',Cell
Write (*,*) '
Write (*,*) '
Write (*,*) 'Hit Return to Continue'
Read (*,*)
Go To 1051
C
5001 FORMAT (30X,A22)
5002 FORMAT (17X,A29,I6)
C
C *****
C
C *** Save Current Test & Cell Parameters To Disk File 'BAT2A.$DF'
C
1700 Call Move (16,30)

```

```

Write (*,*) 'Are you sure? (Y/N)
Call Move (18,52)
Read (*,*) 'a',err=1700 Ans
IF (.Not. ((Ans.EQ. 'Y') .OR. (Ans.EQ. 'y') .OR.
& (Ans.EQ. 'N') .OR. (Ans.EQ. 'n')))) Go To 1700
IF ((Ans.EQ. 'N') .OR. (Ans.EQ. 'n')) Go To 1051
Call Move (IR,IC)
Call Blink
Call Move (IR,IC)
Write (*,*) 'a',err=1700 'Saving'
Open (3,file='Bat2a.$df',status='new')
Write (3,7001,ERR=1000) CycReq
Write (3,7002,ERR=1000) TestT
Write (3,7002,ERR=1000) T
Write (3,7001,ERR=1000) CellPF
Write (3,7001,ERR=1000) Switch
Write (3,7002,ERR=1000) TestI
Write (3,7002,ERR=1000) QInit
Write (3,7002,ERR=1000) E
Write (3,7002,ERR=1000) EMax
Write (3,7002,ERR=1000) EMin
Write (3,7002,ERR=1000) FTFOCR
Write (3,7002,ERR=1000) FTFCCR
Write (3,7002,ERR=1000) WOFOCR
Write (3,7002,ERR=1000) WOFCCR
Write (3,7002,ERR=1000) POCOPEN
Write (3,7002,ERR=1000) OCFOCR
Write (3,7002,ERR=1000) OCFCCR
Write (3,7002,ERR=1000) PODOPEN
Write (3,7002,ERR=1000) ODOFCR
Write (3,7002,ERR=1000) ODFCCR
WRITE (3,7002,ERR=1000) (OCR(I),I=1,10)
Close (3)
Call Restore
Go To 1051

```

```

C
7001 Format (i20)
7002 Format (F30.15)

```

```

C *****
C

```

```

C *** Input Screen 1 (TEST CONDITIONS)

```

```

C
1200 CALL ClrScn
IR = 1
IC = 1
CALL Move (IR,IC)
WRITE (*,2001) 'TEST CONDITIONS'
WRITE (*,2001) 'Input Screen 1'
WRITE (*,*)
WRITE (*,2002) 'Cycle to Analyze',
& CycReq-1,
WRITE (*,2014) 'Duration of Test',
& TestT, 'Hours'
WRITE (*,2014) 'Time Increment',
& T, 'Hours'
WRITE (*,2002) 'Cell Connection: 1=Series-Par. 2=Parallel-Ser. ',
& CellPF,
WRITE (*,2002) 'Failure Switches: 0=None. 1=Closed. 2=Open',
& Switch,
WRITE (*,2014) 'Constant Discharge Current',
& TestI, 'Amps'
WRITE (*,*)
IR = IR+10

```

```

C
C *** Display Menu
C

```

```

WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
1 Modify These Values

```

```

WRITE (*,2010) ' 2 Edit Cell Parameters
WRITE (*,2010) ' 3 Edit Cell Internal Resistances
WRITE (*,2010) ' 4 Return to Main Menu
WRITE (*,2010) ' Enter Selection --->

```

```

IR = IR + 6
IC = 45

```

```

1210 CALL Move (IR,IC)
WRITE (*,*)
CALL Move (IR,IC)
Read (*,*) 'A13',Err=1210 Ans
IF (Ans.EQ. ' ') Go To 1210
READ (Ans,2003,ERR=1210) IAns
IF ((IAns.LT. 1) .OR. (IAns.GT. 4)) Go To 1210
IF (IAns.EQ. 1) Then

```

```

C *** Edit these values
Go To 1250
ELSE IF (IAns.EQ. 2) Then
C *** Edit Cell Parameters
Go To 1300
ELSE IF (IAns.EQ. 3) Then
C *** Edit Cell Internal Resistances
Go To 202
ELSE
C *** Main Menu
Go To 1051
ENDIF

```

```

C
C *****
C
C *** Menu Option 1 EDIT THESE VALUES
C

```

```

1250 IR = 4
IC = 50
DO 1275 ILP = 1,6
1255 CALL Move (IR,IC)
CALL Reverse
WRITE (*,*) 'A1'
CALL Move (IR,IC)
READ (*,*) 'A10' Ans
IF (Ans.NE. ' ') Then
IF (ILP.EQ. 1) Then
READ (Ans,2003,ERR=1255) CycReq
CycReq = CycReq - 1
IF (CycReq.LE. 0) Then
CycReq = 0
ELSE IF (CycReq.GT. MaxCyc) Then
CycReq = MaxCyc
ENDIF
ELSE IF (ILP.EQ. 2) Then
READ (Ans,2004,ERR=1255) TestT
IF (TestT.LT. 0.) TestT = -TestT
ELSE IF (ILP.EQ. 3) Then
READ (Ans,2004,ERR=1255) T
IF (T.LT. 0.) T = -T
ELSE IF (ILP.EQ. 4) Then
READ (Ans,2003,ERR=1255) CellPF
ELSE IF (ILP.EQ. 5) Then
READ (Ans,2003,ERR=1255) Switch
ELSE IF (ILP.EQ. 6) Then
READ (Ans,2004,ERR=1255) TestI
ENDIF
ENDIF

```

```

C
C *** Write Input Back to User
CALL Restore
CALL Move (IR,IC)
IF (ILP.EQ. 1) Then
WRITE (*,2006) CycReq+1
ELSE IF (ILP.EQ. 2) Then

```

```

        WRITE (*,2005) TestT
    ELSE IF (ILP .EQ. 3) Then
        WRITE (*,2005) T
    ELSE IF (ILP .EQ. 4) Then
        WRITE (*,2006) CellPF
    ELSE IF (ILP .EQ. 5) Then
        WRITE (*,2006) Switch
    ELSE IF (ILP .EQ. 6) Then
        WRITE (*,2005) TestI
    ENDIF
    IR = IR+1
1275 CONTINUE
C
C *** Check for Input Errors
IF (T .NE. 0.0) MaxInc = TestT/T
IF (TestT .LE. 0.0) Then
    CALL Move (22,1)
    WRITE (*,2011)
    Go To 1250
ELSE IF (T .LE. 0.0) Then
    CALL Move (22,1)
    WRITE (*,2012)
    Go To 1250
ELSE IF (MaxInc .EQ. 0) Then
    Call Move (22,1)
    WRITE (*,2013)
    Go To 1250
ELSE IF (MaxInc .GT. NoIncr) Then
    Call Move (22,1)
    WRITE (*,2007) NoIncr, TestT, T, MaxInc
    Go To 1250
ELSE IF (.NOT. ((CellPF .EQ. 1) .OR. (CellPF .EQ. 2))) Then
    Call Move (22,1)
    WRITE (*,2008) CellPF
    Go To 1250
ELSE IF (.NOT. ((Switch .EQ. 0) .OR. (Switch .EQ. 1) .OR.
    & (Switch .EQ. 2))) Then
    CALL Move (22,1)
    WRITE (*,2009) Switch
    Go To 1250
ELSE IF (TestI .LT. 0.) Then
    CALL Move (22,1)
    WRITE (*,9910)
    GO TO 1250
ENDIF
C
C *** Re-Write Screen if no errors
C
    Go To 1200
C
C *** Format Statements for this Screen
2000 FORMAT (1X,A49)
2001 FORMAT (33X,A15)
2002 FORMAT (1X,A49,I10,A13)
2014 FORMAT (1X,A49,F10.4,A13)
2015 FORMAT (1X,A49,F10.2,A13)
2003 FORMAT (BN,I10,BZ)
2004 FORMAT (BN,F10.0,BZ)
2005 FORMAT (F10.4\ )
2016 FORMAT (F10.2\ )
2017 FORMAT (26X,A29)
2006 FORMAT (I10\ )
2007 FORMAT (' ERROR! Only ',I3,' time increments available.
    & ' You specified ',F5.1,' total hours, ',F4.2,' hours
    & ' per increment, or ',I4,' total increments.
    & ')
2008 FORMAT (' ERROR! ',I3,' is not a valid cell connection value.
    & ')
2009 FORMAT (' ERROR! ',I3,' is not a valid failure switch value.
    & ')

```

```

    & ')
2010 FORMAT (18X,A42)
2011 FORMAT (' ERROR! Test Duration must be greater than zero.
    & ')
2012 FORMAT (' ERROR! Time Increment must be greater than zero.
    & ')
2013 FORMAT (' ERROR! Test Duration must be at least as long as
    & the Time Increment.
    & ')
9910 FORMAT (' ERROR! Discharge Current must be positive.
    & ')
C
C *****
C
C *** First Half of Input Screen 2 (CELL PARAMETERS)
C
1300 CALL CtrScn
    IR = 1
    IC = 1
    CALL Move (IR,IC)
    WRITE (*,2001) 'CELL PARAMETERS'
    WRITE (*,2017) 'First Half of Input Screen 2 '
    WRITE (*,*) '
    WRITE (*,2014) ' Fully-Charged Open Circuit Cell Voltag
    & E, ' Volts '
    WRITE (*,2014) ' Upper Electrolyte Failure Voltag
    & EMax, ' Volts '
    WRITE (*,2014) ' Lower Electrolyte Failure Voltag
    & EMin, ' Volts '
    WRITE (*,2014) ' Theoretical Cell Capacit
    & QInit, ' Amp-Hours'
    WRITE (*,2014) ' Fully-Charged Cell Capacit
    & Fcharge, ' Amp-Hours'
    WRITE (*,2014) ' Freeze-Thaw Failure Open Circuit Resistanc
    & FTFOCR, ' Ohms '
    WRITE (*,2014) ' Freeze-Thaw Failure Closed Circuit Resistanc
    & FTFCCR, ' Ohms '
    WRITE (*,2014) ' Wearout Failure Open Circuit Resistanc
    & WOFOCR, ' Ohms '
    WRITE (*,2014) ' Wearout Failure Closed Circuit Resistanc
    & WOFCCR, ' Ohms '
    WRITE (*,*) '
    IR = IR+13
C
C *** Display Menu
C
    WRITE (*,2010) '
    WRITE (*,2010) '
    WRITE (*,2010) '
    WRITE (*,2010) '
    WRITE (*,2010) '
    WRITE (*,2010) '
    WRITE (*,2010) '
    WRITE (*,2010) '
    IR = IR + 7
    IC = 46
1310 CALL Move (IR,IC)
    WRITE (*,*) '
    CALL Move (IR,IC)
    Read (*,'(A10)',Err=1310) Ans
    IF (Ans .EQ. ' ') Go To 1310
    READ (Ans,2003,ERR=1310) IAns
    IF ((IAns .LT. 1) .OR. (IAns .GT. 5)) Go To 1310
    IF (IAns .EQ. 1) Then
C *** Edit these values
        Go To 1350
    
```

MENU	
1	Modify These Values
2	Edit 2nd Half of Cell Parameters
3	Edit Test Conditions
4	Edit Cell Internal Resistances
5	Return to Main Menu
Enter Selection --->	

```

ELSE IF (IAns .EQ. 2) Then
C *** Edit Second Half of Cell Parameters
  Go To 1400
ELSE IF (IAns .EQ. 3) Then
C *** Edit Test Conditions
  Go To 1200
ELSE IF (IAns .EQ. 4) Then
C *** Edit Cell Internal Resistances
  Go To 202
ELSE
C *** Main Menu
  Go To 1051
ENDIF
C
C *****
C
C *** Menu Option 1 EDIT THESE VALUES
C
1350 IR = 4
IC = 50
DO 1375 ILP = 1,9
1355 CALL Move (IR,IC)
CALL Reverse
WRITE (*, '(A)') ' '
CALL Move (IR,IC)
READ (*, '(A10)') Ans
IF (Ans .NE. ' ' .OR. (ILP .EQ. 5)) Then
  IF (ILP .EQ. 1) Then
    READ (Ans,2004,ERR=1355) E
  ELSE IF (ILP .EQ. 2) Then
    READ (Ans,2004,ERR=1355) EMax
  ELSE IF (ILP .EQ. 3) Then
    READ (Ans,2004,ERR=1355) EMin
  ELSE IF (ILP .EQ. 4) Then
    READ (Ans,2004,ERR=1355) QInit
  ELSE IF (ILP .EQ. 5) Then
    Fcharge = (.95 - (.45 * (EMin-1.78)/(E-1.78))) * Qinit
  ELSE IF (ILP .EQ. 6) Then
    READ (Ans,2004,ERR=1355) FTFOCR
  ELSE IF (ILP .EQ. 7) Then
    READ (Ans,2004,ERR=1355) FTFCCR
  ELSE IF (ILP .EQ. 8) Then
    READ (Ans,2004,ERR=1355) WFOOCR
  ELSE IF (ILP .EQ. 9) Then
    READ (Ans,2004,ERR=1355) WOFCCR
  ENDIF
ENDIF
ENDIF
C
C *** Write Input Back to User
CALL Restore
CALL Move (IR,IC)
IF (ILP .EQ. 1) Then
  WRITE (*,2005) E
ELSE IF (ILP .EQ. 2) Then
  WRITE (*,2005) EMax
ELSE IF (ILP .EQ. 3) Then
  WRITE (*,2005) EMin
ELSE IF (ILP .EQ. 4) Then
  WRITE (*,2005) QInit
ELSE IF (ILP .EQ. 5) Then
  WRITE (*,2005) Fcharge
ELSE IF (ILP .EQ. 6) Then
  WRITE (*,2005) FTFOCR
ELSE IF (ILP .EQ. 7) Then
  WRITE (*,2005) FTFCCR
ELSE IF (ILP .EQ. 8) Then
  WRITE (*,2005) WFOOCR
ELSE IF (ILP .EQ. 9) Then
  WRITE (*,2005) WOFCCR
ENDIF

```

```

IR = IR+1
1375 CONTINUE
C
C *** Check for Input Errors
C
IF (QInit .LE. 0.) Then
  Call Move (22,1)
  Write (*,3001)
  Go To 1350
ELSE IF (E .LE. 1.78) Then
  Call Move (22,1)
  Write (*,3002)
  Go To 1350
ELSE IF (EMax .LE. E) Then
  Call Move (22,1)
  Write (*,3003)
  Go To 1350
ELSE IF (EMin .LE. 0.) Then
  Call Move (22,1)
  Write (*,3004)
  Go To 1350
ELSE IF (EMin .GE. E) Then
  Call Move (22,1)
  Write (*,3005)
  Go To 1350
ELSE IF (FTFOCR .LT. 0.0003) Then
  Call Move (22,1)
  Write (*,3007) FTFOCR
  Go To 1350
ELSE IF (FTFCCR .LT. 0.0003) Then
  Call Move (22,1)
  Write (*,3008) FTFCCR
  Go To 1350
ELSE IF (WFOOCR .LT. 0.0003) Then
  Call Move (22,1)
  Write (*,3009)
  Go To 1350
ELSE IF (WOFCCR .LT. 0.0003) Then
  Call Move (22,1)
  Write (*,3010)
  Go To 1350
ENDIF
C *** Re-Write Screen if no errors
C
  Go To 1300
C
C *** Second Half of Input Screen 2 (CELL PARAMETERS)
C
1400 CALL ClrScn
IR = 1
IC = 1
CALL Move (IR,IC)
WRITE (*,2001) 'CELL PARAMETERS'
WRITE (*,2017) 'Second Half of Input Screen 2'
WRITE (*,*) ' '
WRITE (*,2014) 'Over-Voltage Failure Resistance Parameters:'
WRITE (*,2015) 'Over-Voltage Failure Open Circuit Percentag
& POCOPEN, ' Percent '
WRITE (*,2015) 'Over-Voltage Failure Closed Circuit Percentag
& POCCLDS, ' Percent '
WRITE (*,2014) 'Over-Voltage Failure Open Circuit Resistanc
& OCFOCR, ' Ohms '
WRITE (*,2014) 'Over-Voltage Failure Closed Circuit Resistanc
& OCFCCR, ' Ohms '
WRITE (*,2000) 'Over-Discharge Failure Resistance Parameters:'
WRITE (*,2015) 'Over-Discharge Failure Open Circuit Percentag
& PODOPEN, ' Percent '
WRITE (*,2015) 'Over-Discharge Failure Closed Circuit Percentag
& PODCLOS, ' Percent '
WRITE (*,2014) 'Over-Discharge Failure Open Circuit Resistanc

```

```

& ODFOCR, ' Ohms '
WRITE (*,2014) ' Over-Discharge Failure Closed Circuit Resistance',
& ODFCCR, ' Ohms '
WRITE (*,*) '
IR = IR + 14
C
C *** Display Menu
C
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
IR = IR + 7
IC = 45
1410 Call Move (IR,IC)
WRITE (*,*) '
Call Move (IR,IC)
Read (*,'(A10)',Err=1410) Ans
IF (Ans .EQ. ' ') Go To 1410
READ (Ans,2003,ERR=1410) IAns
IF ((IAns .LT. 1) .OR. (IAns .GT. 5)) Go To 1410
IF (IAns .EQ. 1) Then
C *** Edit these values
Go To 1450
ELSE IF (IAns .EQ. 2) Then
C *** Edit First Half of Cell Parameters
Go To 1300
ELSE IF (IAns .EQ. 3) Then
C *** Edit Test Conditions
Go To 1200
ELSE IF (IAns .EQ. 4) Then
C *** Edit Cell Internal Resistances
Go To 202
ELSE
C *** Main Menu
Go To 1051
ENDIF
C
C *****
C
C *** Menu Option 1 EDIT THESE VALUES
C
1450 IR = 5
IC = 50
DO 1475 ILP = 1,9
IF (ILP .NE. 2 .AND. ILP .NE. 5 .AND. ILP .NE. 7) THEN
1455 Call Move (IR,IC)
Call Reverse
WRITE (*,'(A)') '
Call Move (IR,IC)
READ (*,'(A10)') Ans
IF (Ans .NE. ' ') Then
IF (ILP .EQ. 1) Then
READ (Ans,2004,ERR=1455) POCOPEN
POCCLOS = 100. - POCOPEN
ELSE IF (ILP .EQ. 3) Then
READ (Ans,2004,ERR=1455) OCFOCR
ELSE IF (ILP .EQ. 4) Then
READ (Ans,2004,ERR=1455) OCFCCR
ELSE IF (ILP .EQ. 6) Then
READ (Ans,2004,ERR=1455) PODOPEN
PODCLOS = 100. - PODOPEN
ELSE IF (ILP .EQ. 8) Then
READ (Ans,2004,ERR=1455) ODFOCR
ELSE IF (ILP .EQ. 9) Then

```

```

      MENU
      1 Modify These Values
      2 Edit 1st Half of Cell Parameters
      3 Edit Test Conditions
      4 Edit Cell Internal Resistances
      5 Return to Main Menu
      Enter Selection --->

```

```

READ (Ans,2004,ERR=1455) ODFCCR
ENDIF
ENDIF
ENDIF
C
C *** Write Input Back to User
IF (ILP .NE. 5) Then
Call Restore
Call Move (IR,IC)
IF (ILP .EQ. 1) Then
WRITE (*,2010) POCOPEN
ELSE IF (ILP .EQ. 2) Then
WRITE (*,2010) POCCLOS
ELSE IF (ILP .EQ. 3) Then
WRITE (*,2005) OCFOCR
ELSE IF (ILP .EQ. 4) Then
WRITE (*,2005) OCFCCR
ELSE IF (ILP .EQ. 6) Then
WRITE (*,2010) PODOPEN
ELSE IF (ILP .EQ. 7) Then
WRITE (*,2010) PODCLOS
ELSE IF (ILP .EQ. 8) Then
WRITE (*,2005) ODFOCR
ELSE IF (ILP .EQ. 9) Then
WRITE (*,2005) ODFCCR
ENDIF
ENDIF
IR = IR + 1
1475 CONTINUE
C
C *** Check for Input Errors
C
IF (POCOPEN .LT. 0. .OR. POCOPEN .GT. 100.) Then
Call Move (22,1)
Write (*,3011)
Go To 1450
ELSE IF (OCFOCR .LT. 0.0003) Then
Call Move (22,1)
Write (*,3012)
Go To 1450
ELSE IF (OCFCCR .LT. 0.0003) Then
Call Move (22,1)
Write (*,3013)
Go To 1450
ELSE IF (PODOPEN .LT. 0. .OR. PODOPEN .GT. 100.) Then
Call Move (22,1)
Write (*,3014)
Go To 1450
ELSE IF (ODFOCR .LT. 0.0003) Then
Call Move (22,1)
Write (*,3015)
Go To 1450
ELSE IF (ODFCCR .LT. 0.0003) Then
Call Move (22,1)
Write (*,3016)
Go To 1450
ENDIF
C
C *** Re-Write Screen if no errors
C
GO TO 1400
C
C *** Format Statements for Cell Parameters Screen
C
3001 FORMAT (' ERROR! Cell Capacity must be greater than zero
& ' , Amp-Hours.
& '
3002 FORMAT (' ERROR! Fully Charged Voltage must be greater than
& ' , 1.78 Volts.
& '

```

```

3003 FORMAT (' ERROR! Upper Electrolyte Failure Voltage must be
      &      , greater than Fully Charged Voltage.
      &      ,
3004 FORMAT (' ERROR! Lower Electrolyte Failure Voltage must be
      &      , greater than zero.
      &      ,
3005 FORMAT (' ERROR! Lower Electrolyte Failure Voltage must be
      &      , less than Fully Charged Voltage.
      &      ,
3007 FORMAT (' ERROR! Freeze-Thaw Open Circuit Resistance value
      &      , must be at least 0.0003 ohms.
      &      ,
3008 FORMAT (' ERROR! Freeze-Thaw Closed Circuit Resistance value
      &      , must be at least 0.0003 ohms.
      &      ,
3009 FORMAT (' ERROR! Wearout Open Circuit Resistance value must
      &      , be at least 0.0003 ohms.
      &      ,
3010 FORMAT (' ERROR! Wearout Closed Circuit Resistance value must
      &      , be at least 0.0003 ohms.
      &      ,
3011 FORMAT (' ERROR! Over-Voltage Open Circuit Failure Percentage
      &      , must lie between 0 and 100.
      &      ,
3012 FORMAT (' ERROR! Over-Voltage Open Circuit Resistance value
      &      , must be at least 0.0003 ohms.
      &      ,
3013 FORMAT (' ERROR! Over-Voltage Closed Circuit Resistance value
      &      , must be at least 0.0003 ohms.
      &      ,
3014 FORMAT (' ERROR! Over-Discharge Open Circuit Failure
      &      , Percentage must lie between 0 and 100.
      &      ,
3015 FORMAT (' ERROR! Over-Discharge Open Circuit Failure
      &      , Resistance value must be at least 0.0003 ohms.
      &      ,
3016 FORMAT (' ERROR! Over-Discharge Closed Circuit Failure
      &      , Resistance value must be at least 0.0003 ohms.
      &      ,

```

```

C *****
C

```

```

C *** Edit Cell Internal Resistance Values
C

```

```

C this portion of BAT2A allows the user to input internal resistance
C values for each 10% increment of depth of discharge.

```

```

202 CALL CLRSCN
      IR = 1
      IC = 1
      CALL MOVE (IR,IC)
      WRITE(*,80) '
      CELL INTERNAL RESISTANCE '
68  FORMAT(1X,A50)
      WRITE(*,80) '
      THEORETICAL          RESISTANCE'
      WRITE(*,80) '
      CAPACITY (%)          (Ohms) '
      WRITE(*,80) '
      WRITE(*,82) (TCARAY(I),OCR(I),I=1,10)
62  FORMAT(1X,23X,F4.2,15X,F6.4)
      Write (*,*) '

```

```

C
C *** Display the Menu

```

```

WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '
WRITE (*,2010) '

```

```

      MENU
      1 Modify These Values
      2 Edit Test Conditions
      3 Edit Cell Parameters
      4 Return to Main Menu
      Enter Selection --->

```

```

      IR = IR + 21
      IC = 45
1510 CALL MOVE (IR,IC)
      Write (*,*) '
      Call Move (IR,IC)
      Read (*,'(a10)',Err=1510) Ans
      IF (Ans .EQ. ' ') Go To 1510
      Read (Ans,2003,ERR=1510) IAns
      IF ((IAns .LT. 1) .OR. (IAns .GT. 4)) Go To 1510
      IF (IAns .EQ. 1) Then
C *** Edit These Values
      Go To 1550
      ELSE IF (IAns .EQ. 2) Then
C *** Edit Test Conditions
      Go To 1200
      ELSE IF (IAns .EQ. 3) Then
C *** Edit Cell Parameters
      Go To 1300
      ELSE
C *** Main Menu
      Go To 1051
      ENDIF
C
C *** Edit These Values
C
1550 IR = 5
      IC = 41
      Do 1575 I = 1,10
1555 CALL MOVE (IR,IC)
      Call Reverse
      Write (*,*) '
      Call Move (IR,IC)
      Read (*,'(A7)') Ans
      IF (Ans .NE. ' ') Then
      IF (I .EQ. 1) READ (ANS,100,ERR=1555) OCR(1)
      IF (I .EQ. 2) READ (ANS,100,ERR=1555) OCR(2)
      IF (I .EQ. 3) READ (ANS,100,ERR=1555) OCR(3)
      IF (I .EQ. 4) READ (ANS,100,ERR=1555) OCR(4)
      IF (I .EQ. 5) READ (ANS,100,ERR=1555) OCR(5)
      IF (I .EQ. 6) READ (ANS,100,ERR=1555) OCR(6)
      IF (I .EQ. 7) READ (ANS,100,ERR=1555) OCR(7)
      IF (I .EQ. 8) READ (ANS,100,ERR=1555) OCR(8)
      IF (I .EQ. 9) READ (ANS,100,ERR=1555) OCR(9)
      IF (I .EQ. 10) READ (ANS,100,ERR=1555) OCR(10)
      END IF

```

```

C
100  FORMAT(BN,F7.0,BZ)
73  FORMAT(1X,F7.4)
      CALL RESTORE
      CALL MOVE (IR,IC)
      IF (I .EQ. 1) WRITE (*,73) OCR(1)
      IF (I .EQ. 2) WRITE (*,73) OCR(2)
      IF (I .EQ. 3) WRITE (*,73) OCR(3)
      IF (I .EQ. 4) WRITE (*,73) OCR(4)
      IF (I .EQ. 5) WRITE (*,73) OCR(5)
      IF (I .EQ. 6) WRITE (*,73) OCR(6)
      IF (I .EQ. 7) WRITE (*,73) OCR(7)
      IF (I .EQ. 8) WRITE (*,73) OCR(8)
      IF (I .EQ. 9) WRITE (*,73) OCR(9)
      IF (I .EQ. 10) WRITE (*,73) OCR(10)
      IR = IR + 1

```

```

1575 CONTINUE

```

```

C
C *** Check for errors in inputs
C

```

```

      IF ((OCR(1) .LT. 0.0003) .OR. (OCR(2) .LT. 0003) .OR.
      & (OCR(3) .LT. 0003) .OR. (OCR(4) .LT. 0003) .OR. (OCR(5) .LT. 00
      & .OR. (OCR(6) .LT. 0003) .OR. (OCR(7) .LT. 0.0003) .OR.
      & (OCR(8) .LT. 0003) .OR. (OCR(9) .LT. 0003) .OR.
      & (OCR(10) .LT. 0003)) Then

```

```

        Call Move (23,1)
        Write (*,4001)
        Go To 1550
    ENDIF
C
C *** Redo Screen if no errors
    GO TO 202
C
4001 FORMAT ('ERROR! Resistance values must be greater than ' /
&      ' 0.0003 ohms.')
C
C *****
C *** RUN SIMULATION *****
C
201 CONTINUE
*****
* Section 3: Initialization of Cell Attributes *
*
*****
IF (CELLPF.EQ.2) PARLEL = .TRUE.
    itime = 1
    time = 0.
C *** closed-circuit failure switch
    IF (switch .eq. 1) sresist = 0.0003
C *** open-circuit failure switch
    IF (switch .eq. 2) sresist = 1.E0
C *** closed-circuit or open-circuit failure switches present
    IF (switch .ne. 0) THEN
C      save original values of 8 types of resistances
        xresis = .true.
        xftfocr = ftfocr
        xftfocr = ftfocr
        xwofocr = wofocr
        xwofocr = wofocr
        xocfocr = ocfocr
        xocfocr = ocfocr
        xodfocr = odfocr
        xodfocr = odfocr
C      set new values for 8 types of resistances
        ftfocr = sresist
        ftfocr = sresist
        wofocr = sresist
        wofocr = sresist
        ocfocr = sresist
        ocfocr = sresist
        odfocr = sresist
        odfocr = sresist
    ENDIF
DO 801 I=1,MODULE
    DO 802 J=1,STRING
        qcell(i,j) = 0
        DO 803 K=1,CELL
            bcell1(i,j,k) = E
            bcell2(i,j,k) = fcharge
            bcell3(i,j,k) = ocr(1)
            bcell5(i,j,k) = .TRUE.
            bcell6(i,j,k) = .TRUE.
603 CONTINUE
602 CONTINUE
601 CONTINUE
C *** Read cycle when each cell fails (from RELY program)
C      = -1 good cell
C      > 0 failed cell. Fractional part of cycle indicates type
C      of failure as follows:
C      0.1 = open-circuit freeze-thaw failure
C      0.2 = closed-circuit freeze-thaw failure
C      0.3 = open-circuit wearout failure
C      0.4 = closed-circuit wearout failure

```

```

        READ (2,998,END=595)
        1      (((bcell4(i,j,k),k=1,cell),j=1,string),i=1,module)
998 FORMAT(4f20.10)
*****
* Section 4: Cell Failure (from RELY program) *
*
*****
        totcel = module * string * cell
        badcel = 0
        ovrdis = 0
        ovrchg = 0
        nftocf = 0
        nftccf = 0
        nwoccf = 0
        nwoccf = 0
        DO 807 I = 1,MODULE
            DO 808 J = 1,STRING
                DO 809 K = 1,CELL
                    IF(bcell4(i,j,k) .le. cycreq*0.5 .and.
1      bcell4(i,j,k) .gt. 0.0) THEN
                        bcell1(i,j,k) = 0.0
                        bcell2(i,j,k) = 0.0
                        remain = amod(bcell4(i,j,k),1.0)
                        if(remain .ge. 0.09 .and. remain .le. 0.11) then
C *** (Remain = 0.1) is freeze-thaw open-circuit failure
                            bcell3(i,j,k) = ftfocr
                            nftocf = nftocf + 1
                        else if (remain .ge. 0.19 .and. remain .le. 0.21) the
C *** (Remain = 0.2) is freeze-thaw closed-circuit failure
                            bcell3(i,j,k) = ftfocr
                            nftccf = nftccf + 1
                        else if (remain .ge. 0.29 .and. remain .le. 0.31) the
C *** (Remain = 0.3) is wearout open-circuit failure
                            bcell3(i,j,k) = wofocr
                            nwoccf = nwoccf + 1
                        else if (remain .ge. 0.39 .and. remain .le. 0.41) the
C *** (Remain = 0.4) is wearout closed-circuit failure
                            bcell3(i,j,k) = wofocr
                            nwoccf = nwoccf + 1
                        endif
                        bcell5(i,j,k) = .false.
                        badcel = badcel + 1
                    END IF
                END DO
            CONTINUE
609 CONTINUE
608 CONTINUE
607 CONTINUE
            goodcel = totcel - badcel
            OPEN(7,file='bat2a.out',form='formatted',status='new')
            *****
            * Section 5: OPEN CIRCUIT CELL VOLTAGE *
            *
            *****
500 CALL CLRSCN
        WRITE(*,'(A,F10.3)')'Calculating Battery Discharge at Time =',T
        DO 5039 I = 1,MODULE
            DO 5038 J = 1,STRING
                DO 5037 K = 1,CELL
                    HIRES(I,J,K) = 0
2037 CONTINUE
5038 CONTINUE
5039 CONTINUE
        VOLTWIN = E
        DO 850 I=1, MODULE
            DO 851 J=1, STRING
                DO 852 K=1, CELL
                    IF (bcell5(i,j,k) .AND. bcell8(i,j,k)) THEN
C *** Set knee of curve at 55% depth of discharge (i.e., at 45% of fu
C *** capacity when default EMIN is used). Set the voltage at 100%

```

```

C *** depth of discharge to be 1.78 volts.
      IF (bcell12(i,j,k) .lt. fcharge-0.5*qinit) THEN
        bcell1(i,j,k) = ((bcell2(i,j,k) -
1      (fcharge - Qinit*0.95))/Qinit) * ((E-1.78)/.45) + 1.78
      IF (bcell1(i,j,k) .lt. voltmin) voltmin = bcell1(i,j,k)
      if (bcell1(i,j,k) .le. emin) THEN
        bcell1(i,j,k) = 0.0
        bcell2(i,j,k) = 0.0
        if (podopen .eq. 0.) then
C *** All over-discharge failures are closed-circuit
          open = 1.
        else if (podopen .gt. 0. .and. podopen .lt. 100.) then
C *** Determine over-discharge failures that are open-circuit by
C *** randomly sampling and compare with input percentage (PODOPEN)
          call ranf(open,1)
        else if (podopen .eq. 100.) then
C *** All over-discharge failures are open-circuit
          open = 0.
        endif
      if (open .le. podopen/100.) then
C *** Over-discharge failure open-circuit resistance
        bcell3(i,j,k) = odfocr
      else
C *** Over-discharge failure closed-circuit resistance
        bcell3(i,j,k) = odfccr
      endif
      bcell6(i,j,k) = .false.
      badcel = badcel + 1
      ovrdis = ovrdis + 1
    endif
  endif
endif
ENDIF
END IF
852 CONTINUE
851 CONTINUE
850 CONTINUE
*****
* Section 6: CELL INTERNAL RESISTANCE *
*****
      DO 853 I=1, MODULE
        DO 854 J=1, STRING
          DO 855 K=1, CELL
C *** Calculate current charge on cell as percent of Theoretical for
C *** Resistance Calculation (TFRC). Then do a binary search on a
C *** monotonically decreasing table (TCARAY(indx),indx=1,10) and
C *** linearly interpolate to obtain Cell Resistance as a function of
C *** Theoretical Cell Capacity for Calculating Resistance.
C
          IF (bcell15(i,j,k) .AND. bcell16(i,j,k)) THEN
            tfrc = (bcell12(i,j,k) - (fcharge - .95*qinit)) / qinit
            IF (tcaray(1) - tfrc) 161,161,162
161          bcell13(i,j,k) = ocr(1)
            Go To 170
            IF (tcaray(10) - tfrc) 164,163,163
162          bcell13(i,j,k) = ocr(10)
163          Go To 170
            indx = 5
164          IF (tcaray(indx) - tfrc) 167,166,166
165          bcell13(i,j,k) = ocr(indx)
166          Go To 170
            indx = indx-1
167          Go To 165
            indx = indx-1
168          IF (tcaray(indx) - tfrc) 169,166,166
169          frac = (tfrc-tcaray(indx))/(tcaray(indx-1)-tcaray(indx))
            bcell13(i,j,k) = ocr(indx)+ frac *(ocr(indx-1)-ocr(indx))
          IF (parallel) goto 618
C **** SERIES CONNECTED BATTERIES ONLY
C
          DO 615 I=1,MODULE
            DO 616 J=1,STRING
              strvol(i,j) = 0.
              rs(i,j) = 0.
            DO 617 K=1,CELL
              strvol(i,j) = strvol(i,j) + bcell1(i,j,k)
              rs(i,j) = rs(i,j) + bcell3(i,j,k)
            CONTINUE
          617 CONTINUE
          616 CONTINUE
          615 CONTINUE
          618 CONTINUE
          *****
          * Section 8: EQUIVALENT PARALLEL RESISTANCE OF MODULE *
          *****
          6184 CONTINUE
          IF (parallel) GOTO 956
C
C **** SERIES CONNECTED BATTERIES ONLY
C
          DO 950 i=1,module
            temp(i) = 0.
            DO 951 j=1,string
              if (rs(i,j).ne.0.0) then
                stron = .true.
                DO 9511 k=1,cell
                  if (hires(i,j,k) .eq. 1) then
                    stron = .false.
                    go to 9512
                  endif
                CONTINUE
                9511 CONTINUE
                if (stron) then
                  temp(i) = temp(i) + (1./rs(i,j))
                endif
              endif
            CONTINUE
            951 CONTINUE
            if(temp(i).ne.0.0) then
              rm(i) = 1./temp(i)
            end if
          950 CONTINUE
          GOTO 956
C
C **** PARALLEL CONNECTED BATTERIES ONLY
C
          parallel is calculated just like series, except
          each cell is treated as a module. hence the strings
          are looped over both modules and cells
C
          955 CONTINUE
          DO 952 i=1,module
            DO 953 k=1,cell
              temp(i) = 0.
              DO 954 j=1,string
                if(bcell13(i,j,k).ne.0.0 and. hires(i,j,k) .eq. 0) then
                  temp(i) = temp(i) + (1./bcell13(i,j,k))

```



```

        end if
954    CONTINUE
        if(temp(i).ne.0.0) then
            rmp(i,k) = 1./temp(i)
        end if
953    CONTINUE
952    CONTINUE
956    CONTINUE
*****
*
* Section 9: Calculation of module voltage...
*
* Module voltage is calculated by use of the
* equation  $V_m = R_{eq}(-I_m + V_{s1}/R_{s1} + V_{s2}/R_{s2} + \dots$ 
*  $\dots + V_{sn}/R_{sn})$ 
*
*****
IF (par1el) GOTO 412
C
C **** SERIES CONNECTED BATTERIES ONLY
C
    totvol=0
    DO 410 i=1,module
        tapvol(i) = 0.
        DO 411 j=1,string
            if (rs(i,j).ne.0.0) then
                stron = .true.
                DO 4111 k=1,cell
                    if (hires(i,j,k) .eq. 1) then
                        stron = .false.
                        go to 4112
                    endif
                CONTINUE
            if (stron) then
                tapvol(i) = tapvol(i) + (strvol(i,j)/rs(i,j))
            endif
        end if
    411    CONTINUE
    411    CONTINUE
    vm(i) = rm(i)*(-testi-tapvol(i))
    totvol=totvol+vm(i)
410    CONTINUE
    GOTO 413
C
C **** PARALLEL CONNECTED BATTERIES ONLY
C
C    parallel is calculated just like series, except
C    each cell is treated as a module. hence the strings
C    are looped over both modules and cells
C
412    CONTINUE
    totvol=0
    DO 414 i=1,module
        DO 415 k=1,cell
            tapvlp(i,k) = 0.
            DO 416 j=1,string
                if(bcell3(i,j,k).ne.0.0 .and. hires(i,j,k) .eq. 0) then
                    tapvlp(i,k) = tapvlp(i,k) + (bcell1(i,j,k)/bcell3(i,j,k))
                end if
            CONTINUE
        416    CONTINUE
        vmp(i,k) = rmp(i,k)*(-testi+tapvlp(i,k))
        totvol=totvol+vmp(i,k)
    415    CONTINUE
    414    CONTINUE
    413    CONTINUE
*****
*
* Section 10: Data collection
*
*****
    celvol = 0.0
    celchg = 0.0

```

```

    celres = 0.0
    out(itime,1)=time
    out(itime,2)=totvol
    out(itime,3)=totvol*cellp/module
    out(itime,4)=(testi*totvol)/1000.0
    DO 350 i=1, module
        DO 351 j=1, string
            DO 352 k=1, cell
                celvol = celvol + bcell1(i,j,k)
                celchg = celchg + bcell2(i,j,k)
                celres = celres + bcell3(i,j,k)
            CONTINUE
        351    CONTINUE
    350    CONTINUE
    x = cell*string*module-badcell
C
C    x = the number of working cells.
C    if(x .ne. 0) then
        out(itime,5) = celvol/x
        out(itime,6) = celchg/x
        out(itime,7) = celres/(x-badcell)
    else
        out(itime,5) = 0.0
        out(itime,6) = 0.0
        out(itime,7) = celres/badcell
        totvol = 0.0
    endif
    out(itime,8) = ovrdis
    out(itime,9) = ovrchg
    out(itime,10)= voltmin
*****
*
* Section 11: Output conditions
*
*****
C
    IF(totvol .le. 0.001) GO TO 501
C
*****
*
* Section 12: Cell Discharge
*
*****
C
C    Charging by neighboring strings can push a cell to its charging
C    limit. The 1's in the HIRES matrix mark cells that have reached
C    the theoretical fully charged capacity limit imposed by this
C    model (95% of theoretical capacity when the default values are
C    used). At this point, the internal resistance of the marked
C    cells is assumed to be a virtual open circuit. Later when
C    conditions allow these cells to discharge, normal internal
C    resistance resumes.
C
C    QIN95 = FCHARGE + .001
C    Save initial cell capacity
    DO 6874 I = 1,MODULE
        DO 6873 J=1,STRING
            DO 6872 K=1,CELL
                BCELL7(I,J,K) = BCELL2(I,J,K)
            CONTINUE
        6873    CONTINUE
    6874    CONTINUE
    IF (par1el) GOTO 683
C
C **** SERIES CONNECTED BATTERIES ONLY
C
    DO 682 I=1,MODULE
        DO 681 J=1,STRING
            if(rs(i,j).le. 1.0E-6) rs(i,j) = 1.0E-6
            is(i,j) = (strvol(i,j)-vm(i))/rs(i,j)

```

```

      qcell(i,j) = is(i,j)*t
      DO 3621 K=1,CELL
      IF(HIRES(I,J,K).EQ.1)GOTO 3623
3621  CONTINUE
      DO 680 K=1,CELL
      IF (bcell5(i,j,k) .AND. bcell6(i,j,k)) THEN
        bcell2(i,j,k) = bcell2(i,j,k) - qcell(i,j)
      END IF
680   CONTINUE
3623  CONTINUE
681   CONTINUE
682  CONTINUE
      GOTO 684
C
C
C
C **** PARALLEL CONNECTED BATTERIES ONLY
C
C   parallel is calculated just like series, except
C   each cell has a unique current output.
C
683  CONTINUE
      DO 685 I=1,MODULE
      DO 686 J=1,STRING
      DO 687 K=1,CELL
        IF (bcell5(i,j,k) .AND. bcell6(i,j,k)) THEN
          if(bcell3(i,j,k).le. 1.0E-6) bcell3(i,j,k) = 1.0E-6
          icel = (bcell1(i,j,k)-vmp(i,k))/bcell3(i,j,k)
          qcel = icel*t
          IF(HIRES(I,J,K).EQ.1)GOTO 3627
          bcell2(i,j,k) = bcell2(i,j,k) - qcel
          if(bcell2(i,j,k).gt.qin95)hires(i,j,k)=2
        END IF
3627  CONTINUE
687   CONTINUE
686   CONTINUE
685  CONTINUE
      DO 3685 I=1,MODULE
      DO 3686 J=1,CELL
      CAPMAX = 0.
      DO 3687 K=1,STRING
      IF (HIRES(I,J,K) .EQ. 2) THEN
        SETCAP = .TRUE.
        HIRES(I,J,K) = 0
        IF (BCELL2(I,J,K).GT.CAPMAX) THEN
          CAPMAX = BCELL2(I,J,K)
          KCELL=K
        ENDIF
        SETCP = .TRUE.
      ENDIF
3687  CONTINUE
      IF(SETCAP) THEN
        SETCP = .FALSE.
        HIRES(I,J,KCELL) = 1
      ENDIF
3686  CONTINUE
3685  CONTINUE
C
C **** END OF CELL DISCHARGING, ALL CONNECTIONS
C
684  CONTINUE
C
C   For each module...
C   Find cell with maximum capacity, taken care of already
C   for parallel connections in the parallel discharge section
C
      IF(PARLEL)GOTO 6849
      CAPMAX = 0.
      DO 6844 I = 1,MODULE
      DO 6843 J = 1,STRING

```

```

      DO 6842 K = 1,CELL
      IF (BCELL2(I,J,K) .GT. CAPMAX) THEN
        CAPMAX = BCELL2(I,J,K)
        IMOD = I
        JSTR = J
        KCELL = K
      ENDIF
6842  CONTINUE
6843  CONTINUE
      IF (CAPMAX .GT. QIN95) THEN
        SETCAP = .TRUE.
        CAPMAX = 0.
        DO 6845 L = 1,CELL
          IF (BCELL2(IMOD,JSTR,L) .GT. QIN95) THEN
            HIRES (IMOD,JSTR,L) = 1
          ENDIF
6845  CONTINUE
        ENDIF
6844  CONTINUE
6849  CONTINUE
      IF (SETCAP) THEN
C   Reset cell capacity to saved cell capacity
        DO 6848 I = 1,MODULE
        DO 6847 J = 1,STRING
        DO 6846 K = 1,CELL
          BCELL2(I,J,K) = BCELL7(I,J,K)
6846  CONTINUE
6847  CONTINUE
6848  CONTINUE
        SETCAP = .FALSE.
        GO TO 6184
      ENDIF
      IF (parlel) Then
        DO 6891 I = 1,MODULE
        DO 6889 K = 1,CELL
          IF (VMP(I,K) .GT. EMAX) Then
            DO 6888 J = 1,STRING
C   FAIL ALL CELLS AS OPEN OR CLOSED CIRCUIT
            bcell1(i,j,k) = 0.0
            bcell2(i,j,k) = 0.0
            if (pocopen .eq. 0.) then
              open = 1.
            else if (pocopen .gt. 0. .and. pocopen .lt. 100.) then
              call ranf(open,i)
            else if (pocopen .eq. 100.) then
              open = 0.
            endif
            if (open .le. pocopen/100.) then
              bcell3(i,j,k) = ocfcrcr
            else
              bcell3(i,j,k) = ocfcrcr
            endif
            bcell6(i,j,k) = .false.
            badcel = badcel + 1
            ovrchg = ovrchg + 1
6888  CONTINUE
          ENDIF
6889  CONTINUE
6891  CONTINUE
        ELSE
          DO 6899 I = 1,MODULE
          DO 6898 J = 1,STRING
            VHires = 0.
            NHires = 0
            DO 6897 K = 1,CELL
              VHires = VHires + BCELL1(I,J,K)
              NHires = NHires + HIRES (I,J,K)
6897  CONTINUE
            IF (NHires .NE. 0) THEN
              DO 6896 K = 1,CELL

```

```

      IF (HIRES(I,J,K) .EQ. 1) THEN
      IF (EMAX.LT.BCELL1(I,J,K)+((VM(I)-VHIRES)/NHIRES))
      THEN
C      FAIL CELL I,J,K AS OPEN OR CLOSED CIRCUIT
      bcell1(i,j,k) = 0.0
      bcell2(i,j,k) = 0.0
      if (pocopen .eq. 0.) then
      open = 1.
      else if (pocopen .gt. 0. .and. pocopen .lt. 100.) then
      call ranf(open,i)
      else if (pocopen .eq. 100.) then
      open = 0.
      endif
      if (open .le. pocopen/100.) then
      bcell3(i,j,k) = ocfcfr
      else
      bcell3(i,j,k) = ocfcrr
      endif
      bcell6(i,j,k) = .false.
      badcel = badcel + 1
      ovrchg = ovrchg + 1
      ENDIF
6896      CONTINUE
      ELSE
      IF (IS(I,J) .LT. 0.) THEN
      IF (BCELL1(I,J,K) - IS(I,J)*BCELL3(I,J,K) .GT. EMAX) THEN
C      FAIL CELL I,J,K AS OPEN OR CLOSED CIRCUIT
      bcell1(i,j,k) = 0.0
      bcell2(i,j,k) = 0.0
      if (pocopen .eq. 0.) then
      open = 1.
      else if (pocopen .gt. 0. .and. pocopen .lt. 100.) then
      call ranf(open,i)
      else if (pocopen .eq. 100.) then
      open = 0.
      endif
      if (open .le. pocopen/100.) then
      bcell3(i,j,k) = ocfcfr
      else
      bcell3(i,j,k) = ocfcrr
      endif
      bcell6(i,j,k) = .false.
      badcel = badcel + 1
      ovrchg = ovrchg + 1
      ENDIF
      ENDIF
      ENDIF
6898      CONTINUE
6899      CONTINUE
      ENDIF
      time = time + t
      itime = itime + 1
      IF (time .lt. testtt-t/2.0) GO TO 500
      timeup = .true.
      time = time - t
      itime = itime - 1
501      CONTINUE
      CALL CLRSCN
      paralel = .false.
      *****
      *      Section 13:  Output Screen      *
      *      *****
      Call Restore
      Call ClrScn
      Call Beeper
      Write (*,10000)
10000 Format (' Calculations Complete -- Hit Return to Continue',\))

      Read (*,*)
      Call ClrScn
      n = INT(testtt/t + 1)
      write(*,025)
      write(7,025,ERR=1006)
025      format(/,/)
      write(*,026)
      write(7,026,ERR=1006)
026      format(7x,'Battery Configuration')
      write(*,027)
      write(7,027,ERR=1006)
027      format(7x,'-----')
      write(*,028) module
      write(7,028,ERR=1006) module
028      format(7x,'Number of Modules per Battery = ',i6)
      write(*,029) string
      write(7,029,ERR=1006) string
029      format(7x,'Number of Strings per Module = ',i6)
      write(*,030) cell
      write(7,030,ERR=1006) cell
030      format(7x,'Number of Cells per String = ',i6)
      write(*,301) totcel
      write(7,301,ERR=1006) totcel
031      format(7x,'Total Cells per Battery = ',i6)
      Write (*,8001)
      Write (7,8001,ERR=1006)
0001      Format (/ 7X,'Test Conditions')
      Write (*,8002)
      Write (7,8002,ERR=1006)
0002      Format (7X,'-----')
      Write (*,8003) CycReq+1
      Write (7,8003,ERR=1006) CycReq+1
0003      Format(7X,'Cycle to Analyze = '
      & i12)
      Write (*,302) nftocf
      Write (7,302,ERR=1006) nftocf
0302      Format(7x,'Cumulative Freeze-Thaw Open Circuit Failures = '
      & i12,' from RELY')
      Write (*,303) nftccf
      Write (7,303,ERR=1006) nftccf
0303      Format(7x,'Cumulative Freeze-Thaw Closed Circuit Failures = '
      & i12,' from RELY')
      Write (*,304) nwoccf
      Write (7,304,ERR=1006) nwoccf
0304      Format(7x,'Cumulative Wearout Open Circuit Failures = '
      & i12,' from RELY')
      Write (*,305) nwoccf
      Write (7,305,ERR=1006) nwoccf
0305      Format(7x,'Cumulative Wearout Closed Circuit Failures = '
      & i12,' from RELY')
      Write (*,8004) TestT
      Write (7,8004,ERR=1006) TestT
0004      Format(7X,'Duration of Test = '
      & F12.2,' Hours')
      Write (*,8005) T
      Write (7,8005,ERR=1006) T
0005      Format(7X,'Time Increment = '
      & F12.2,' Hours')
      Write (*,8006) CellPF
      Write (7,8006,ERR=1006) CellPF
0006      Format(7X,'Cell Connection: 1=Series-Par. 2=Parallel-Ser. '
      & i12)
      Write (*,8007) Switch
      Write (7,8007,ERR=1006) Switch
0007      Format(7X,'Failure Switches: 0=None. 1=Closed. 2=Open. '
      & i12)
      Write (*,8008) TestI
      Write (7,8008,ERR=1006) TestI
0008      Format(7X,'Constant Discharge Current = '
      & F12.2,' Amps')

```

```

write (*,'(a)') Hit Return to Continue'
Read (*,*)
call clrscr
write(*,031)
write(7,031,ERR=1000)
031 format(/,7x,'Cell Parameters')
write(*,032)
write(7,032,ERR=1000)
032 format(7x,'-----')
write(*,034) qinit
write(7,034,ERR=1000) qinit
034 format(7x,'Theoretical Cell Capacity = ',
& f12.2,' Amp-Hours')
write(*,0310) fcharge
write(7,0310,ERR=1000) fcharge
0310 format(7x,'Fully-Charged Cell Capacity = ',
& f12.2,' Amp-Hours')
write(*,033) e
write(7,033,ERR=1000) e
033 format(7x,'Fully Charged Open Circuit Cell Voltage = ',
& f12.2,' Volts')
write(*,0309) EMax
write(7,0309,ERR=1000) EMax
0309 format(7x,'Upper Electrolyte Failure Voltage = ',
& f12.2,' Volts')
write(*,036) emin
write(7,036,ERR=1000) emin
036 format(7x,'Lower Electrolyte Failure Voltage = ',
& f12.2,' Volts')
write(*,035) ocr(1)
write(7,035,ERR=1000) ocr(1)
035 format(7x,'Initial internal cell resistance = ',
& f12.4,' Ohms')
write(*,0311) FTFOCR
write(7,0311,ERR=1000) FTFOCR
0311 format(7x,'Freeze-Thaw Failure Open Circuit Resistance = ',
& g12.5,' Ohms')
write(*,0312) FTFCCR
write(7,0312,ERR=1000) FTFCCR
0312 format(7x,'Freeze-Thaw Failure Closed Circuit Resistance = ',
& g12.5,' Ohms')
write(*,0313) WFOOCR
write(7,0313,ERR=1000) WFOOCR
0313 format(7x,'Wearout Failure Open Circuit Resistance = ',
& g12.5,' Ohms')
write(*,0314) WFOCCR
write(7,0314,ERR=1000) WFOCCR
0314 format(7x,'Wearout Failure Closed Circuit Resistance = ',
& g12.5,' Ohms')
write(*,0315)
write(7,0315,ERR=1000)
0315 format(7x,'Over-Voltage Failure Resistance Parameters:')
write(*,0316) POCOPEN
write(7,0316,ERR=1000) POCOPEN
0316 format(7x,'Over-Voltage Failure Open Circuit Percentage = ',
& f12.2,' Percent')
write(*,0317) POCCLDS
write(7,0317,ERR=1000) POCCLDS
0317 format(7x,'Over-Voltage Failure Closed Circuit Percentage = ',
& f12.2,' Percent')
write(*,0318) OCFOCR
write(7,0318,ERR=1000) OCFOCR
0318 format(7x,'Over-Voltage Failure Open Circuit Resistance = ',
& g12.5,' Ohms')
write(*,0319) OCFCR
write(7,0319,ERR=1000) OCFCR
0319 format(7x,'Over-Voltage Failure Closed Circuit Resistance = ',
& g12.5,' Ohms')
write(*,0320)
write(7,0320,ERR=1000)

0320 format(7x,'Over-Discharge Failure Resistance Parameters:')
write(*,0321) PODOPEN
write(7,0321,ERR=1000) PODOPEN
0321 format(7x,'Over-Discharge Failure Open Circuit Percentage = ',
& f12.2,' Percent')
write(*,0322) PODCLOS
write(7,0322,ERR=1000) PODCLOS
0322 format(7x,'Over-Discharge Failure Closed Circuit Percentage = ',
& f12.2,' Percent')
write(*,0323) ODFOCR
write(7,0323,ERR=1000) ODFOCR
0323 format(7x,'Over-Discharge Failure Open Circuit Resistance = ',
& g12.5,' Ohms')
write(*,0324) ODFCCR
write(7,0324,ERR=1000) ODFCCR
0324 format(7x,'Over-Discharge Failure Closed Circuit Resistance = ',
& g12.5,' Ohms')
write (*,'(a)') Hit Return to Continue'
Read (*,*)
call clrscr
write(*,025)
write(7,025,ERR=1000)
write(*,701)
write(7,701,ERR=1000)
701 format (14x,16x,'Average',1x,'Minimum',1x,'Average',2x,'Average'
1 ' ' ' Under', ' ' ' Over')
write(*,702)
write(7,702,ERR=1000)
702 format (7x,'Total',3x,'Average',1x,'Output',1x,'Voltage',1x,
1 'Voltage',1x,'Capacity',1x,'Resist.', ' ' ' Voltage', ' ' ' Voltage'
write(*,038)
write(7,038,ERR=1000)
038 format (7x,'Battery',2x,'Module',1x,'Power',2x,'Working',
1 1x,'Working',1x,'Working',4x,'All ' ' ' Electr. ' ' ' Electr.'
write(*,039)
write(7,039,ERR=1000)
039 format(2x,'Time',1x,'Voltage',1x,'Voltage',1x,'(kw)',3x,'Cells
1 1x,'Cells',1x,'Cells',2x,'Cells ' ' ' Fails ' ' ' Fails')
write(*,040)
write(7,040,ERR=1000)
040 format (2x,'(Hr)',3x,'(V)',5x,'(V)',12x,'(V)',5x,'(V)',3x,'(Amp
1)',2x,'(Ohms)')
DO 826 Q=1,itime
write(*,041) out(q,1),out(q,2),out(q,3),out(q,4),out(q,5),
* out(q,10),out(q,6),out(q,7),out(q,8),out(q,9)
write(7,041,ERR=1000) out(q,1),out(q,2),out(q,3),out(q,4),
* out(q,5),out(q,10),out(q,6),out(q,7),out(q,8),out(q,9)
041 format(1x,f5.2,2x,f8.2,1x,f7.2,1x,f5.2,f8.2,f8.2,2x,
* f8.2,2x,g10.3,1x,f5.0,1x,f7.0)
826 CONTINUE
y3 = 5.0
if(timeup) then
write(*,042) time
write(7,042,ERR=1000) time
042 format(/,2x,'Discharge Stopped at ',f7.2,' hours',/)
else
write(*,048) testi,time
write(7,048,ERR=1000) testi,time
048 format(/,1x,'Battery unable to deliver ',f7.2,
1 ' ' ' amps at time ',f7.2,' hours',/)
end if
write(*,*)Results have been written to BAT2A.OUT'
Write (*,'(a)') Hit Return to Continue'
Read (*,*)
*****
*
* Section 14: Graphics Screen
*
*****
9000 Call RsltMenu (IR,IC)

```

```

9001 Call Move (IR,IC)
Write (*,*)
Call Move (IR,IC)
Read (*,'(a10)',Err=9001) Ans
IF (Ans.EQ. ' ') Go To 9001
Read (Ans,2003,err=9001) IAns
IF ((IAns.LT. 1) .OR. (IAns.GT. 3)) Go To 9001
IF (IAns.EQ. 1) Then
  if(itime.eq.1) Then
    Call Move (22,1)
    Write (*,9000)
9000 Format (' Graphs are not available due to limited results')
    Go To 9001
  Else
    Go to 9010
  EndIf
Else IF (IAns.EQ. 2) Then
  Go To 502
Else
  Close (2)
  Go To 509
EndIf
9010 Call GrphMenu (IR,IC)
9002 Call Move (IR,IC)
Write (*,*)
Call Move (IR,IC)
Read (*,'(a10)',Err=9002) Ans
IF (Ans.EQ. ' ') Go To 9002
Read (Ans,2003,Err=9002) k1
IF ((k1.LT. 1) .OR. (k1.GT. 4)) Go To 9002
IF (k1.EQ. 4) Then
  Go To 9000
Else
  Go To 9003
EndIf
9003 k2 = k1 + 1
iorg = 1
xscale = 1.0
xst = 0.0
xfin = time - t
yst = 0.0
yfin = 0.0
n = itime - 1
npt = itime - 1
C
C--> set x and y arrays to plot
DO 627 I=1,n
  xarray(i) = out(i,1)
  yarray(i) = out(i,k2)
627 CONTINUE
C
C *** find max. & min. y values
DO 628 I=1,n
  if(i.eq.1) then
    yst = yarray(i)
    yfin = yarray(i)
  endif
  if(yarray(i).lt.yst) yst = yarray(i)
  if(yarray(i).gt.yfin) yfin = yarray(i)
628 CONTINUE
C
C *** round off axis bounds
i = yst
yst = i
if (yfin.ge. 0.50) then
  i = yfin
  yfin = i + 1.0
else
  yfin = 1.50 * yfin
endif

```

```

i = xfin
xfin = i + 1.0
xfin = xfin * 10.0
round = 4.0
if(xfin.gt.100.0) round = 40.0
DO 76 i = 1, 1000
  r1 = xfin/round
  j = xfin/round
  r2 = j
  if(r1.eq.r2) go to 77
  xfin = xfin + 1.0
76 continue
77 continue
xfin = xfin/10.0
if(yst.lt.4.0) yst = 0.0
ylen = yfin - yst
round = 4.0
nmm = 0
if(ylen.lt.2.0 .and. yfin.ge.1.0) then
  yfin = yfin+10
  nmm = 1
endif
if(ylen.gt.100.0) round = 40.0
if (yfin.lt. 1.0) go to 79
DO 78 i = 1, 1000
  ylen = yfin - yst
  r1 = ylen/round
  j = ylen/round
  r2 = j
  if(r1.eq.r2) go to 79
  yfin = yfin + 1.0
78 continue
79 continue
if(nmm.eq.1) yfin = yfin/10
if(yfin.eq. 0.) yfin = 1.0
C
C *** draw plot
mode = 8
CALL QSMODE (mode)
itype = 1
ndots = 0
lkolor = 3
isymb1 = -1
klrsym = 1
CALL QSETUP (ndots,lkolor,isymb1,klrsym)
CALL QPTABL (iorg,xscale,xst,xfin,yst,yfin,
1 itype,npt,xarray,yarray)
C
nchar = 40
kolor = 1
icol = 20
irow = 2
if (k2.eq. 2) char = ' Total Voltage vs Discharge Time'
if (k2.eq. 3)
1 char = 'Average Module Voltage vs Discharge Time'
if (k2.eq. 4) char = ' Power (kW) vs Discharge Time'
CALL QPTXT (nchar,char,kolor,icol,irow)
if(k2.eq.2.OR.k2.eq.3) then
  nchar = 8
  icol = 11
  irow = 21
  char = '(volts)'
else
  nchar = 5
  icol = 12
  irow = 21
  char = '(kW)'
endif
CALL QPTXT (nchar,char,kolor,icol,irow)
nchar = 8

```

```

icol = 70
irow = 5
char = '(hours)'
CALL QPTXT (nchar,char,kolor,icol,irow)
kolor = 3
nchar = 25
icol = 28
irow = 20
char = 'To Continue Hit Return'
CALL QPTXT (nchar,char,kolor,icol,irow)
read(*,047) c
047 format(a1)
mode = 2
CALL QSMODE (mode)
Call RsltMenu (IR,IC)
Go To 9010

*****
*
* Section 15: Table of bad cells
*
*****
502 call CLRSCN
write (*,*) '
write (7,*,ERR=1006) '
write (*,055) ' R
write (7,055,ERR=1006) ' R
write (*,055) ' E
write (7,055,ERR=1006) ' E
write (*,055) ' L
write (7,055,ERR=1006) ' L
write (*,055) ' M S Y S DETAILED
write (7,055,ERR=1006) ' M S Y S DETAILED
055 format(a25)
write (*,055) ' O T T DISCHARGE'
write (7,055,ERR=1006) ' O T T DISCHARGE'
write (*,055) ' D R C C A MODEL
write (7,055,ERR=1006) ' D R C C A MODEL
write (*,055) ' U I E E T FINAL
write (7,055,ERR=1006) ' U I E E T FINAL
write (*,055) ' L N L L U CELL
write (7,055,ERR=1006) ' L N L L U CELL
write (*,055) ' E G L L S RESISTANCE'
write (7,055,ERR=1006) ' E G L L S RESISTANCE'
write (*,054)
write (7,054,ERR=1006)
054 format(1x,'-- -- -- --',/)
DO 355 i=1, module
DO 356 j=1, string
DO 357 k=1, cell
good = .true.
if (bcell14(i,j,k) .le. cycreq*0.5 .and.
1 bcell14(i,j,k) .ne. -1.0) good = .false.
if (good) then
write (*,056) i,j,k,bcell13(i,j,k)
write (7,056,ERR=1006) i,j,k,bcell13(i,j,k)
056 format(3(1x,i2), ' good ',g11.5)
else
write (*,057) i,j,k,bcell13(i,j,k)
write (7,057,ERR=1006) i,j,k,bcell13(i,j,k)
057 format(3(1x,i2), ' bad ',g11.5)
end if
357 CONTINUE
356 CONTINUE
355 CONTINUE
write (*,*) '
C
C
503 write (*,'(a)\') ' Hit Return to Continue
read(*,*)
Go To 9000

```

```

1000 goto 1002
595 WRITE (*,*) 'mismatch on size of battery'
C *** Branch to 1002 ==> Exit to Life Cycle Model
1002 Open (3, file = 'STOP1.TMP', Status = 'NEW')
Close (3)
C *** Branch to 1004 ==> Exit to DOS
1004 Call ClrScn
Call QSMODE (ModeBeg)
Stop
C *** Branc to 1006 ==> File Error Occurred
1006 Call ClrScn
Write (*,*) ' Additional Storage Space Needed.'
Write (*,*) ' Use Data Disk or Hard Disk.
Call QSMODE (ModeBeg)
Stop
END

```

<< Subroutines >>

```

SUBROUTINE YSCALE (YMAX, IPOWER, PSCALE)

*****
DESCRIPTION:  DETERMINES THE POWER OF 10 SUCH THAT THE MAXIMUM
Y-AXIS ARRAY VALUE FOR PLOTTING CAN BE REPRESENTED
IN SCIENTIFIC NOTATION AS A MANTISSA >= 0.1 AND
< 10. TIMES THIS POWER OF 10. THE LATTER IS USED
AS THE SCALING FACTOR TO APPLY TO THE Y-AXIS ARRAY
PRIOR TO PLOTTING.

ARGUMENTS:    YMAX (INPUT AND OUTPUT) = MAXIMUM VALUE OF Y-AXIS
              ARRAY BEFORE SCALING ON INPUT AND AFTER SCALING
              ON OUTPUT FROM THIS ROUTINE

              IPOWER (OUTPUT) = INTEGRAL POWER OF 10

              PSCALE (OUTPUT) = SCALING FACTOR TO APPLY TO Y-AXIS

```

```

C          ARRAY PRIOR TO PLOTTING
C
C LOGICAL NAMES AND FILES USED:  NONE
C
C ROUTINES USED:  NONE
C
C CONSTANTS (PARAMETER STATEMENTS):  NONE

```

```

*****
C      IPOWER = 0
1      IF (YMAX .GE. 10.) THEN
          IPOWER = IPOWER + 1
          YMAX = YMAX / 10.
          GO TO 1
      ENDIF
2      IF (YMAX .LT. 0.1) THEN
          IPOWER = IPOWER - 1
          YMAX = YMAX * 10.
          GO TO 2
      ENDIF
      PSCALE = 10.** IPOWER
      RETURN
      END

```

```

C      CONSTANTS (PARAMETER STATEMENTS):  NONE
C
C      *****
C
C      IPOWER = 0
1      IF (XMAX .GE. 10000.) THEN
          IPOWER = IPOWER + 1
          XMAX = XMAX / 10.
          GO TO 1
      ENDOF
2      IF (XMAX .LT. 0.1) THEN
          IPOWER = IPOWER - 1
          XMAX = XMAX * 10.
          GO TO 2
      ENDOF
      PSCALE = 10.** IPOWER
      RETURN
      END

```

```

C
SUBROUTINE FAILURE(BAD)
C
C *****
C DESCRIPTION: calculates random cell failure value.
C
C ARGUMENTS:
C BAD (0) = random failure value
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED:
C RANF = returns random #
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS:
C
$INCLUDE: 'WEIBUL.INC'
C
C WEIBUL.INC -- Weibul distribution parameters
C
C VARIABLES:
C

```

```

SUBROUTINE XSCAL (XMAX, IPOWER, PSCALE)
C
C *****
C DESCRIPTION:  DETERMINES THE POWER OF 10 SUCH THAT THE MAXIMUM
C X-AXIS ARRAY VALUE FOR PLOTTING CAN BE REPRESENTED
C IN SCIENTIFIC NOTATION AS A MANTISSA >= 0.1 AND
C < 10,000 TIMES THIS POWER OF 10.  THE LATTER IS
C USED AS THE SCALING FACTOR TO APPLY TO THE X-AXIS
C ARRAY PRIOR TO PLOTTING.
C
C ARGUMENTS:  XMAX (INPUT AND OUTPUT) = MAXIMUM VALUE OF X-AXIS
C ARRAY BEFORE SCALING ON INPUT AND AFTER SCALING ON
C OUTPUT FROM THIS ROUTINE.

```

```

C
C *****
C
C---> calculate random failure
C      RANF returns random number between 0.0 and 1.0
C      ALOG is natural log
C      neg. sign makes number pos. (natural logs of 0-1 are neg.
CALL RANF(R,L)
BAD = LOCATE * SCALE*((-ALOG(R))**(1/SHAPE))
RETURN
END

```

```

C      IPOWER (OUTPUT) = INTEGRAL POWER OF 10
C
C      PSCALE (OUTPUT) = SCALING FACTOR TO APPLY TO X-AXIS ARRAY PRIOR
C                        TO PLOTTING
C
C      LOGICAL NAMES AND FILES USED:  NONE
C
C      ROUTINES USED:  NONE

```

```

C      FUNCTION GAMMA(X)
C
C      *****
C
C      DESCRIPTION:  CALCULATES GAMMA FUNCTION OF (1.-X) USING ALGORITHM
C                   FROM "APPROXIMATIONS FOR DIGITAL COMPUTERS"
C
C                   (PAGE 158) BY C. HASTINGS (1955)

```

```

C
C ARGUMENTS: 0 <= X <=1.
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C REAL X,Y,Z,TEMP1,TEMP2,A1,A2,A3,A4,A5,A6,A7,A8
C DATA A1 /-.577191852/
C DATA A2 /-.988205891/
C DATA A3 /-.897056937/
C DATA A4 /-.918208857/
C DATA A5 /-.758704078/
C DATA A6 /-.482199394/
C DATA A7 /-.193527818/
C DATA A8 /-.035888343/
C *****
C
C Y = 1.-X
C TEMP1 = 1.
C 1 IF (Y .GT. 2.) THEN
C   TEMP1 = (Y-1.)*TEMP1
C   Y = Y-1.
C   GOTO 1
C ENDIF
C Z = Y-1.
C TEMP2 = 1. + A1*Z + A2*Z**2 + A3*Z**3 + A4*Z**4 + A5*Z**5
C      + A6*Z**6 + A7*Z**7 + A8*Z**8
C GAMMA = TEMP1 * TEMP2
C RETURN
C END

```

```

C
C SUBROUTINE RESCHCK(A,B,C,RESIT,CYCLE,STRSTAT)
C
C *****
C DESCRIPTION:
C
C ARGUMENTS:
C A (I) = 'X' dimension in CELLDAT array
C B (I) = 'Y' dimension in CELLDAT array
C RESIT (I) = Type of cell failure (see definition of
C CELLDAT in RELY.INC)
C CYCLE (I) = Cycle in which failure occurred
C STRSTAT(I,J) = Status of string J, module I
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS:
C
C $INCLUDE: 'PARM.INC'
C $INCLUDE: 'RELY.INC'
C
C PARM.INC -- size of battery
C RELY.INC -- data info for RELY
C
C VARIABLES:
C
C INTEGER A, B, C, CYCLE, STRSTAT(ROWSIZ, COLSIZ)
C CHARACTER RESIT*2

```

```

C *****
C
C IF (RESIT .EQ. 'F0') THEN
C
C ---> Open-circuit freeze-thaw failure
C
C   CELLDAT(A,B,C,1) = FLOAT(CYCLE) + 0.1
C   IF (STRSTAT(A,B) .EQ. -1) STRSTAT(A,B) = CYCLE
C   ELSEIF (RESIT .EQ. 'FS') THEN
C
C ---> Closed-circuit freeze-thaw failure
C
C   CELLDAT(A,B,C,1) = FLOAT(CYCLE) + 0.2
C   ELSEIF (RESIT .EQ. 'W0') THEN
C
C ---> Open-circuit wearout failure
C
C   CELLDAT(A,B,C,1) = FLOAT(CYCLE) + 0.3
C   IF (STRSTAT(A,B) .EQ. -1) STRSTAT(A,B) = CYCLE
C   ELSE
C
C ---> Closed-circuit wearout failure
C
C   CELLDAT(A,B,C,1) = FLOAT(CYCLE) + 0.4
C ENDIF
C RETURN
C END

```

```

C
C SUBROUTINE PG2HEAD(OPM)
C
C *****
C DESCRIPTION: Writes the page heading for the second output p
C
C ARGUMENTS:
C OPM (I) = output mode - if 0, output to screen,
C if not 0, output written to logical unit
C OPM output file
C
C LOGICAL NAMES AND FILES USED:
C OPM = logical unit for output file
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C INTEGER OPM
C
C *****
C
C WRITE (OPM,95)
C WRITE (OPM,97) 'CYCLE LIFE AND FAILURE TOTALS:'
C WRITE (OPM,96)
C IF (OPM .EQ. 0) THEN
C   WRITE (*,'(A)') ' Hit Return to Continue '
C   READ (*,*)
C   CALL CLRSCRN
C ENDIF
C WRITE (OPM,'(///)')
C WRITE (OPM,98) 'NUMBER OF FAILURES'
C WRITE (OPM,99) '      FREEZE-THAW      WEAROUTS'
C WRITE (OPM,99) 'CYCLE      -----'
C WRITE (OPM,97) 'RUN LIFE OPEN CLOSED TOTAL OPEN CLOSED TOTAL'
C WRITE (OPM,97) '-----'
C WRITE (OPM,96)

```



```

RETURN
95 FORMAT ('1'//)
96 FORMAT (/)
97 FORMAT (9X,A)
98 FORMAT (28X,A)
99 FORMAT (14X,A)
END

```

SUBROUTINE PG3HEAD (OPM)

```

C
C *****
C DESCRIPTION: Writes the heading for the third output page.
C
C ARGUMENTS:
C     OPM (I) = output mode - if 0, output to screen,
C               if not 0, output written to logical unit
C               OPM output file
C
C LOGICAL NAMES AND FILES USED:
C     OPM = logical unit for output XXX file
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C INTEGER OPM

```

```

C *****
C IF (OPM .EQ. 0) THEN
C   WRITE (*,*) ' '
C   WRITE (*, '(A)') ' Hit Return to Continue '
C   READ (*,*)
C   CALL CLRSCN
C ENDIF
C WRITE (OPM,105)
C WRITE (OPM,106) 'FAILURE DISTRIBUTIONS:'
C WRITE (OPM,106)
C 1 '
C   AVERAGE NUMBER OF FAILURES'
C WRITE (OPM,106)
C 1 '
C   FREEZE-THAW      WEAROUTS'
C WRITE (OPM,106)
C 1 '
C   -----'
C WRITE (OPM,106)
C 1 'RANGE
C   OPEN CLOSED      OPEN CLOSED'
C WRITE (OPM,106)
C 1 '-----'
C   ----
C RETURN
105 FORMAT ('1'//)
106 FORMAT (11X,A)
END

```

SUBROUTINE RANF(R,L)

```

C
C *****
C DESCRIPTION: returns a pseudo-random number rectangularly
C               distributed between 0 and 1.
C               algorithm AS 183 APPL.STATIST. (1982) VOL.31, NO.2
C
C ARGUMENTS:
C     R (0) = random number

```

```

C     L (0) = counter of no. times routine called
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C INTEGER IX, IY, IZ
C REAL R
C DATA IX, IY, IZ / 1111, 2222, 3333 /
C
C IX, IY, and IZ should be set to integer values between
C 1 and 30,000 before first entry.
C *****
C
C IX = MOD(171*IX,30269)
C IY = MOD(172*IY,30307)
C IZ = MOD(170*IZ,30323)
C
C ----> calculate random number
C R = AMOD(FLOAT(IX) / 30269.0 + FLOAT(IY) / 30307.0 +
C * FLOAT(IZ) / 30323.0, 1.0)
C L = L + 1
C RETURN
C END

```

SUBROUTINE MainMenu (IR,IC)

```

C
C *** This subroutine prints the main menu for the Detailed
C *** Discharge Model
C
C *****
C **
C ** DISPLAY MAIN MENU
C **
C *****
C
C CALL ClrScn
C IR = 1
C IC = 1
C CALL Move (IR,IC)
C WRITE (*,801) 'DETAILED DISCHARGE MODEL'
801 FORMAT (29X, A24)
802 FORMAT (20X, A41)
C IR = IR+2
C CALL Move (IR,IC)
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C WRITE (*,802) '
C IR = IR+9
C IC = 45
C CALL Move (IR,IC)
C RETURN
C END

```

MAIN MENU	
1	EDIT Performance Data
2	VIEW Battery Configuration
3	RUN Simulation
4	SAVE Performance Data
5	EXIT to Life-Cycle Model
6	EXIT to DOS
Enter Selection --->	

```

SUBROUTINE ScrnMenu (IR,IC)

```

```

C
C *** This subroutine displays the Screen Selection Menu
C *** below the main menu and prompts the user for a
C *** selection
C

```

```

IR = IR+3
IC = 1
CALL Move (IR,IC)
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
801 FORMAT (17X,A45)
IR = IR+6
IC = 43
CALL Move (IR,IC)
RETURN
END

```

```

SELECT INPUT SCREEN
1 Test Conditions
2 Cell Parameters
3 Edit Cell Internal Resistance
4 Return to Main Menu
Enter Selection --->

```

```

SUBROUTINE RsltMenu (IR,IC)

```

```

C
C *** This menu gives the user the choice between graphical
C *** analysis, listing a table of cells, and returning to
C *** the main menu.
C
C

```

```

CALL ClrScn
IR = 3
IC = 1
CALL Move (IR,IC)
801 FORMAT (29X, A24)
802 FORMAT (20X, A41)
WRITE (*,802) '
WRITE (*,802) '
WRITE (*,802) '
WRITE (*,802) '
WRITE (*,802) '
WRITE (*,802) '
WRITE (*,802) '
WRITE (*,802) '
IR = IR+6
IC = 45
CALL Move (IR,IC)
RETURN
END

```

```

ANALYSIS OF RESULTS
1 GRAPHICAL Analysis
2 TABLE of Cells
3 RETURN to Main Menu
Enter Selection --->

```

```

SUBROUTINE GrphMenu (IR,IC)

```

```

C
C *** This menu gives the user the choice of several graphs
C *** to help interpret the results
C

```

```

IR = IR+3
IC = 1
CALL Move (IR,IC)
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '
WRITE (*,801) '

```

```

GRAPHICAL ANALYSIS
1 Total Voltage vs Time
2 Average Module Voltage vs Time
3 Total Power vs Time

```

```

WRITE (*,801) ' 4 Return to Previous Menu
WRITE (*,801) ' Enter Selection --->
WRITE (*,801) '
801 FORMAT (17X,A45)
IR = IR+6
IC = 43
CALL Move (IR,IC)
RETURN
END

```

```

SUBROUTINE OUTPG1(OUT,OPM)

```

```

C
C *****
C DESCRIPTION: writes output page
C

```

```

C ARGUMENTS:

```

```

C OUT (I) = specifies output:

```

```

C F = output to file

```

```

C S = output to screen

```

```

C OPM (O) = output mode - if 0, output to screen,
C if not 0, output written to logical unit
C OPM output file
C

```

```

C LOGICAL NAMES AND FILES USED:

```

```

C if OPM not equal to zero, output file created
C

```

```

C ROUTINES USED: (NONE)
C

```

```

C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C

```

```

C COMMON BLOCKS:
C

```

```

C $INCLUDE: 'PARM.INC'

```

```

C $INCLUDE: 'RELY.INC'

```

```

C $INCLUDE: 'WEIBUL.INC'
C

```

```

C PARM.INC -- size of battery

```

```

C RELY.INC -- data info for RELY

```

```

C WEIBUL.INC -- Weibul distribution parameters
C

```

```

C VARIABLES:
C

```

```

C CHARACTER OUT*1

```

```

C LOGICAL OPFLAG

```

```

C INTEGER OPM

```

```

C DATA OPFLAG /.TRUE./
C

```

```

C NOTE : THE COMMON VARIABLES CELLDAT AND FDATA
C ARE NOT USED IN THIS SUBROUTINE.
C

```

```

C PARAMETERS SET BY THE USER IN THE MAIN PROGRAM:

```

```

C SHAPE,SCALE,PREMAY,DIMCAPA

```

```

C CELLREQ, STRGREQ, MODREQ, LOCATE

```

```

C FDATA(4,100)

```

```

C RESIST
C

```

```

C VARIABLES DESCRIBING THE CELL CONFIGURATION:

```

```

C CELLDAT(10,10,20,3)

```

```

C MODULE, STRING, CELLS
C

```

```

C VARIABLES SIGNIFYING THE OUTPUT MODE:

```

```

C OUT*1, OPM, OPFLAG
C

```

```

C ----> prepare output mode: clear screen or open output file
C IF (OUT.EQ. 'S') THEN
C CALL CLRSCN

```

```

      OPM = 0
    ELSE
      OPM = 7
      WRITE(*, '(A)') ' writing output to file 'RELY.OUT'...'
      IF(OPFLAG) THEN
        OPEN(OPM, FILE='RELY.OUT', ACCESS='SEQUENTIAL', STATUS='NEW')
      ENDIF
      OPFLAG = .FALSE.
    ENDIF
  C
  C---> write output
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) '          ESTIMATE OF BATTERY LIFE '
  WRITE (OPM, 715) '          ----- '
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) 'BATTERY CONFIGURATION TESTED: '
  WRITE (OPM, 715) ' '
  WRITE (OPM, 700) CELLS
  WRITE (OPM, 701) STRING
  WRITE (OPM, 702) MODULE
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) 'FAILURE CRITERIA: '
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) ' MINIMUM ACCEPTABLE '
  WRITE (OPM, 703) CELLREQ
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) ' MINIMUM ACCEPTABLE'
  WRITE (OPM, 704) STRGREQ
  WRITE (OPM, 715) ' '
  WRITE (OPM, 715) ' MINIMUM ACCEPTABLE'
  WRITE (OPM, 705) MODREQ
  WRITE (OPM, 715) ' '
  IF (OPM .EQ. 0) THEN
    WRITE (*, '(A)') ' Hit Return to Continue '
    READ (*, *)
    CALL CLRSCN
  ENDIF
  WRITE (OPM, 715) 'FAILURE RATES: '
  WRITE (OPM, 715) ' '
  WRITE (OPM, 710) FTFREQ
  WRITE (OPM, 706) PREMAY
  WRITE (OPM, 708)
  WRITE (OPM, 709) LOCATE
  WRITE (OPM, 710) SCALE
  WRITE (OPM, 711) SHAPE
  WRITE (OPM, 715) ' '
  WRITE (OPM, 712)
  WRITE (OPM, 715) ' '
  WRITE (OPM, 713) PFOpen, PFShort
  WRITE (OPM, 714) PWOpen, PWShort
  RETURN
700 FORMAT(1X, ' CELLS PER STRING   = ', I3)
701 FORMAT(1X, ' STRINGS PER MODULE = ', I3)
702 FORMAT(1X, ' MODULES PER BATTERY = ', I3)
703 FORMAT(1X, ' NUMBER OF CELLS PER STRING = ', I3)
704 FORMAT(1X, ' NUMBER OF STRINGS PER MODULE = ', I3)
705 FORMAT(1X, ' NUMBER OF MODULES PER BATTERY = ', I3)
706 FORMAT(1X, ' FREEZE-THAW CELL FAILURE RATE PER CYCLE= ', F8.4)
710 FORMAT(1X, ' NO. CYCLES BETWEEN FREEZE-THAWS = ', F5.0)
707 FORMAT(1X, ' DIMINISHED CAPACITY PER CYCLE= ', F4.2)
708 FORMAT(1X, ' FAILURE DUE TO WEAROUT: ')
709 FORMAT(1X, ' WEIBULL PARAMETERS - LOCATION = ', I5)
710 FORMAT(1X, ' SCALE = ', F8.2)
711 FORMAT(1X, ' SHAPE = ', F5.2)
712 FORMAT(1X, ' POST FAILURE RESISTANCE PARAMETERS : ')
713 FORMAT(1X, ' FREEZE-THAW FAILURE OPEN   CIRCUIT PERCENTAGE = ',

```

```

1 F8.2 /1X, ' FREEZE-THAW FAILURE CLOSED CIRCUIT PERCENTAGE = '
2 F8.2)
714 FORMAT(1X, ' WEAROUT FAILURE OPEN   CIRCUIT PERCENTAGE   = '
1 F8.2 /1X, ' WEAROUT FAILURE CLOSED CIRCUIT PERCENTAGE   = '
2 F8.2)
715 FORMAT(1X, A)
END

```

```

SUBROUTINE SIMULAT(RUN, COUNTER, CYCLE)
C
C *****
C DESCRIPTION: Simulates battery life. Calculates failure of
C              battery cells.
C
C ARGUMENTS:
C   RUN (I) = number of simulation runs
C   COUNTER (O) = number of cycles of battery life
C   AVELIFE (O) = average cycle life
C
C LOGICAL NAMES AND FILES USED:
C   OPM = output written to output mode; screen or output
C         file.
C
C ROUTINES USED:
C   UPCAS, OUTPG1, PG2HEAD, FAILURE, RESCHCK, PG3HEAD, P.
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS:
C $INCLUDE: 'PARM.INC'
C $INCLUDE: 'RELY.INC'
C
C   PARM.INC -- size of battery
C   RELY.INC -- data info for RELY
C
C VARIABLES:
C CHARACTER*1 OUT
C LOGICAL FTFLAG
C INTEGER A, B, C, OPM, FLMAX, RUN, STRSTAT(ROWSIZ, COLSIZ)
C INTEGER PREMIES, WEROUTS, CYCLE, WEARSUM, PRESUM, SUMLIFE
C INTEGER COUNTER, N, IFTFRQ, NROW, NN, L, IFLG
C INTEGER AA, STSUM, MODSUM, CSUM, RANGE
C INTEGER LIFESQ, M, WEARSQ, PRESQ, P, R, S
C INTEGER FTOPEN, FTSHORT, WROpen, WRShort, FTOSUM, FTSSUM
C INTEGER WROSUM, WRSSUM, FTOSQ, FTSSQ, WROSQ, WRSSQ
C REAL BAD, RFTFRQ, R1, R2, PREM
C REAL AVELIFE, STDEV, SQRT, PREAV, WEARAV
C REAL CYLFSO, PRESO, WEARSO, Q
C REAL FTOAV, FTSV, FTOSD, FTSSD, WROAV, WRSV
C REAL WROSD, WRSSD
C
C VARIABLES SET BY THE USER:
C RUN, OPM, LOCATE
C CELLREQ, STRGREQ, MODREQ
C DIMCAPA, PREMAY, SHAPE, SCALE, BAD
C RESIST, OUT
C
C VARIABLES REPRESENTING THE BATTERY CONFIGURATION:
C MODULE, STRING, CELLS, A, B, C
C CELLDAT(10, 10, 20, 1)
C
C VARIABLES FOR RESULTS:
C PREMIES, WEROUTS, CYCLE, WEARSUM, PRESUM, SUMLIFE
C
C FOR WORKING CALCULATIONS:

```

```

C      COUNTER, FDATA(4,100), N
C      AA, STSUM, MODSUM, CSUM, RANGE, STRSTAT
C      LIFESQ, W, WEARSQ, PRESQ, P, R, S, PREM
C      AVELIFE, STDEV, SQRT, PREAV, WEARAV
C      CYLFSQ, PRESQ, WEARSD, Q
C
*****
C
402  CONTINUE
      WRITE(*, '(//A)\') ' DELIVER OUTPUT TO FILE OR TO SCREEN? (F/S):' 10
      READ (*, '(A)') OUT
      IF (.NOT.(OUT .EQ. 'F' .OR. OUT .EQ. 'f' .OR.
1      OUT .EQ. 'S' .OR. OUT .EQ. 's')) GOTO 402
C
C---> write first output page, header for second page
      CALL UPCAS(OUT)
      CALL OUTPG1 (OUT,OPW)
      CALL PG2HEAD (OPW)
C
C---> initialize variables, start monte carlo simulation
      SUMLIFE = 0
      LIFESQ = 0
      WEARSUM = 0
      WEARSQ = 0
      PRESUM = 0
      PRESQ = 0
      FTOSUM = 0
      FTSSUM = 0
      FTOSQ = 0
      FTSSQ = 0
      WROSUM = 0
      WRSSUM = 0
      WROSQ = 0
      WRSSQ = 0
      FLMAX = 0
      NROW = 9
      DO 990 N = 1,4
      DO 990 NN = 1, FLGRP
      FDATA(N,NN) = 0
990  CONTINUE
      DO 1000 N = 1,RUN
      NROW = NROW + 1
      IF(NROW.GE.24.AND.OPW.EQ.0) THEN
      NROW = 10
      DO 639 NN = 10, 24
      CALL MOVE(NN,1)
      WRITE(*,*) ' ',
1
639  CONTINUE
      ENDIF
      CALL MOVE(1,40)
      WRITE(*, '(A,I7)') 'CALCULATING RUN',N
C
C---> assign each cell with a cycle at which it will wear out.
      DO 701 I = 1,MODULE
      DO 702 J = 1,STRING
      STRSTAT(I,J) = -1
      DO 703 K = 1,CELLS
      CALL FAILURE (CELLDAT(I,J,K,2))
      CELLDAT(I,J,K,1) = -1.0
703  CONTINUE
702  CONTINUE
701  CONTINUE
C
C---> THE FOLLOWING CODE SIMULATES CYCLES OF BATTERY LIFE UNTIL
C      BATTERY CAPACITY FALLS BELOW MINIMUM USEFUL CAPACITY.
C---> initializations for each simulation run
      RANGE = 0
      WEROUTS = 0
      PREMIES = 0
      FTOPEN = 0
      FTSHORT = 0
      WROPEN = 0
      WRSHORT = 0
      MODSUM = 0
      CYCLE = 0
      COUNTER = COUNTER + 1
      IFTFRQ = FTFREQ
      RFTFRQ = IFTFRQ
      CONTINUE
      CALL MOVE(2,40)
      WRITE(*, '(A,I9)') 'CALCULATING DISCHARGE CYCLE',CYCLE+1
C---> freeze-thaw failures only during cycles that have
C      freeze thaws. (no. cycles between freeze thaws)
      FTFLAG = .FALSE.
      IF(FTFREQ.GT.1.0) THEN
      R1 = (CYCLE-RFTFRQ)/RFTFRQ
      NN = (CYCLE-RFTFRQ)/RFTFRQ
      R2 = NN
      IF(R1.EQ.R2) FTFLAG = .TRUE.
      ENDIF
      IF(FTFREQ.LE.1.0) FTFLAG = .TRUE.
C
C---> calculate which display group this cycle belongs in (for
C      accumulating freeze-thaw and wearout failures)
      IF (CYCLE .LE. MXFLCY) THEN
      IFLG = (CYCLE/FLGRP) + 1
      ELSE
      IFLG = FLGRP
      ENDIF
      MODSUM = 0
      DO 20 A = 1,MODULE
      STSUM = 0
      DO 30 B = 1,STRING
      CSUM = 0
      DO 40 C = 1,CELLS
      IF (CELLDAT(A,B,C,1) .EQ. -1.0) THEN
      IF(FTFLAG) THEN
      CALL RANF (PREM,L)
      IF (PREM .LE. PREMAX) THEN
C
C---> Freeze-thaw failure
C
      PREMIES = PREMIES + 1
      IF (PFOPEN .EQ. 0.) THEN
      OPEN = 1.
      ELSE IF (PFOPEN .GT. 0. .AND. PFOPEN .LT. 100.) T
      CALL RANF (OPEN,L)
      ELSE IF (PFOPEN .EQ. 100.) THEN
      OPEN = 0.
      ENDIF
      IF (OPEN .LE. PFOPEN/100.) THEN
C
C---> Open-circuit freeze-thaw failure
C
      FTOPEN = FTOPEN + 1
      FDATA(1,IFLG) = FDATA(1,IFLG) + 1
      RESIST = 'FO'
      ELSE
C
C---> Closed-circuit freeze-thaw failure
C
      FDATA(2,IFLG) = FDATA(2,IFLG) + 1
      FTSHORT = FTSHORT + 1
      RESIST = 'FS'
      ENDIF
      CALL RESCHCK(A,B,C,RESIST,CYCLE,STRSTAT)
      GO TO 40
      ENDIF
      ENDIF

```



```

R2 = FLOAT(FDATA(2,K+1))/FLOAT(RUN)
R3 = FLOAT(FDATA(3,K+1))/FLOAT(RUN)
R4 = FLOAT(FDATA(4,K+1))/FLOAT(RUN)
KK = K*FLGRP+1
KKK = (K+1)*FLGRP
WRITE (OPM,140) KK, KKK, R1, R2, R3, R4
1110 CONTINUE
140 FORMAT (6X,I4,'-'I4,1X,'CYCLES',9X,F10.2,F8.2,3X,F9.2,F8.2)
RETURN
END

```

```

SUBROUTINE CLRSCN
C
C *****
C DESCRIPTION: Clears screen
C
C ARGUMENTS: (NONE)
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED:
C MOVE (1,1)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C CHARACTER*1 CLRSTR(4)
C DATA CLRSTR /' ','[','2','J'/
C
C *****
C
C CLRSTR(1)=CHAR(27)
C WRITE (*,'(1X,4A1)') CLRSTR
C CALL MOVE(1,1)
C RETURN
C END

```

```

SUBROUTINE MOVE (IR,IC)
C
C *****
C DESCRIPTION: performs misc. screen operations
C
C ARGUMENTS:
C IR (I) = specifies screen command
C IC (I) = specifies screen command
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C CHARACTER*8 MOVSTR
C CHARACTER*1 BRAC, SEMI, H
C DATA BRAC, SEMI, H / '[',';',',','H'/
C
C *****

```

```

C
C WRITE (MOVSTR,5) CHAR(27), BRAC, IR, SEMI, IC, H
5 FORMAT (2A1,I2.2,A1,I2.2,A1)
C WRITE (*,8) MOVSTR
6 FORMAT (1X,A8\ )
C RETURN
C END

```

SUBROUTINE BLINK

```

C
C *****
C DESCRIPTION: makes the screen blink
C
C ARGUMENTS: (NONE)
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C CHARACTER*1 WINK(4)
C DATA WINK /' ','[','5','m'/
C
C *****
C
C WINK(1)=CHAR(27)
C WRITE (*,'(1X,4A1)') WINK
C RETURN
C END

```

SUBROUTINE REVERSE

```

C
C *****
C DESCRIPTION: changes screen to negative - from bright charac
C dark background to dark characters, bright
C background.
C
C ARGUMENTS: (NONE)
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C CHARACTER*1 REV(4)
C DATA REV /' ','[','7','m'/
C
C *****
C
C REV(1)=CHAR(27)
C WRITE (*,'(1X,4A1)') REV
C RETURN
C END

```

```

C
C SUBROUTINE RESTORE
C
C *****
C DESCRIPTION: restores screen from negative (REVERSE routine) to
C positive - bright background, dark characters to
C dark background, bright characters.
C
C ARGUMENTS: (NONE)
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C CHARACTER*1 RES(4)
C DATA RES /' ',' ','0','a'/
C
C *****
C
C RES(1)=CHAR(27)
C WRITE (*,'(1X,4A1)') RES
C RETURN
C END

```

```

C
C SUBROUTINE RANGE(TEMP,MAX,MIN)
C
C *****
C DESCRIPTION: This routine determines if the temporary value
C 'TEMP' is within the range MIN < TEMP < MAX. If not, a
C message is shown on the screen which prompts the user
C for another value. When an appropriate value is given,
C control is returned to the main program.
C
C ARGUMENTS:
C TEMP (I) = data value
C MAX (I) = maximum allowed value
C MIN (I) = minimum allowed value
C MIN = -99 temp must be greater than zero
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C REAL TEMP, Max, Min
C INTEGER MAX, MIN
C
C *****
C---> check if input value greater than zero (MIN= -99)
99 CONTINUE
IF ( MIN .EQ. -99) THEN
IF (TEMP.GT.0.0) GO TO 101
WRITE(*,1)'THE MINIMUM VALUE MUST BE GREATER THAN ZERO'
WRITE(*,2)'ENTER A NEW VALUE:'
READ(*,'(8N,F10.0)',ERR=199) TEMP
GO TO 99
ENDIF

```

```

C
C---> check if input value greater than or equal to minimum
100 CONTINUE
IF ( TEMP .GE. MIN ) GO TO 101
200 WRITE (*,3) 'AT PRESENT, THE MINIMUM VALUE CAN BE ',MIN,'.'
WRITE (*,2) 'ENTER A NEW VALUE:'
READ (*,'(8N,F10.0)',ERR=200) TEMP
GO TO 100
C
C---> check if input value less than or equal to maximum
101 CONTINUE
IF (TEMP .LE. MAX) GO TO 102
201 WRITE(*,3) 'AT PRESENT, THE MAXIMUM VALUE CAN BE ',MAX,'.'
WRITE(*,2)'ENTER A NEW VALUE:'
READ(*,'(8N,F10.0)',ERR=201)TEMP
GO TO 100
102 CONTINUE
C
C---> return to program
RETURN
1 FORMAT (10X,A)
2 FORMAT (10X,A\A)
3 FORMAT (10X,A,f15.6,A)
END

```

```

C
C SUBROUTINE INTEGER (TEMP, FINAL)
C
C *****
C DESCRIPTION: This routine checks to see if the user has
C supplied an integer number. if not a message is displaye
C followed by a prompt for a new number. When an integer
C is given control is returned to the main program.
C
C ARGUMENTS:
C TEMP (I) = input integer value
C FINAL (I) = final return integer
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C
C INTEGER FINAL
C REAL AMOD, TEMP, REMAIN
C
C *****
C---> check if integer, get new value if not
200 CONTINUE
REMAIN = AMOD (TEMP, 2.0)
IF ((REMAIN .EQ. 1.0) .OR. (REMAIN .EQ. 0.0)) GO TO 201
300 WRITE (*,1) 'AN INTEGER VALUE IS NEEDED FOR THIS PARAMETER.'
WRITE (*,2) 'ENTER A NEW VALUE:'
READ (*,'(8N,F5.0)',ERR=300)TEMP
GO TO 200
201 CONTINUE
FINAL = INT(TEMP)
C
C---> return to program
RETURN
1 FORMAT (10X,A)
2 FORMAT (10X,A\A)
END

```

```

SUBROUTINE PERCENT (TEMP)
C
C *****
C DESCRIPTION: This routine insures the proper form of the
C              given percentile. A decimal fraction is required.
C
C ARGUMENTS:
C     TEMP (I) = input percentile. returns new percentile
C               if wrong.
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C     REAL TEMP
C
C *****
C---> check if decimal fraction
C     get new value if not
C 300 CONTINUE
C     IF ( TEMP .LE. 1.0 ) GOTO 301
C 400 WRITE (*,1) ' A DECIMAL FRACTION IS NEEDED.'
C     WRITE (*,2) ' ENTER A NEW VALUE: '
C     READ (*, '(BN,F5.0)',ERR=400) TEMP
C     GOTO 300
C 301 CONTINUE
C
C---> return to program
C     RETURN
C 1  FORMAT (10X,A)
C 2  FORMAT (10X,A)
C     END

```

```

ICHR = CHAR (ICHAR(ICH) - ICHAR('a') + ICHAR('A'))
ICH = ICHR
ENDIF
RETURN
END

```

```

Subroutine Beeper
C
C *** This subroutine beeps the computer speaker
C
C Write (*, '(a\)' ) 'G'
C Return
C End

```

```

REAL FUNCTION STDEV (A,B,C,D)
C
C *****
C DESCRIPTION: Calculates standard deviation
C
C ARGUMENTS:
C     A = Sum of all x values squared
C     B = Average x value
C     C = Sum of all x values
C     D = Total number of x values
C
C INTEGER A,C,D
C REAL B
C
C *****
C IF (D .EQ. 1) THEN
C     STDEV = 0.
C ELSE
C     STDEV = SQRT ((A - 2*B*C + D*B**2)/FLOAT(D-1))
C ENDIF
C RETURN
C END

```

```

SUBROUTINE UPCAS(ICH)
C
C *****
C DESCRIPTION: Routine to translate given character*1 variable
C              to uppercase.
C
C ARGUMENTS:
C     ICH (I,0) = input character, returns upper case character
C
C LOGICAL NAMES AND FILES USED: (NONE)
C
C ROUTINES USED: (NONE)
C
C CONSTANTS (PARAMETER STATEMENTS): (NONE)
C
C COMMON BLOCKS: (NONE)
C
C VARIABLES:
C     CHARACTER*1 ICH, ICHR
C
C *****
C
C IF (ICH .GE. 'a' .AND. ICH .LE. 'z') THEN

```



```

c bat2a.inc
c
c battery info for batla
c Janis Littlefield, Battelle Northwest, Sep 1985
c
COMMON /BAT2A1/ BCELL1
COMMON /BAT2A2/ BCELL2
COMMON /BAT2A3/ BCELL3
COMMON /BAT2A4/ BCELL4
COMMON /BAT2A5/ BCELL5
COMMON /BAT2A6/ BCELL6
COMMON /BAT2A7/ RS, IS, QCELL
COMMON /BAT2A8/ CELTYP
REAL BCELL1(ROWSIZ, COLSIZ, PLNSIZ)
REAL BCELL2(ROWSIZ, COLSIZ, PLNSIZ)
REAL BCELL3(ROWSIZ, COLSIZ, PLNSIZ)
REAL BCELL4(ROWSIZ, COLSIZ, PLNSIZ)
LOGICAL*2 BCELL5(ROWSIZ, COLSIZ, PLNSIZ)
LOGICAL*2 BCELL6(ROWSIZ, COLSIZ, PLNSIZ)
REAL RS(ROWSIZ, COLSIZ)
REAL IS(ROWSIZ, COLSIZ)
REAL QCELL(ROWSIZ, COLSIZ)
REAL STRVOL(ROWSIZ, COLSIZ)
REAL TMPVOL(ROWSIZ)
REAL TMPVLP(ROWSIZ, PLNSIZ)
REAL RM(ROWSIZ)
REAL RMP(ROWSIZ, PLNSIZ)
REAL VM(ROWSIZ)
REAL VMP(ROWSIZ, PLNSIZ)
REAL TEMP(ROWSIZ)

c BCELL arrays -- storage for description of the battery
c bcell1 (i,j,k) is:
c i = number of modules
c j = number of strings
c k = number of cells
c bcell1 : stores cell voltage
c bcell2 : stores cell capacity
c bcell3 : stores cell internal resistance
c bcell4 : stores cycle when failure occurred
c bcell5 : true=good cell false=failed cell (from RELY program)
c bcell6 : true=good cell false=over-charge or over-discharge
failure
c (from BAT2A program)
c rs -- equivalent resistance of a string
c is -- string current
c qcell -- cell capacity lost over the time increment

<< Include Files >>
C RELY.INC
C
C INTEGER MXFLCY, MXFLPT, FLGRP
C PARAMETER (MXFLCY = 5000)
C PARAMETER (MXFLPT = 100)
C PARAMETER (FLGRP = MXFLCY/MXFLPT)
COMMON /GNRL/ MODULE, STRING, CELLS, CELLREQ, STRGREQ, MODREQ,
1 PREMA, DIMCAPA, RESIST, FTFREQ, PFOPEN, PFSHORT,
2 PWOPEN, PWSHORT
COMMON /CELLDT/ CELLDAT
COMMON /FDAT/ FDATA
REAL CELLDAT(ROWSIZ, COLSIZ, PLNSIZ, 2), PREMA, FTFREQ
INTEGER MODULE, STRING, CELLS, CELLREQ, STRGREQ, MODREQ
INTEGER FDATA(4, FLGRP)
CHARACTER*2 RESIST
c celldat -- contains data about the battery being simulated.
c 1st subscript -- number of modules
c 2nd subscript -- number of strings in a module
c 3rd subscript -- number of cells in a string
c 4th subscript -- info about the cell
c value 1 -- whether cell has failed or not and its type of failure
c = -1.0 has not failed; is still live
c >= 0.0 has failed. Integer part of value indicates
c which cycle failure occurred. This cycle
c number includes both premature and wearout
c failures. Fractional part of value
c indicates
c type of failure as follows:
c 0.1 = open-circuit freeze-thaw failure
c 0.2 = closed-circuit freeze-thaw failure
c 0.3 = open-circuit wearout failure
c 0.4 = closed-circuit wearout failure
c value 2 -- cycle number at which this cell will fail if
c it does not prematurely fail (obtained from routine
c FAILURE).
c fdata -- contains info about type of failures. Each row in fdata
c has data about the failures during a particular group of cycles.
c It is assumed that 5000 cycles is an overstatement of battery life.
c It is conjectured that 100 point can be displayed graphically to
c show premature and wearout failures. Thus the grouping, FLGRP
c is 5000/100 or 50 cycles for each data point. For each row, the
c columns are:
c 1 -- number of open-circuit freeze-thaw failures
c 2 -- number of closed-circuit freeze-thaw failures
c 3 -- number of open-circuit wearout failures
c 4 -- number of short-circuit wearout failures

C parm.inc
c contains size for battery. To change size of battery you must change
these
c parameter statements and then recompile all routines used in programs
rely
c and batla.
INTEGER ROWSIZ, COLSIZ, PLNSIZ
PARAMETER (ROWSIZ = 20)
PARAMETER (COLSIZ = 20)
PARAMETER (PLNSIZ = 20)
c rowsiz -- number of modules
c colsiz -- number of strings
c plnsiz -- number of cells

C weibul.inc -- include file for Weibul distribution parameters
C
COMMON /WEIBUL/ LOCATE, SHAPE, SCALE
INTEGER LOCATE
REAL SHAPE, SCALE

```


APPENDIX D

MODEL VERIFICATION

APPENDIX D

MODEL VERIFICATION

This appendix contains verifications of the two primary models, the Life Cycle Model and the Detailed Discharge Model.

D.1 VERIFICATION OF THE LIFE-CYCLE MODEL

Two example battery systems are presented in this appendix to verify the logic of the RELY program. RELY simulates a battery's life by generating random numbers to determine whether a given cell fails on the current charge-discharge cycle. Thus, in order to verify the logic, it is necessary to use precisely the same random numbers.

Both systems discussed here use parameters for the Weibull distribution of: i) LOCATION = 0.0, ii) SCALE = 20.0, and iii) SHAPE = 1.0. The configuration of both systems is [(3,3,2),(2,2,2)] as shown in Figure D.1. That is, there are 3 cells per string, 3 strings per module, and 2 modules per battery. The minimum operating requirements are 2 cells per string, 2 strings per module, and two modules. Freeze-thaw conditions are assumed to occur every 3 cycles, with a freeze-thaw failure probability of 0.10. The differences between the two systems are the failure modes: System I has 100% closed-circuit failure modes for both wearout and freeze-thaw failures, while System II has 100% open circuit failure modes. Thus, in System II, an entire string fails as soon as one cell in the string fails.

In the discussion below, cell (i,j,k) refers to the k^{th} cell of the j^{th} string of the i^{th} module. Similarly, string (i,j) means the j^{th} string of the i^{th} module. References to specific cells and strings can easily be made with this terminology.

Battery Test Configuration:

3 Cells per String
3 Strings per Module
2 Modules per Battery

Performance Requirements:

2 Good Cells per Strings
2 Good Strings per Module
2 Good Modules per Battery

Failures Modeled:

Freeze-Thaw Failures
Failures Due to Wearout

Failure Modes:

SYSTEM I - Closed Circuit Failures
SYSTEM II - Open Circuit Failures

FIGURE D.1. Model Verification Battery Configuration

D.1.1 System I

After user input is obtained, RELY calculates the cycle during which each cell will wear out (using the Weibull distribution), if the cell has not previously failed due to a freeze-thaw. These wearout cycles are shown in Table D.1.

The first cycle is a freeze-thaw cycle (they occur every three cycles), so a uniform random number between zero and one is generated to determine if a

TABLE D.1. Individual Cell Wearout Cycles

<u>Module 1</u>					<u>Module 2</u>				
		String					String		
		1	2	3			1	2	3
Cell	1	12	26	1		1	17	11	5
	2	4	5	12	Cell	2	10	17	51
	3	11	2	2		3	17	7	10

cell fails after a freeze-thaw. If the generated number is less than the freeze-thaw failure probability (0.10 in this case), the cell fails prematurely.

1st Cycle (freeze-thaw occurs)

Freeze-Thaw Failure: cell (1,1,2) (uniform # = 0.05 < 0.10)

Wearout Failure: cell (1,3,1)

Result: Since system I has 100% closed circuit failure modes, all strings remain operational.

2nd Cycle (no freeze-thaw)

Wearout Failures: cells (1,2,3) and (1,3,3)

Result: String (1,3) fails, since 2 of its cells are failed. However, module 1 is still operational, since 2 strings remain functional.

3rd Cycle (no freeze-thaw)

No Wearouts

4th Cycle (freeze-thaw occurs)

Freeze-Thaw Failures: cell (2,1,1) (uniform # = 0.018)

cell (2,3,1) (uniform # = 0.026)

No Wearouts

Result: Battery functions, because strings (2,1) and (2,3) still have two operating cells each, resulting in module 2 being functional.

5th Cycle (no freeze-thaw)

Wearout Failure: cell (1,2,2)

Result: String (1,2) fails, since two of its cells ((1,2,2) and (1,2,3)) have failed. Module 1 fails because strings (1,2) and (1,3) are failed. Since two modules are required, the battery ceases to function.

BATTERY FUNCTIONS FOUR CYCLES

Total Wearout Failures: 4

Total Freeze-Thaw Failures: 3

D.1.2 System II

The difference between the two systems is that System I has closed-circuit failure modes, while System II has open-circuit failure modes. Thus, the wear-out cycles generated previously (Table D.1) also apply to this system.

1st Cycle (freeze-thaw occurs)

Freeze-Thaw Failure: cell (1,1,2)

Wearout Failure: cell (1,3,1)

Result: Strings (1,1) and (1,3) fail due to the open-circuit failure mode. Hence, module 1 fails because two strings are failed. Thus, the entire battery fails.

BATTERY FUNCTIONS ZERO CYCLES

Total Wearout Failures: 1

Total Freeze-Thaw Failures: 1

The results obtained in this appendix can be duplicated by running RELY with the two systems. To be certain that random numbers are "matched," RELY should be started from the directory prompt (e.g., "A>") for each system.

D.2 VERIFICATION OF THE DETAILED DISCHARGE MODEL

The Detailed Discharge Model was verified by inserting instructions to dump all the state variables. Dumps were inserted to occur before and after each calculation block. Calculation blocks are the way in which the Fortran source code is laid out, the first few blocks being open circuit cell voltage, internal cell resistance, string equivalent voltage and resistance. This output was then directly verified by hand calculations.

To reduce the number of hand calculations required, a sampling of the output was verified. This approach enabled reasonableness checks and

analytical verification of the model workings. As a final measure, the version of the detailed discharge submodel that prints all state variables was compared to the unmodified version.

The battery configuration used in the Detailed Discharge Model verification is [(3,2,2),(2,2,2)]. That is, there are 3 cells per string, 2 strings per module, and 2 modules per battery. The minimum operating requirements used in running the Life-Cycle Model were 2 cells per string, 2 strings per module, and two modules. As in the Life-Cycle Model verification, the freeze-thaw conditions were assumed to occur every 3 cycles; however, the freeze-thaw failure probability was set to 0 so that a case with no failures could be evaluated. For wearout failures, the Weibull distribution parameters used were: i) LOCATION = 1.0, ii) SCALE = 20.0, and iii) SHAPE = 1.0. Since the location parameter was set to one, this will assure that the first cycle will have no failures.

What follows is a sampling of the output from the variable dump version. The total output obtained during the verification process was considerable and the small example of the output contained in this document should not be interpreted as the total effort undertaken to assure the performance of this model. Numbers in parentheses illustrate the calculations matched by hand.

Battery Configuration

Number of modules per battery	= 2
Number of strings per module	= 2
Number of cells per string	= 3
Total Cells per Battery	= 12

Test Conditions

Cycle to analyze	= 1
Cumulative Freeze-Thaw Open Open Circuit Failures	= 0 from RELY
Cumulative Freeze-Thaw Closed Circuit Failures	= 0 from RELY
Cumulative Wearout Open Circuit Failures	= 0 from RELY
Cumulative Wearout Closed Circuit Failures	= 0 from RELY
Duration of Test	= 6.00 Hours

Test Conditions (contd)

Time Increment	=	.25 Hours
Cell Connection: 1=Series-Par. 2=Parallel-Ser.		1
Failure Switches: 0=None. 1=Closed. 2=Open		0
Constant Discharge Current	=	45.00 Amps

Cell Parameters

Theoretical Cell Capacity	=	50.00 Amp-Hours
Fully Charged Cell Capacity	=	47.50 Amp-Hours
Fully Charged Open Circuit Cell Voltage	=	2.08 Volts
Upper Cutoff Voltage	=	10.00 Volts
Lower Cutoff Voltage	=	1.78 Volts
Initial Internal Cell Resistance	=	.0350 Ohms
Freeze-Thaw Failure Open Circuit Resistance	=	.20000 Ohms
Freeze-Thaw Failure Closed Circuit Resistance	=	.70000E-01 Ohms
Wearout Failure Open Circuit Resistance	=	.20000 Ohms
Wearout Failure Closed Circuit Resistance	=	.70000E-01 Ohms
Over-Voltage Failure Resistance Parameters:		
Over-Voltage Failure Open Circuit Percentage	=	30.00 Percent
Over-Voltage Failure Closed Circuit Percentage	=	70.00 Percent
Over-Voltage Failure Open Circuit Resistance	=	.20000 Ohms
Over-Voltage Failure Closed Circuit Resistance	=	.70000E-01 Ohms
Over Discharge Failure Resistance Parameters:		
Over-Discharge Failure Open Circuit Percentage	=	30.00 Percent
Over-Discharge Failure Closed Circuit Percentage	=	70.00 Percent
Over-Discharge Failure Open Circuit Resistance	=	.20000 Ohms
Over-Discharge Failure Closed Circuit Resistance	=	.70000E-01 Ohms

Time (Hr)	Total Voltage Battery (V)	Average Module Voltage (V)	Output Power (kw)	Average Voltage Working Cells (V)	Minimum Voltage Working Cells (V)	Average Capacity Working Cells (Amp-Hr)	Average Resistance All Cells (Ohms)	# Under Voltage Electr. Fails	# Over Voltage Electr. Fails
.00	7.73	3.87	.35	2.08	2.08	47.50	.350E-01	0.	0.
.25	7.73	3.87	.35	2.08	2.08	41.88	.350E-01	0.	0.
.50	7.73	3.87	.35	2.08	2.08	36.25	.350E-01	0.	0.
.75	7.73	3.87	.35	2.08	2.08	30.63	.350E-01	0.	0.
1.00	7.73	3.87	.35	2.08	2.08	25.00	.350E-01	0.	0.
1.25	7.48	3.74	.34	2.03	2.03	19.38	.350E-01	0.	0.
1.50	7.04	3.52	.32	1.96	1.96	13.75	.350E-01	0.	0.
1.75	6.60	3.30	.30	1.89	1.89	8.13	.350E-01	0.	0.
2.00	6.15	3.08	.28	1.81	1.81	2.50	.350E-01	0.	0.
2.25	-10.57	-5.28	-.48	1.74	1.74	.00	.808E-01	12.	0.

Battery unable to deliver 45.00 amps at time 2.25 hours

time: .00

MOD	LOCATION: STR	SECTION 5: Cell	OPEN CIRCUIT OCV	CELL VOLTAGE Charge	Resis.
1	1	1	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01
1	1	2	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01
1	1	3	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01
1	2	1	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01
1	2	2	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01

time: .00

MOD	LOCATION: STR	SECTION 6: Cell	CELL INTERNAL RESISTANCE OCV	Charge	Resis.
1	1	1	2.0760	47.500	.35000E-01
			2.0760	(47.500)	.35000E-01
1	1	2	(2.0760)	47.500	.35000E-01
			2.0760	47.500	.35000E-01
1	1	3	2.0760	47.500	(.35000E-01)
			2.0760	47.500	.35000E-01
1	2	1	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01

time: .00

LOCATION: SECTION 7: STRING VOLTAGE AND RESISTANCE

<u>MOD</u>	<u>STR</u>	<u>OCV</u>	<u>Resis.</u>
1	1	.0000	.00000
		(6.2280)	.10500
1	2	.0000	.00000
		6.2280	.10500
2	1	.0000	.00000
		6.2280	.10500
2	2	.0000	.00000
		6.2280	.10500

time: .00

LOCATION: SECTION 8: SERIES-PARALLEL RESISTANCE OF MODULE

<u>MOD</u>	<u>STR</u>	<u>Cell</u>	<u>OCV</u>	<u>Charge</u>	<u>Resis.</u>
1					.00000
					(.52500E-01)
2					.00000
					.52500E-01

time: .00

LOCATION: SECTION 9: MODULE VOLTAGE

<u>MOD</u>	<u>STR</u>	<u>Cell</u>	<u>OCV</u>	<u>Charge</u>	<u>Resis.</u>
1			.00000		
			(3.8655)		
2			.00000		
			3.8655		

time: .00

LOCATION: SECTION 10: DATA COLLECTION

<u>MOD</u>	<u>STR</u>	<u>Cell</u>	<u>OCV</u>	<u>Charge</u>	<u>Resis.</u>
1	1	1	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01
1	1	2	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01
1	1	3	2.0760	47.500	.35000E-01
			2.0760	47.500	.35000E-01

time (.00000)
 total battery voltage (7.7310)
 avg. module voltage (3.8655)
 output power (.34790)
 average voltage (2.0760)
 Minimum voltage working cells (2.0760)
 average capacity working cells (47.500)
 average resistance all cells (.35000E-01)
 # under voltage electrolyte failures (.00000)
 # over voltage electrolyte failures (.00000)

time: .00

MOD	STR	LOCATION: Cell	SECTION 12: OCV	CELL DISCHARGE Charge	Resis.
1	1	1	2.0760	47.500	.35000E-01
			2.0760	(41.875)	.35000E-01
1	1	2	2.0760	47.500	.35000E-01
			2.0760	41.875	.35000E-01
1	1	3	2.0760	47.500	.35000E-01
			2.0760	41.875	.35000E-01
1	2	1	2.0760	47.500	.35000E-01
			2.0760	41.875	.35000E-01

time: .25

MOD	STR	LOCATION: Cell	SECTION 5: OPEN OCV	CIRCUIT CELL VOLTAGE Charge	Resis.
1	1	1	2.0760	41.875	.35000E-01
			2.0760	(41.875)	.35000E-01
1	1	2	2.0760	41.875	.35000E-01
			2.0760	41.875	.35000E-01
1	1	3	2.0760	41.875	.35000E-01
			2.0760	41.875	.35000E-01

time: 1.50

LOCATION: SECTION 5: OPEN CIRCUIT CELL VOLTAGE

<u>MOD</u>	<u>STR</u>	<u>Cell</u>	<u>OCV</u>	<u>Charge</u>	<u>Resis.</u>
1	1	1	2.0349	47.500	.35000E-01
			(1.9609)	47.500	.35000E-01
1	1	2	2.0349	(47.500)	.35000E-01
			1.9609	47.500	.35000E-01
1	1	3	(2.0349)	47.500	(.35000E-01)
			1.9609	47.500	.35000E-01

time: 2.00

LOCATION: SECTION 5: OPEN CIRCUIT CELL VOLTAGE

<u>MOD</u>	<u>STR</u>	<u>Cell</u>	<u>OCV</u>	<u>Charge</u>	<u>Resis.</u>
1	1	1	1.8129	(2.5000)	.35000E-01
			1.8129	(-3.1250)	.35000E-01
1	1	2	1.8129	2.5000	.35000E-01
			1.8129	-3.1250	.35000E-01
1	1	3	1.8129	2.5000	.35000E-01
			1.8129	-3.1250	.35000E-01
1	2	1	1.8129	2.5000	.35000E-01
			1.8129	-3.1250	.35000E-01

time: 2.25

LOCATION: SECTION 5: OPEN CIRCUIT CELL VOLTAGE

<u>MOD</u>	<u>STR</u>	<u>Cell</u>	<u>OCV</u>	<u>Charge</u>	<u>Resis.</u>
1	1	1	1.8129	(-3.1250)	.35000E-01
			.00000	(.00000)	.70000E-01
1	1	2	(1.8129)	-3.1250	.35000E-01
			(.00000)	.00000	.70000E-01
1	1	3	1.8129	-3.1250	.35000E-01
			.00000	.00000	.70000E-01
1	2	1	1.8129	-3.1250	.35000E-01
			.0000	.0000	.20000

This example just shows part of one case, using default parameters and all cells in the battery are working at time zero. At PNL other cases confirmed the operation of all the options available, on both good and initially failed cells.

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

10 Mr. J. Quinn
U.S. Department of Energy
Forrestal Building, RM 6A049
1000 Independence Ave., SW
Washington, D.C. 20585

5 Dr. A. R. Landgrebe
U.S. Department of Energy
CE-141, MS 5 E-036
Forrestal Building
1000 Independence Ave., SW
Washington, D.C. 20585

30 DOE Technical Information
Center

Dr. George E. Blomgren
Corporate Technology Fellow
Union Carbide Corporation
P.O. Box 45035
Westlake, OH 44145

Elton J. Cairns
Head, Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Sanjay L. Deshpande
Vice President, Engineering
GNB Incorporated
2010 Cabot Boulevard West
Langhorne, PA 19047

Dr. Curtis F. Holmes
Vice President, Technology
Electrochem Industries
10000 Wehrle Drive
Clarence, NT 14031

J. J. Iannucci
Program Manager
Pacific Gas and Electric Co.
3400 Crow Canyon Road
San Ramon, CA 94583

Tadao Ishikawa
Senior Research Engineer
Electrical Engineering
Laboratory
Central Research Institute
of Electric Power Industry
11-1, Iwato Kita 2-Chome
Komae-Shi
Tokyo 201 Japan

Kazumasa Matsui
Acting Supervisory Manager
1st Research Department
Central Laboratory
Yuasa Battery Co., LTD.
Takatsuki, Osaka, Japan

Henry Oman
Electrical Power Systems
MS 19-27
Boeing Aerospace Co.
P.O. Box 3999
Seattle, WA 98124

James R. Rasmussen
Program Manager
Ceramatec, Inc.
163 West 1700 South
Salt Lake City, UT 84115

Hiry B. West
Product Engineering Manager
McGraw-Edison Co.
P.O. Box 28
Bloomfield, NJ 07003

No. of
Copies

David Yalom
Consultant
Catalyst Research Corp.
1421 Clarkview Road
Baltimore, MD 21209

Jon W. Hurwitch
Energetics, Inc.
9210 Route 108
Dolumbia, MD 21045

ONSITE

DOE-Richland Operations

J. J. Sutey

44 Pacific Northwest Laboratory

W. B. Ashton
R. V. Badalamente
D. R. Brown
J. A. Dirks (5)
W. H. Doggett (2)
J. V. Dovey
L. L. Fassbender
R. B. Grinde (2)
C. J. Hostick (10)
H. D. Huber (2)
H. K. Humphreys
C. H. Imhoff
J. S. Littlefield
P. C. Rieke
R. K. Sen
C. Winter (5)
Publishing Coordination MH (2)
Technical Information (5)