COMPUTER PROGRAM FOR
DESIGN AND PERFORMANCE ANALYSIS
OF NAVIGATION-AID POWER SYSTEMS

Program Documentation
Volume I
Software Requirements Document

July 1977
Final Report

Prepared for
DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD
Office of Research and Development
Washington, D.C. 20590

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DONALD L. BIRKIMER, Ph.D., P.E.
Technical Director
U.S. Coast Guard Research and Development Center
Avery Point, Groton, Connecticut 06340
The Jet Propulsion Laboratory has developed a computer program for designing and analyzing the performance of solar array/battery power systems for the U.S. Coast Guard Navigational Aids. This program is called the Design Synthesis/Performance Analysis (DSPA) Computer Program. The basic function of the Design Synthesis portion of the DSPA program is to evaluate functional and economic criteria to provide specifications for viable solar array/battery power systems. The basic function of the Performance Analysis portion of the DSPA program is to simulate the operation of solar array/battery power systems under specific loads and environmental conditions.

This document establishes the software requirements for the DSPA computer program, discusses the processing that occurs within the program, and defines the necessary interfaces for operation.
# Metric Conversion Factors

## Approximate Conversions to Metric Measures

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## Approximate Conversions from Metric Measures

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- 1°C = 1.8°F
- 1°F = 5/9°C

**Note:** For exact conversions, see the table above. For approximate conversions, see the table on the next page.
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1. **INTRODUCTION**

The Jet Propulsion Laboratory (JPL) has developed a computer program for designing and analyzing the performance of solar array/battery power systems for the U.S. Coast Guard Navigational Aids. This program is called the Design Synthesis/Performance Analysis (DSPA) Computer Program. The basic function of the Design Synthesis portion of the DSPA program is to evaluate functional and economic criteria to provide specifications for viable solar array/battery power systems. The basic function of the Performance Analysis portion of the DSPA program is to simulate the operation of solar array/battery power systems under specific loads and environmental conditions.

This document establishes the software requirements for the DSPA computer program, discusses the processing that occurs within the program, and defines the necessary interfaces for operation.
The DSPA computer program combines the elements of design synthesis and performance analysis. A functional block diagram of the main driver program is shown in Figure 2-1. As shown in this figure and the algorithms which follow, the DSPA computer program utilizes the following methodology.

a. The program user selects the desired power system arrangement.

b. If a design synthesis is not required, then the program user must provide information on the electrical size of the equipment.

c. If a design synthesis is requested, the program user must supply information on the parameters used in determining the various profiles. The computer program then calculates the load and environmental profiles needed for a local profile analysis. Based on a profile energy balance determined as part of the load profile analysis, the computer estimates the electrical size of the equipment required and then determines the physical characteristics of the selected equipment. The calculated data along with significant input data is printed out in the appropriate output data format.

d. If performance analysis is not required, the execution of the DSPA program is terminated.

e. If performance analysis is required, the program user must provide information on the parameters used in determining the various profiles. The computer program then calculates the values of the load and environment at the start of the selected mission period. These stimuli (load and environment) are used to calculate the response (operational characteristics) of the equipment at that point in time. The process is repeated for selected time increments until the power system operational characteristics for the entire mission period have been determined. This information is then printed in the appropriate output data formats, and execution of the program is terminated.

Flow charts of the DSPA subprograms were not furnished in the Program Documentation volumes since:

- Most computer facilities have programs which automatically produce subroutine flow charts. If such charts are desired, the program user can easily select the subroutine of interest and obtain a copy of the latest version of the subroutine.

- Preparation, reproduction, and inclusion of all of the present versions of the DSPA subroutines in the Program Documentation would be more costly than if the flow charts were prepared by the program user automatically. Additionally, these flow charts would become obsolete as modifications were made to the DSPA computer program.
FIGURE 2-1. DESIGN SYNTHESIS PERFORMANCE ANALYSIS COMPUTER PROGRAM
PROGRAM ALGORITHMS

Step 1  Obtain Program Parameters

IPRG = Program Selector:
   0 = Design Synthesis only
   1 = Performance Analysis only
   2 = Both Design Synthesis and Performance Analysis

ITAPE = Weather Data Input Selector:
   -1 = Statistical Input Tape
   0 = User Input Data
   YYDDD = Merge Tape Input beginning at year = YY and day = DDD

DEBUG = Debug Printout Request Flag:
   0 = No printout
   1 = Printout

XLN = Length of X-axis (in inches) for summary plots

YLN = Length of Y-axis (in inches) for summary plots

Step 2  Execute Design Synthesis program if requested

If:      IPRG ≠ 1
Then:    Call DSDRVR

Step 3  Execute Performance Analysis program if requested

If:      IPRG ≠ 0
Then:    Call PADRVR

Step 4  STOP DS/PA
3. DESIGN SYNTHESIS

The Design Synthesis portion of the DSPA program uses load and environmental profiles to set the power system requirements. Based on these requirements and on the electrical characteristics of the system equipment, the computer program determines the electrical size (volts, amperes, watts, ampere-hours, watt-hours) and the physical characteristics (weight, area, cost) of the power system. A functional block diagram of the Design Synthesis driver program is shown in Figure 3-1. As shown, the selection of lamp and flasher combinations as well as the day/night load durations enables the computer program to estimate a power load profile. This profile, after modification using battery charge-efficiency and a number of power system cabling and diode losses, is used in the load profile analysis. The object of the load profile analysis is to determine the electrical size of a balanced power source as well as the minimum theoretical electrical size of the battery. Once this information is obtained, it is a fairly straightforward process to determine the electrical size of the remaining items of equipment.

*Balanced power source: a power source which provides just enough energy to the batteries (during recharge periods) to offset or balance the energy loss sustained during discharge periods.*
FIGURE 3-1. POWER SYSTEM DESIGN SYNTHESIS
PROGRAM ALGORITHMS

Step 1 Obtain Pertinent Mission and Equipment Information

Q\textsubscript{ON} = Solar Insolation Level for Lamp Flasher
Turn-On - Watts/Meter\(^2\)

Q\textsubscript{OFF} = Solar Insolation Level for Lamp Flasher
Turn-Off - Watts/Meter\(^2\)

V\text{BUS} = Nominal value of Raw Power Bus Operating level - VDC

V\text{BUS\,MIN} = Minimum allowable Raw Power Bus Operating
voltage - VDC

T\text{AVE} = Average yearly temperature in location selected - °F

\text{INDFLS} = Lamp Flasher Condition Indicator

Where: 0 = Lamp Flasher is Off (Lamp Not Flashing)
1 = Lamp Flasher is On (Lamp Flashing)

D\text{TESG} = Energy Storage Group Temperature Rise - °F

Q\text{BRES} = Battery Reserve (as Stage-of-Charge)

BR\text{CEST} = Estimated Normalized Battery Charge Current - Hours\(^{-1}\)

BR\text{DEST} = Estimated Normalized Battery Discharge
Current - Hours\(^{-1}\)

I\text{CHRT} = Battery Charger Type

Where: 0 = No Battery Charger
1 = Constant Voltage Charger with Current Limit

D\text{TPSG} = Power Source Group Equipment Temperature Rise - °F

D\text{URAM} = Duration of Mission - Years

S\text{ARES} = Solar Array Reserve (as a fraction of total area)

N\text{PREQ} = Number of Solar Cells in Parallel Required for
each Solar Cell Array Electrical Section
CELPAC = Solar Cell Packing Factor on Solar Array

NSAP = Total Number of Solar Arrays to be Procured

BRCHMX = Maximum Allowable Normalized Battery Charge Current - Hours⁻¹

ISH = Shunt Limiter Type

0 = No Shunt Limiter
1 = Ordinary Zener Diode
2 = Temperature-Compensated Zener Diode
3 = Active Shunt Limiter

FRCELL = Biasing Factor for Selecting the Number of Storage Cells in Series in the Battery

\(0.0 \leq \text{FRCELL} \leq 1.0\)

as: \(\text{FRCELL} \times 0.0\) the minimum number of cells tend to be selected

as: \(\text{FRCELL} \times 1.0\) the maximum number of cells tend to be selected

BRDSTD = Standard Normalized Battery Discharge Current - Hours⁻¹

TBDSTD = Standard Battery Discharge Temperature - °F

CRAVAL(JB) = Table of Available Storage Cell Capacities, from a Given Manufacturer, in increasing order of size - Amp-Hours/Cell

(JB = 1, 30 maximum)

CBMAX = Maximum desired capacity of each battery - Amp-Hours

HDZMAX = Maximum Heat Dissipation of a Single Zener Diode - Watts

HDEN = Heat Dissipation Derating Factor for a Single Zener Diode

ACELL = Single Solar Cell Area - cm²
### Step 1a
Compare Raw Power Bus Voltage with Allowable Minimum

If: \( VBUS < VBUSMN \),
Then: \( VBUS = VBUSMN + 4.0 \), and,
Then: Print out the following statement:

"VBUS ADJUSTED TO (... VBUS ...) VOLTS"

### Step 1b
Obtain Yearly Temperature Extremes

If: \( ITAPE = 0 \)
Then: GO TO STEP 2

If: \( ITAPE \neq 0 \)
Then: Obtain \( TTABMX \) and \( TTABMN \) from 'MERGE' File, and,
Then: GO TO STEP 5

Where:

- \( TTABMX \) = Maximum Value of the Ambient Temperature - °F
- \( TTABMN \) = Minimum Value of the Ambient Temperature - °F

### Step 2
Calculate Daily Temperature Increment Extremes

\[
DTTA = DT TA1 (DATE)
\]

- \( DTTAMX \) = Maximum Value of \( DT TA \) over the range:
  - \( DATE = 1;365 \) days
- \( DTTAMN \) = Minimum Value of \( DT TA \) over the range:
  - \( DATE = 1;365 \) days

Where:

- \( DT TA \) = Average Daily Temperature Increment - °F
- \( DATE \) = Days from start of the year - days (1-365)
- \( DT TA1 \) = Input table of \( DT TA \) as a function of \( DATE \)

### Step 3
Calculate Hourly Temperature Increment Extremes

\[
DT TAMB = DT AMB1 (TIMEH)
\]

- \( DT ABMX \) = Maximum Value of \( DT AMB \) over the range:
  - \( TIMEH = 0;24 \) hours
Step 3 (contd)

DTABMN = Minimum Value of DTAMB over the range:
TIMEH = 0:24 hours

Where: DTAMB = Average Hourly Temperature Increment - °F
TIMEH = Daily Time - Hours after Midnight (0-24)
DTAMB = Input Table of DTAMB as a function of TIMEH

Step 4
Calculate Ambient Temperature Extremes

TTABMX = TTAVE + DTTAMX + DTABMX
TTABMN = TTAVE + DTTAMN + DTABMN

Step 5
Obtain Power Conditioning and Distribution Group (PCDG)
Characteristics at the Raw Power Bus

(Based on ambient temperature extreme which will yield the
largest values of PCD Group Current)

XX(J,K) = Power Conditioning and Distribution Group Voltage - VDC
XI(J,K) = Power Conditioning and Distribution Group Current at
XX(J,K) - Amperes

J = 1,51 (Number of Data Points)
K = PCD Group Load Selector
1 = Lamp Off
2 = Effective Load,
   Lamp Flashing
3 = Lamp On

Step 6
Calculate PCD Group Loads

IP0FF = P(XI(J,1),XX(J,K)) at XX(J,K) = VBUS
IP0N = P(XI(J,2),XX(J,K)) at XX(J,K) = VBUS
PF0N = VBUS * IP0N
PP0FF = VBUS * IP0FF
Step 6 (contd)

Where:

IF\(_{OFF}\) = PCD Group Lamp-Off Operating Current - Amperes

IF\(_{ON}\) = PCD Group Lamp-Flashing Operating Current - Amperes

PF\(_{OFF}\) = PCD Group Lamp-Off Load - Watts

PF\(_{ON}\) = PCD Group Lamp-Flashing Load - Watts

Step 7

Obtain Free Format Data on Week Number and Compare with Reference

LWEEK = Weeks after Start of the year - (1,52)

If: LWEEK < 0, OR,

If: LWEEK > 52,

Then: GO TO STEP 53

NWEEK = LWEEK

Step 8

Calculate Date After Start of the Year

DATE = (7.0 * NWEEK) - 6.0

Step 9

Obtain Terminator Characteristics

SRT = Sunrise Time - Hours after Midnight

SST = Sunset Time - Hours after Midnight

THETLA = Buoy Latitude - Radians (+ North, - South)

HOURT = Terminator Hour Angle - Radians

ET = Equation of Time Difference - Hours

DECL = Solar Declination Angle - Radians

ALPHAEQ = Solar Vector Location - Radians
Step 11  Calculate Daily Time Increment

\[ \text{DTIMEH} = \frac{\text{SST} - \text{SRT}}{10.0} \]

Where: \( \text{DTIMEH} = \) Daily Time Increment for Clear Day Solar Insolation Calculations - Hours

Step 12  Initialize Daily Time and Time Increment Counter

\( \text{LTIME} = 1 \)
\( \text{TIMEH} = \text{SRT} \)

Where: \( \text{LTIME} = \) Time Increment Counter

Step 13  Compare Time Increment Counter With Reference

If: \( \text{LTIME} = 1, \)
\( \{ \text{QDTC} = 0.0 \} \)
Then: \( \{ \text{SALT} = 0.0 \}, \) AND, GO TO STEP 16
\( \{ \text{QSOL}(1) = 0.0 \} \)

Where: \( \text{QDTC} = \) Clear Day Solar Insolation Incident on Solar Array - Watts/Meter\(^2\)
\( \text{SALT} = \) Solar Altitude - Radians

Step 14  Compare Time Increment Counter With Reference

If: \( \text{LTIME} = 11, \)
\( \{ \text{QDTC} = 0.0 \} \)
Then: \( \{ \text{SALT} = 0.0 \}, \) AND GO TO STEP 16
\( \{ \text{QSOL}(11) = 0.0 \} \)

Step 14a  Compare Environmental Tape Index with Reference

If: \( \text{ITAPE} = 0 \)
Then: GO TO STEP 15

Step 14b  Obtain Solar Insolation from "MERGE" File

\( \text{QDT} = \) Solar Insolation Incident on Solar Array - Watts/Meter\(^2\)
Step 14c Calculate Solar Insolation Incident on Solar Array

\[ QSOL(LTIME) = QDT \]

GO TO STEP 16

Where: \( QSOL \) = Solar Insolation Incident on Solar Array at TIMEC - Watts/Meter\(^2\)

Step 15 Obtain Clear Day Solar Insolation and Solar Altitude

\[ QDTC = \text{Clear Day Solar Insolation Incident on Solar Array - Watts/Meter}^2 \]

\[ SALT = \text{Solar Altitude - Radians} \]

Step 16 Calculate Clear Day Solar Insolation Array and Solar Altitude Array

\[ QSOLC(LTIME) = QDTC \]

\[ SALTA(LTIME) = SALT \]

\[ TIMEC(LTIME) = TIMEH \]

Where: \( QSOLC \) = Clear Day Solar Insolation Incident on Solar Array at TIMEC - Watts/Meter\(^2\)

\( SALTA \) = Solar Altitude at TIMEC - Radians

\( TIMEC \) = Daily Time - Hours after Midnight

\( LTIME \) = 1,11 (Number of data points)

Step 17 Increment Daily Time and Time Increment Counter

\[ LTIME = LTIME + 1 \]

\[ TIMEH = TIMEH + DTIMEH \]
Step 18  Compare Time Increment Counter With Reference

If:   LTIME > 11,
Then:  GO TO STEP 19

RETURN TO STEP 13

Step 19  Initialize Day Counter and Weekly Summary Arrays

LDAY = 1
NMR(NWEEK) = 0
TJT(NWEEK) = 0.0
TKT(NWEEK) = 0.0
TLT(NWEEK) = 0.0
QQSOLT(NWEEK) = 0.0
QSOLMX(NWEEK) = 0.0

Where:   LDAY = Day of the Week Indicator - (Range 1,7)
NMR = Weekly Number of Battery Operating Mode Reversals - (Charging or Discharging)
TJT = Weekly Duration of Solar Occultations - Hours
TKT = Weekly Duration of Share-Mode Operations - Hours
TLT = Weekly Duration of Battery-Charging Periods - Hours
QQSOLT = Weekly Total of Solar Insolation Incident on Solar Array - Watt-Hours/Meter$^2$
QSOLMX = Maximum Solar Insolation, Incident on Solar Array, Encountered during week - Watts/Meter$^2$

Step 19a  Compare Environmental Tape Index with Reference

If:   ITAPE = 0
Then:  GO TO STEP 20

GO TO STEP 23
**Step 20** Obtain Cloud Cover Conditions

CT(LDAY) = Cloud type

- 0.0 = Cirrus or Cirrostratus Clouds
- 1.0 = Stratus Clouds
- 2.0 = Other Cloud Types

TC(LDAY) = Total Cloud Cover

- 1.0 = 1/10 of sky covered
- 2.0 = 2/10 of sky covered
- 9.0 = 9/10 of sky covered
- 10.0 = 10/10 of sky covered

ICT = 1 + IFIX(CT)

Where: ICT = Cloud Type indicator

- 1 = Cirrus or Cirrostratus Clouds
- 2 = Stratus Clouds
- 3 = Other Cloud Types

**Step 21** Calculate Cloud Cover Modifier

If: TC = 0.0,
Then: CCM(LTIME) = 1.0 AND GO TO STEP 22

If: SALTA(LTIME) < π/4.0,
Then: ISALT = 1

If: SALT(LTIME) > π/4.0,
Then: ISALT = 2

CCM(LTIME) = PC(ICT,ISALT) * P1(ICT,ISALT) * TC * ...
+ P2(ICT,ISALT) * (TC**2.0) + ...
+ P3(ICT,ISALT) * (TC**3.0)

For LTIME = 1,11
Step 21 (contd)

Where:

\[ ISALT = \text{Solar Altitude Indicator} \]

\[ \text{CCMM}(LTIME) = \text{Cloud Cover Modifier} \]

\[ P_0, P_1, P_2, P_3 = \text{Polynomial Coefficients obtained from input data tables "Cloud Cover Modifier Polynomial Coefficients".} \]

Step 22 Calculate Solar Insolation Incident on Solar Array

\[ QSOL(LTIME) = \text{CCMM}(LTIME) \times QSOLC(LTIME) \]

For \( LTIME = 1,11 \)

Step 23 Calculate Total Daily Solar Radiation Incident on Solar Array

\[ QSOL = \int_{LTIME=1}^{LTIME=11} QSOL(LTIME) \times \text{DTIMEH} \quad \text{[Using Simpsons' Rule of Integration]} \]

Where: \( QSOL = \text{Total Daily Solar Insolation Incident on Solar Array - Watt-Hours/Meter}^2 \)

Step 24 Calculate Maximum Solar Radiation

\[ QSOLM(LDAY) = \text{AMAX} \left( QSOL(LTIME) \right) \text{ over the range: } LTIME = 1,11 \]

Where: \( QSOLM = \text{Maximum Solar Insolation, Incident on Solar Array, Encountered during the Day - Watts/Meter}^2 \)

Step 25 Initialize Time Increment and Flasher Load Counters

\[ LTIME = 2 \]
\[ JTOFF = 1 \]
\[ JTON = 1 \]
\[ JOFFMX = 0 \]
\[ JONMX = 0 \]
Step 25 (contd)

Where:  
JTOFF = Flasher Load Turn-off Period Counter  
JTON = Flasher Load Turn-on Period Counter  
JOFFMX = Flasher Turn-off Counter  
JONMX = Flasher Turn-on Counter

Step 26
Compare Solar Insolation Incident on Solar Array With Reference

If:  
QSOL(LTIME) > QOFF
Then:  
GO TO STEP 27
GO TO STEP 31

Step 27
Compare Lamp Flasher Condition Indicator With Reference

If:  
INDFLS = 1
Then:  
GO TO STEP 28
GO TO STEP 31

Step 28
Calculate Time of Lamp Flasher Turn-Off

TOFF(JTOFF) = F {TIMEC(LTIME), QSOL(LTIME)}

at:  
QSOL(LTIME) = QOFF and during the time interval:  
TIMEC(LTIME - 1) to TIMEC(LTIME)

Where:  
TOFF = Time at which Lamp Flasher Turns Off - Hours after Midnight

Step 29
Reset Lamp Flasher Condition Indicator

INDFLS = 0

Step 30
Increment Load Counters

JTOFF = JTOFF + 1  
JOFFMX = JTOFF - 1
GO TO STEP 36
Step 31  Compare Solar Insolation Incident on Solar Array With Reference
If:   QSOL(LTIME) < QON
Then: GO TO STEP 32
      GO TO STEP 36

Step 32  Compare Lamp Flasher Condition Indicator With Reference
If:   INDFLS = 0
Then: GO TO STEP 33
      GO TO STEP 36

Step 33  Calculate Time of Lamp Flasher Turn-On
TON(JTON) = F(TIMEC(LTIME), QSOL(LTIME))
            at:    QSOL(LTIME) = QON, and during the time
            interval:    TIMEC(LTIME - 1) to TIMEC(LTIME)
Where:    TON = Time at which lamp flasher turns-on - Hours after
          Midnight

Step 34  Reset Lamp Flasher Conditions Indicator
INDFLS = 1

Step 35  Increment Load Counters
JTON = JTON + 1
JONMX = JTON - 1

Step 36  Increment Daily Time Counter
LTIME = LTIME + 1

Step 37  Compare Daily Time Counter With Reference
If:   LTIME > 11,
Then: GO TO STEP 38
      RETURN TO STEP 26
Step 38  Calculate Daily Mode Reversals of Battery

\[ \text{DNMR} = \text{JOFFMX} + \text{JONMX} \]

Where: \( \text{DNMR} = \text{Daily Operational Mode Reversals of Battery} \)

Step 39  Calculate Daily Solar Occultation Periods

\[ TJ = \text{SRT} + (24.0 - \text{SST}) \]

Where: \( TJ = \text{Duration of Daily Solar Occultation Periods - Hours} \)

Step 40  Initialize Daily Share-Mode and Battery Charging Periods

\[ TL = 0 \]
\[ TK = \text{TOFF}(1) - \text{SRT} \]

Where: \( TL = \text{Duration of Daily Battery Charging Periods - Hours} \)
\( TK = \text{Duration of Daily Share-Mode Periods - Hours} \)

Step 41  Initialize Load Counters

\[ JTON = 1 \]
\[ JTOFF = 1 \]

Step 42  Compare Load Counters

\[ \text{If: } JT OFF = J T ON, \]
\[ \text{Then: GO TO STEP 43} \]
\[ \text{GO TO STEP 46} \]

Step 43  Calculate Daily Battery Charging Periods

\[ DTL = \text{TON}(JTON) - \text{TOFF}(JTOFF) \]
\[ TL = TL + DTL \]

Where: \( DTL = \text{Battery Charge Period Increment - Hours} \)
### Step 44
Increment Turn-Off Load Counter

\[ J_{TOFF} = J_{TOFF} + 1 \]

### Step 45
Compare Turn-Off Load Counter With Reference

**If:** \( J_{TOFF} > J_{OFFMX} \),
**Then:** GO TO STEP 48

RETURN TO STEP 42

### Step 46
Calculate Daily Share-Mode Periods

\[ DTK = TOFF(J_{TOFF}) - TON(J_{TON}) \]

\[ TK = TK + DTK \]

Where: \( DTK = \) Share-Mode Period Increment \(-\) Hours

### Step 47
Increment Turn-On Load Counter

\[ J_{TON} = J_{TON} + 1 \]

RETURN TO STEP 42

### Step 48
Calculate Weekly Summary of Operational Mode Periods

\[ TJT(NWEEK) = TJT(NWEEK) + TJ \]

\[ TKT(NWEEK) = TKT(NWEEK) + TK \]

\[ TLT(NWEEK) = TLT(NWEEK) + TK \]

### Step 49
Calculate Weekly Summary of Battery Mode Reversals

\[ NHR(NWEEK) = NHR(NWEEK) + DNMR \]

### Step 50
Calculate Weekly Summary of Solar Insolation

\[ QQSOL(NWEEK) = QQSOL(NWEEK) + QQSol \]

\[ QSOLMAX(NWEEK) = \text{AMAX}(QSOLEX(NWEEK), QSOLM(LDAY)) \]
Step 51  Increment Day Counter
LDAY = LDAY + 1

Step 52  Compare Day Counter With Reference
If:   LDAY > 7,
Then: RETURN TO STEP 7
RETURN TO STEP 20

Step 53  Calculate Yearly Solar Occultation Load Energy

EPCDJ = PFON \* \sum_{I=1}^{NWE} TJT(I)

Where: EPCDJ = Yearly Solar Occultation Load Energy - Watts-Hours

Step 54  Calculate Yearly Share-Mode Load Energy

EPCDK = PFON \* \sum_{I=1}^{NWE} TKT(I)

Where: EPCDK = Yearly Share-Mode Load Energy - Watt-Hours

Step 55  Calculate Yearly Battery Charging Mode Load Energy

EPCDL = PPOFF \* \sum_{I=1}^{NWE} TLT(I)

Where: EPCDL = Yearly Battery Charging Mode Load Energy - Watt-Hours
Step 56  Calculate Maximum Energy Storage Group Temperature

\[ \text{TTESMX} = \text{TTABMX} + \text{DTTESG} \]

Where: \( \text{TTESMX} = \) Energy Storage Group Maximum Temperature - °F

Step 57  Obtain Normalized Battery Current Rates

\[ \text{BRR}(J,K,L) = \text{BCQT}(VCC(J,K,L), QBB(K), TBB(L)) \]

Where: \( \text{BRR} = \) Normalized Battery Current Rates (Expressed as the Ratio of Battery Current to Battery Capacity) - Hours\(^{-1}\)

\( \text{VCC} = \) Cell Voltage - VDC
\( \text{QBB} = \) Battery State-of-Charge
\( \text{TBB} = \) Battery Temperature - °F

\( \text{BCQT} = \) Input Table of BRR as a function of VCC, QBB and TBB

\( J = 1, 9 \) (Data Points)
\( K = 1, \text{NQBB} \) (Data Points)
\( L = 1, \text{NTBB} \) (Data Points)

\( \text{NQBB} = \) Number of QBB entries in BCQT
\( \text{NTBB} = \) Number of TBB entries in BCQT

Step 58  Calculate Minimum Storage Cell Discharge Voltage

\[ \text{VCDMN} = F(\text{BRR}(J,K,L), QBB(K), TBB(L)) \]

at: \( \text{BRR}(J,K,L) = -|\text{BRDEST}| \)
\( \text{QBB}(K) = \text{QBRES} \)
\( \text{TBB}(L) = \text{TTESMX} \)

Where: \( \text{VCDMN} = \) Minimum Storage Cell Discharge Voltage - VDC
<table>
<thead>
<tr>
<th>Step 59</th>
<th>Calculate Minimum Storage Cell Charge Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ V_{CCMN} = F{BRR(J,K,L),QBB(K),TBB(L)} ]</td>
</tr>
<tr>
<td></td>
<td>at: ( BRR(J,K,L) = BRCES )</td>
</tr>
<tr>
<td></td>
<td>( QBB(K) = QBRES )</td>
</tr>
<tr>
<td></td>
<td>( TBB(L) = TTESMX )</td>
</tr>
<tr>
<td>Where:</td>
<td>( V_{CCMN} = \text{Minimum Storage Cell Charge Voltage} - , \text{VDC} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 60</th>
<th>Calculate Minimum Battery Potential Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ ETABVN = \frac{V_{CDMN}}{V_{CCMN}} ]</td>
</tr>
<tr>
<td>Where:</td>
<td>( ETABVN = \text{Minimum Battery Potential Efficiency} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 61</th>
<th>Calculate Battery State-of-Charge Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ DQBB1 = \frac{(1.0 - QBRES)}{10.0} ]</td>
</tr>
<tr>
<td>Where:</td>
<td>( DQBB1 = \text{Battery State-of-Charge Increment} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 62</th>
<th>Initialize Battery SOC Counter and SOC Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( IQBB = 1 )</td>
</tr>
<tr>
<td></td>
<td>( QBB1 = QBRES )</td>
</tr>
<tr>
<td>Where:</td>
<td>( IQBB = \text{Battery State-of-Charge Counter} )</td>
</tr>
<tr>
<td></td>
<td>( QBB1 = \text{Battery State-of-Charge} )</td>
</tr>
</tbody>
</table>
Step 63  Calculate Instantaneous Battery Coulombic (Charge) Efficiency

\[ \text{ETA}(\text{IQBB}) = A \{\text{BRR}, \text{QBB}, \text{TBB}\} \]

at: \[ \text{BRR} = \text{BRCEST} \]
\[ \text{TBB} = \text{TTESMX} \]
\[ \text{QBB} = \text{QBB}1 \]

Where: \[ \text{ETA}(\text{IQBB}) = \text{Instantaneous Battery Coulombic Efficiency} \]

\[ A = \text{A series of Input Data Tables (A1, A2, A3, A4, A5) giving ETA as a function of BRR, QBB and TBB} \]

Step 64  Increment Battery SOC Counter and SOC Values

\[ \text{IQBB} = \text{IQBB} + 1 \]
\[ \text{QBB}1 = \text{QBB}1 + D\text{QBB}1 \]

Step 65  Compare Battery SOC Counter With Reference

If: \[ \text{IQBB} > 11, \]
Then: GO TO STEP 67
RETURN TO STEP 63

Step 66  Calculate Average Battery Coulombic (Charge) Efficiency

\[ \text{ETABQ} = \left(\frac{1.0}{1 - \text{QBBRES}}\right) \int_{\text{IQBB}=1}^{\text{IQBB}=11} \text{ETA}(\text{IQBB}) \times \text{DQBB}1 \text{ Rule of Integration} \]

Where: \[ \text{ETABQ} = \text{Average Battery Coulombic Efficiency} \]

Step 67  Calculate Battery Energy Charge/Discharge Ratio

\[ \text{RATBAT} = 1.0 / (\text{ETABVN} \times \text{ETABQ}) \]

Where: \[ \text{RATBAT} = \text{Battery Energy Charge/Discharge Ratio} \]
Step 68  Compare Battery Charger Type With Reference

If:   ICHPT = 0,
Then:  GO TO STEP 75

Step 69  Calculate Battery Discharge Line Efficiency

ETAD = VBUS/(VBUS + 1.0)

Where: ETAD = Battery Discharge Line Efficiency

Step 70  Compare Raw Power Bus Operating Level With Reference

VCHIO = VCHIOT (TTESG) at: TTESG = TTESMX

If:   VBUS < VCHIO,
Then:  GO TO STEP 74

Where: VCHIO = Battery Charger Input Voltage at Turn-on
       (Minimum Voltage Drop at zero current level) - VDC

VCHIOT = Input Table of VCHIO as a function of TTESG
TTESG = Energy Storage Group Temperature - °F

Step 71  Compare Raw Power Bus Operating Level With Reference

VCHISA = VCHIST (TTESG) at: TTESG = TTESMX

If:   VBUS < VCHISA,
Then:  GO TO STEP 72

GO TO STEP 73

Where: VCHISA = Battery Charger Input Voltage wherein Charger
       Changes From "Saturated" operation to "Active"
       Operation - VDC

VCHIST = Input Table of VCHISA as a function of TTESG
Step 72  Calculate Battery Charger Efficiency
ETACHG = 1.0 - (VCHIO/VBUS)
GO TO STEP 76
Where: ETACHG = Battery Charger Efficiency

Step 73  Calculate Battery Charger Efficiency
ETACHG = (VCHISA - VCHIO)/VBUS
GO TO STEP 76

Step 74  Calculate Battery Charger Efficiency
ETACHG = 0.0
GO TO STEP 76

Step 75  Calculate Battery Discharge Line Efficiency and Charger Efficiency
ETAD = 1.0
ETACHG = 1.0

Step 76  Calculate Duration of Yearly Share-Mode Loads

\[ TKTT = \sum_{I=1}^{N\text{WEEK}} TKT(I) \]

Where: TKTT = Duration of Yearly Share-Mode Loads - Hours
Step 77 Calculate Duration of Yearly Battery Charge Mode Loads

\[ TLTT = \sum_{i=1}^{N\text{WEEK}} TL(T(i)) \]

Where: TLTT = Duration of Yearly Battery Charge Mode Loads - Hours

Step 78 Calculate Power Source Group (PSG) Average Power Level

\[ PPSGAV = \frac{RATBAT \cdot (EPCDJ + EPCDK) + (ETAD \cdot ETACHG \cdot EPCDL)}{(ETAD \cdot ETACHG \cdot TLTT) \cdot (RATBAT \cdot TKTT)} \]

Where: PPSGAV = PSG Average Power Level During Year - Watts

Step 79 Calculate PSG Energy Requirement

\[ EPSG = PPSGAV \cdot (TKTT + TLTT) \]

Where: EPSG = PSG Yearly Energy Requirement - Watt-Hours

Step 80 Calculate Solar Array Energy Requirement

\[ ESA = EPSG / \left( \frac{V_{BUS}}{V_{BUS} + 1.0} \right) \]

Where: ESA = Solar Array Yearly Energy Requirement - Watt-Hours

Step 81 Calculate Maximum Solar Array Temperature

\[ \begin{align*}
TSAFMX &= TTABMX + DTTPSG \\
TSARMX &= TSAFMX + 459.67 \\
TSAKMX &= (5.0/9.0) \cdot TSARMX \\
TSACKX &= TSAKMX - 273.15
\end{align*} \]

Where: TSAFMX = Maximum Solar Array Temperature - °F \\
TSARMX = Maximum Solar Array Temperature - °R \\
TSAKMX = Maximum Solar Array Temperature - °K \\
TSACKX = Maximum Solar Array Temperature - °C
Step 82

Calculate Maximum Instantaneous Solar Radiation

\[ Q_{DTMX} = \text{AMAX} \left( Q_{SOLMX(I)} \right) \text{ over the range: } I = 1, \ldots, \text{WEEK} \]

Where:

- \( Q_{DTMX} \) = Maximum Instantaneous Total Solar Radiation Incident on Solar Array - Watts/Meter\(^2\)

Step 83

Obtain Solar Array Electrical Characteristics

Under the conditions:

(a) \( TSAC = TSAC_{MX} \)
(b) \( QDT = QDT_{MX} \)
(c) \( DATEM = \text{DURAM} \times 365.242 \)
(d) \( NS1 = 50 \)
(e) \( NP = 50 \)
(f) \( NESP = 1 \)

Where:

- \( TSAC \) = Solar Array Temperature - °C
- \( QDT \) = Instantaneous Total Solar Radiation Incident on Solar Array - Watts/Meter\(^2\)
- \( DATEM \) = Elapsed Time from start of mission - Days
- \( NS1 \) = No. of Solar Cells in Series in each circuit
- \( NP \) = No. of Solar Cells in Parallel in each circuit
- \( NESP \) = Number of Parallel Electrical Circuits in Solar Array

Then:

- \( V_{2(L)} \) = Solar Array Voltage - VDC
- \( I_{2(L)} \) = Solar Array Current at \( V_{2(L)} \) - Amperes

\[ L = 1, \text{MFINAL} \]

- \( MSAPWR \) = Solar Array Maximum Power - Watts
- \( \text{MAXV} \) = Solar Array Voltage at Maximum Power Point - VDC
- \( \text{MAXI} \) = Solar Array Current at Maximum Power Point - Amperes
Step 83a  Calculate Single Cell Maximum Power

\[ \text{PWRMX1} = \frac{\text{MSAPWR}}{(N_{S1} \times N_P \times N_{ESP})} \]

Where: \( \text{PWRMX1} = \) Single Cell Maximum Power Output - Watts

Step 84  Calculate Solar Cell Efficiency for End of Mission

\[ \text{ETAEOM} = \frac{\text{PWRMX1}}{(QDT \times A_{CELL} \times 10^{-6})} \]

Where: \( \text{ETAEOM} = \) End-of-Mission Solar Cell Efficiency

Step 85  Calculate Total Yearly Solar Radiation

\[ \text{QQSTOT} = \sum_{i=1}^{N_{WEEK}} \text{QQSOLT}(i) \]

Where: \( \text{QQSTOT} = \) Total Yearly Solar Radiation Incident on Solar Array - Watt-Hours/Meter\(^2\)

Step 86  Calculate Nominal Estimate of Total Solar Cell Area

\[ \text{ASCTNM} = \frac{\text{QQSTOT} \times \text{ETAEOM} \times (1.0 - \text{SARES})}{\text{E}_{SA}} \]

Where: \( \text{ASCTNM} = \) Nominal estimate of total solar cell area - Meter\(^2\)

Step 87  Calculate Nominal Estimate of Total Solar Cells

\[ \text{XNSCNM} = \frac{\text{ASCTNM}}{A_{CELL} \times (1.0 \times 10^{-6})} \]

Where: \( \text{XNSCNM} = \) Nominal Estimate of Total Solar Cells

Step 88  Calculate Solar Array Open Circuit Voltage

\[ \text{VSCOC} = F\{ V_2(L), I_2(L) \} \text{ at } I_2(L) = 0.0 \]

Where: \( \text{VSCOC} = \) Array Open Circuit Voltage - VDC
Step 89  Calculate Number of Solar Cells in Series Required

\[ XNS = \frac{VBUS \times 1.0}{\left(\frac{VSCOC + MAXV}{2.0 \times N31}\right)} \]

\[ NS = \text{IFIX}(XNS) + 1.0 \]

Where:  \( XNS = \) Estimate of Cells in Series

\( NS = \) Number of Solar Cells in Series Required

Step 90  Calculate Number of Solar Array Electrical Sections in Parallel

\[ XNESP = \frac{XNSCNM}{\text{FLOAT}(NS) \times \text{FLOAT}(NPREQ)} \]

\[ NESP = \text{IFIX}(XNESP) + 1.0 \]

Where:  \( XNESP = \) Estimate of Electrical Sections in parallel

Step 91  Calculate Total Solar Cells Required

\[ NSCTOT = NESP \times NS \times NPREQ \]

Where:  \( NSCTOT = \) Total Number of Solar Cells Required for the Solar Array

Step 92  Calculate Total Solar Cell Area

\[ ASCTOT = NSCTOT \times ACELL \left(1.0 \times 10^{-4}\right) \]

Where:  \( ASCTOT = \) Total Solar Cell Area Required for Solar Cell Array - Meter\(^2\)

Step 93  Calculate Total Solar Array Area

\[ ASA = \frac{ASCTOT}{CLOPAC \times \left(9.290 \times 10^{-2}\right)} \]

Where:  \( ASA = \) Total Solar Array Area Required - Foot\(^2\)
Step 94  Calculate Solar Array Weight

\[ DWDA = DWDAT \times ASA \]

\[ WSA = ASA \times DWDA \]

Where:  \( DWDA \) = Solar Array Specific Weight - Lbs/Ft

\[ WSA = \text{Solar Array Weight - Lbs} \]

\[ DWDAT = \text{Input Table of DWDA as a function of ASA} \]

Step 95  Calculate Solar Array Cost

\[ ASATP = ASA \times \text{FLOAT (NSAP)} \]

\[ DCDA = \text{DCDAT (ASATP)} \]

\[ CSA = ASA \times DCDA \]

Where:  \( ASATP \) = Total Area of Solar Arrays to be procured - Ft

\[ CSA = \text{Solar Array Cost - $} \]

\[ DCDA = \text{Solar Array Specific Cost - $/Ft} \]

\[ DCDAT = \text{Input Table of DCDA as a Function of ASATP} \]

Step 96  Calculate Minimum Solar Array Temperature

\[ TSAFMN = TTABMN + DTTPSG \]

\[ TSARMN = TSAFMN + 459.67 \]

\[ TSAKMN = (5.0/9.0) \times TSARMN \]

\[ TSACMN = TSAKMN - 273.15 \]

Where:  \( TSAFMN \) = Minimum Solar Array Temperature - °F

\[ TSARMN = \text{Minimum Solar Array Temperature - °R} \]

\[ TSAKMN = \text{Minimum Solar Array Temperature - °K} \]

\[ TSACMN = \text{Minimum Solar Array Temperature - °C} \]
### Step 97
Obtain Solar Array Current Voltage Characteristics at the Beginning of Life

**Under the conditions:**

- (a) TSAC = TSACMN
- (b) QDT = QDTMX
- (c) DATEM = 0.0
- (d) NP = NFREQ
- (e) NS = NS \(\text{from above}\)
- (f) NESP = NESP \(\text{Calculations}\)

Then:
- \(V2(L) = \text{Solar Array Voltage - VDC}\)
- \(I2(L) = \text{Solar Array Current at } V2(L) - \text{Amperes}\)
- \(L = 1, MFINAL\)

\(MSAPWR = \text{Solar Array Maximum Power - Watts}\)

\(MAXV = \text{Solar Array Voltage at Maximum Power Point - VDC}\)

\(MAXI = \text{Solar Array Current at Maximum Power Point - Amperes}\)

### Step 98
Calculate Solar Array Open Circuit Voltage (at BOL)

\(VSAOC = F(V2(L), I2(L)) \text{ at } I2(L) = 0.0\)

Where: \(VSAOC = \text{Solar Array Open Circuit Voltage - VDC}\)

### Step 99
Calculate Maximum Blocking Diode Power Loss

\[ MSABDP = \left(\frac{1.0}{VBUS + 1.0}\right) \times MSAPWR \]

Where: \(MSABDP = \text{Maximum Power Loss in all Solar Array Blocking Diodes - Watts}\)
Step 100  Calculate Solar Array Electrical Section Blocking Diode Rating

\[ P_{ESBD} = \frac{MS_{ABDP}}{\text{FLOAT} \times N_{ESP}} \]

Where: \( P_{ESBD} \) = Electrical Section Blocking Diode Power Rating - Watts

Step 101  Initialize Weekly Counter and Battery State

\[ NWEEK = 1.0 \]
\[ BSTATE = 0.0 \]
\[ EBTHMX = 0.0 \]
\[ EBTHMN = 0.0 \]

Where: \( BSTATE \) = Relative Energy State of the Battery - Watt-Hours
\( EBTHMX \) = Maximum Battery Energy State - Watt-Hours
\( EBTHMN \) = Minimum Battery Energy State - Watt-Hours

Step 102  Compare Weekly Counter With Reference

\[ \text{If: } NWEEK < 0 \text{ ; OR} \]
\[ \text{If: } NWEEK > 52 \text{ ; OR} \]
\[ \text{If: } NWEEK > LWEEK : \]
\[ \text{Then: GO TO STEP 113} \]

Step 103  Calculate Average Weekly Solar Insolation

\[ Q_{QSOLA} = \frac{Q_{QSTOT}}{\text{FLOAT} \times NWEEK} \]

Where: \( Q_{QSOLA} \) = Average Weekly Solar Radiation Incident on Solar Array - Watt-Hours/Meter\(^2\)
**Step 104** Calculate Modified PSG Power Output

\[
PPSGL = \frac{PPSGAV \times QSOLT(NWEEK)}{QSOLA}
\]

\[
PPSGK = \frac{PPSGL \times QOFF}{QSOLMX(NWEEK)}
\]

Where:
- \( PPSGL \) = Weekly Average PSG power output during battery charging periods - Watts
- \( PPSGK \) = Weekly Average PSG power output during Share-Mode Operational periods - Watts

**Step 105** Calculate Battery Load Profile Power Levels

\[
PBJ = \frac{-PFON/LTAD}{ETAD}
\]

\[
PBK = -\left(\frac{PFON - PPSGK}{ETAD}\right)
\]

\[
PBL = \left(\frac{ETACHG/RATBAT}{ETAD}\right) \times (PPSGL - PFOFF)
\]

Where:
- \( PBJ \) = Battery Discharge Power during Solar Occultation periods - Watts
- \( PBK \) = Battery Discharge Power during Share-Mode Operation periods - Watts
- \( PBL \) = Battery Charge Power, adjusted to reflect Net gain in discharge energy, during Battery Charging periods - Watts

**Step 106** Compare Share-Mode Battery Discharge Power with Reference

If: \( PBK > 0.0 \),

Then: \( PBK = 0.0 \)
Step 107  Calculate Battery Energy Profile Levels

\[
\begin{align*}
EBX(1) &= PBJ \times TJI(NWEEK) \\
EBX(2) &= PBK \times TKT(NWEEK) \\
EBX(3) &= PBL \times TLT(NWEEK) \\
EBDX(1) &= EBX(1)/7.0 \\
EBDX(2) &= EBX(2)/7.0 \\
EBDX(3) &= EBX(3)/7.0
\end{align*}
\]

Where: \( EBX(I) \) = Battery Discharge Energy during a particular operational period - Watt-Hours
\( EBDX(I) \) = Average Daily Battery Discharge Energy

\[I = 1 = \text{During Solar Occultation periods} \]
\[I = 2 = \text{During Share-Mode periods} \]
\[I = 3 = \text{During Battery charging periods} \]

Step 108  Initialize Period Counter

\[I = 1\]

Step 109  Compare Period Counter With Reference

If: \[I > 3,\]
Then: \[\text{GO TO STEP 112}\]

Step 110  Calculate Battery Energy State

\[BSTATE = BSTATE + EBDX(I)\]
\[EBTHMX = \max(EBTHMX, BSTATE)\]
\[EBTHMN = \min(EBTHMN, BSTATE)\]
Step 111  Increment Period Counter

\[ I = I + 1 \]

RETURN TO STEP 109

Step 112  Increment Weekly Counter

\[ \text{NWEK} = \text{NWEK} + 1 \]

RETURN TO STEP 102

Step 113  Calculate Theoretical Battery Discharge Energy Requirement

\[ \text{EBDTH} = \text{ABS} (\text{EBTHMX} - \text{EBTHMN}) \]

Where: \( \text{EBDTH} = \) Theoretical Battery Discharge Energy - Watt-Hours

Step 114  Calculate First Criterion for Energy Storage Group Discharge Energy

\[ \text{EESG1} = \frac{\text{EBDTH}}{1.0 - \text{QBRES}} \]

Where: \( \text{EESG1} = \) First Criterion for ESG Discharge Energy - Watt-Hours

Step 115  Calculate Yearly Battery Mode Reversals

\[ \text{NMRT} = \sum_{I=1}^{\text{NWEK}} \text{NMRT}(I) \]

Where: \( \text{NMRT} = \) Total Yearly Reversals of Battery Operating Mode

Step 116  Calculate Total Mission Battery Cycle Requirements

\[ \text{NCYCLE} = \text{FLOAT} \left( \frac{52.0 \cdot \text{DURAM}}{2.0} \cdot \left( \frac{\text{FLOAT(NMRT)}}{\text{FLOAT(NWEK)}} \right) \right) + 1 \]

Where: \( \text{NCYCLE} = \) Battery Charge/Discharge Cycle Requirement
Step 117 Calculate Theoretical Battery Depth-of-Discharge

\[ \text{DOD} = \text{DODT} \left( \ln \text{NCYCLE} \right) \]

Where: \( \text{DOD} \) = Theoretical Battery Depth of Discharge

\( \text{DODT} \) = Input Table of DOD as a function of the natural logarithm of NCYCLE

Step 118 Compare Theoretical Depth of Discharge With Reference

If: \( \text{DOD} < 0.0 \),
Then: \( \text{DOD} = 0.001 \)

If: \( \text{DOD} > 1.0 \),
Then: \( \text{DOD} = 1.0 \)

Step 119 Calculate Second Criterion for Battery Discharge Energy Requirement

\[ \text{EESG2} = \frac{\text{EBDTH}}{\text{DOD}} \]

Where: \( \text{EESG2} \) = Second Criterion for ESG Discharge Energy - Watt-Hours

Step 120 Calculate PSG Maximum Power Output

\[ \text{PPSGMX} = \text{MSAPWR} - \text{MSAPDP} \]

Where: \( \text{PPSGMX} \) = PSG Maximum Power Output - Watts

Step 121 Calculate Maximum Battery Charge Power

\[ \text{PBCHMX} = \text{ETACHG} \times (\text{PPSGMX} - \text{PPOFF}) \]

Where: \( \text{PBCHMX} \) = Maximum Power Available for Battery Charging - Watts
**Step 122**  Calculate ESG Minimum Temperature

\[ T_{TESMN} = T_{TABMN} + D_{TESG} \]

Where:  \( T_{TESMN} \) = Minimum Temperature of ESG - °F

**Step 123**  Calculate Maximum Storage Cell Discharge Voltage

\[ V_{CDMX} = F\{BRR(J,K,L),QBB(K),TBB(L)\} \]

at:  \( BRR(J,K,L) = -|BRDEST| \)

\( QBB(K) = 1.0 \)

\( TBB(L) = T_{TESMN} \)

Where: \( V_{CDMX} \) = Maximum Storage Cell Discharge Voltage - VDC

**Step 124**  Calculate Maximum Storage Cell Charge Voltage

\[ V_{CCMX} = F\{BRR(J,K,L),QBB(K),TBB(L)\} \]

at:  \( BRR(J,K,L) = BRCEST \)

\( QBB(K) = 1.0 \)

\( TBB(L) = T_{TESMN} \)

Where: \( V_{CCMX} \) = Maximum Storage Cell Charge Voltage - VDC

**Step 125**  Calculate Maximum Battery Potential Efficiency

\[ E_{TABVX} = V_{CDMX}/V_{CCMX} \]

Where:  \( E_{TABVX} \) = Maximum Battery Potential Efficiency

**Step 126**  Calculate Third Criterion for Battery Discharge Energy Requirement

\[ E_{EESG3} = \frac{PBCHMX \times E_{TABVX}}{BRCHMX} \]

Where:  \( E_{EESG3} \) = Third criterion for ESG Discharge Energy - Watt-Hours
Step 127 Calculate Actual Battery Energy Discharge Capability

\[ EESG = \text{AMAX}(EESG1, EESG2, EESG3) \]

Where: \( EESG \) = ESG Discharge Energy Capability - Watt-Hours

Step 129 Compare Battery Charger Type With Reference

If: \( ICHRT > 0 \),
Then: GO TO STEP 133

Step 130 Compare Shunt Limiter Type With Reference

If: \( ISH > 0 \),
Then: GO TO STEP 132

Step 131 Calculate Maximum Battery Charge Voltage

\[ VBCHMX = VSAOC - 1.0 \]

GO TO STEP 139

Where: \( VBCHMX \) = Maximum Battery Charge Voltage - VDC

Step 132 Calculate Maximum Battery Charge Voltage

\[ VBCHMX = VBUS + (0.75) \times ((VSAOC - 1.0) - VBUS) \]

GO TO STEP 139

Step 133 Compare Shunt Limiter Type with Reference

If: \( ISH > 0 \),
Then: \( ISH = 0 \)

Step 134 Calculate Battery Charger Reference Voltages

\[ \begin{align*}
VCHIO &= VCHIOT \{ TTESG \} \\
VCHISA &= VCHIST \{ TTESG \}
\end{align*} \]

at: \( TTESG = TTESMN \)
Step 134 (contd)

Where:  
- VCHIO = Battery Charger Input Voltage at Turn-On - VDC
- VCHISA = Battery Charger Input Voltage at which charger changes from "Saturated" to "Active" operation - VDC
- VCHIOT = Input Table of VCHIO as a function of TTESG
- VCHIST = Input Table of VCHISA as a function of TTESG

Step 135  Compare Solar Array Open Circuit Voltage With Reference

If:   (VSAOC - 1.0) > VCHIO,
Then: GO TO STEP 136

Print Out Error Message:
"VBUS too low to turn-on battery charger"
Return to Main Program and Stop Computer Run

Step 136  Compare Solar Array Open Circuit Voltage With Reference

If:   (VSAOC - 1.0) > VCHISA,
Then: GO TO STEP 138

Step 137  Calculate Maximum Battery Charge Voltage

VBCHMX = (VSAOC - 1.0) - VCHIO
GO TO STEP 139

Step 138  Calculate Maximum Battery Charge Voltage

VBCHMX = F (VESA, TTESG)

at:  VESA = VSAOC - 1.0
     TTESG = TTESMH
Step 138 (contd)

Where:

\[ VESA = VCHIT \{ \text{VCHOOA, TTESG} \} \]

\[ VCHOOA = \text{VBCHMx} \]

\[ VESA = \text{Estimate of Battery Charger Input Voltage in "active" condition - VDC} \]

\[ VCHOOA = \text{Battery Charger Output Voltage, in "active" condition at zero current - VDC} \]

\[ VCHIT = \text{Input Table of VESA as a function of VCHOOA and TTESG} \]

Step 139 Calculate Storage Cell Minimum Charge Voltage

\[ VCCHMN = \{ BRR(J,K,L),QBB(K),TBB(L) \} \]

at: \( BRR(J,K,L) = 0.0 \)
\[ QBB(K) = 1.0 \]
\[ TBB(L) = TTESMX \]

Where: \( VCCHMN = \text{Storage Cell Minimum Charge Voltage - VDC} \)

Step 140 Calculate Maximum Number of Storage Cells in Series

\[ XNCBMX = \text{VBCHMX}/VCCHMN \]

Where: \( XNCBMX = \text{Estimated Maximum Number of Storage Cells in Series} \)

Step 141 Calculate Storage Cell Maximum Charge Voltage

\[ VCCHMX = \{ BRR(J,K,L),QBB(K),TBB(L) \} \]

at: \( BRR(J,K,L) = 0.0 \)
\[ QBB(K) = 1.0 \]
\[ TBB(L) = TTESMN \]

Where: \( VCCHMX = \text{Storage Cell Maximum Charge Voltage - VDC} \)
Step 142 Calculate Minimum Number of Storage Cells in Series

\[ X_{NCBMN} = \frac{V_{BUSMN}}{V_{CCMX}} \]

Where: \( X_{NCBMN} = \) Estimated Minimum Number of Storage Cells in Series

Step 143 Calculate Estimated Storage Cells in Series

\[ X_{NCELL} = X_{NCBMN} + (FRCELL) \cdot (X_{CCRMX} - X_{NCBMN}) \]

Where: \( X_{NCELL} = \) Estimated Storage Cells in Series

Step 144 Calculate Actual Number of Storage Cells in Series

\[ NCELL = \text{IFIX}(X_{NCELL}) \]
\[ Y_{NCELL} = \text{FLOAT}(NCELL) \]
\[ D_{NCELL} = X_{NCELL} - Y_{NCELL} \]

If: \( D_{NCELL} \geq 0.5 \),
Then: \( NCELL = NCELL + 1 \)

Where: \( NCELL = \) Number of Storage Cells in Series in the Battery

Step 145 Initialize Voltage Counter and Battery State-of-Charge

\[ I = 1 \]
\[ Q_{BS} = 0.0 \]

Where: \( Q_{BS} = \) Dummy Variable used for Battery State-of-Charge

Step 146 Compare Voltage Counter With Reference

\[ \text{If: } I > 11, \]
Then: GO TO STEP 149
Step 147  Calculate Storage Cell Discharge Voltage

\[ V_{CDSTD}(I) = F(BRR(J,K,L), QBB(K), TBB(L)) \]

at: \[ BRR(J,K,L) = -|BRR| \]

\[ QBB(K) = QBS \]

\[ TBB(L) = TBDSTD \]

Where: \( V_{CDSTD} \) = Storage Cell Discharge Voltage under Standard Conditions of BRDSTD and TBDSTD - Volts

Step 148  Increment Voltage Counter and Battery State-of-Charge

\[ QBS = QBS + 0.1 \]

\[ I = I + 1 \]

RETURN TO STEP 146

Step 149  Calculate Average Storage Cell Discharge Voltage

\[ V_{CDAVG} = \frac{1}{11} \sum_{I=1}^{11} V_{CDSTD}(I) \times (0.1) \]

Using Simpsons' Rule

Where: \( V_{CDAVG} \) = Average Storage Cell Discharge Voltage Under Standard Conditions - VDC

Step 150  Calculate Total ESG Discharge Capacity

\[ CBDSTD = \frac{EESG}{V_{CDAVG} \times \text{FLOAT(NCELL)}} \]

Where: \( CBDSTD \) = Total ESG Discharge Capacity Under Standard Conditions - Amp-Hours

Step 151  Initialize Storage Cell Size Counter

\[ JB = 1 \]

Where: \( JB \) = Tabular Location Size of Available Storage Cell
Step 152
Compare Storage Cell Size Counter With Reference

If:   JB > 30
Then: GO TO STEP 154

Step 153
Compare Storage Cell Size With Reference

If:   CBAVAL(JB) > 0.0,
Then: JB = JB + 1, AND
Then: RETURN TO STEP 152

Step 154
Calculate Maximum Number of Storage Cell Table Entries

JBTOT = JB

Where: JBTOT = Max. No. of Entries in Storage Cell Table

Step 155
Initialize Storage Cell Size Counter

JB = 1

Step 156
Compare Storage Cell Size Counter With Reference

If:   JB > JBTOT,
Then: JBMAX = JBTOT, AND
Then: GO TO STEP 159

Where: JBMAX = Location of Max. Available Battery Capacity in Storage Cell Table

Step 157
Compare Maximum Desired Battery Capacity With Reference

If:   CBMAX > CBAVAL(JB),
Then: JB = JB + 1, AND
Then: RETURN TO STEP 156

Step 158
Calculate Location of Maximum Desired Battery Capacity in Available Storage Cell Table

JBMAX = JB - 1
Step 159  Calculate Estimate of Batteries Required

\[ XNBATT = \frac{CBDSTD}{CBAVAL(JBMAX)} \]

Where: \( XNBATT \) = Estimate of Number of Batteries in Parallel

Step 160  Compare Estimate of Batteries Required With Reference

If: \( XNBATT > 1.0 \),
Then: \( JBB = JBMAX \), AND
Then: GO TO STEP 166

Where: \( JBB \) = Location of Selected Design Capacity in Storage Cell Table

Step 161  Initialize Counter

\( J = 1 \)

Step 162  Compare Counter With Reference And Select Battery Attribute

If: \( J = JBMAX \),
Then: \( NBATT = 1 \), AND,
Then: \( CBDT = CBDSTD \), AND,
Then: \( CBD = CBDT \), AND,
Then: GO TO STEP 174

Where: \( NBATT \) = Number of Batteries in Parallel

\( CBDT = \) Total Discharge Capacity of all batteries - Amp-Hours\n
\( CBD = \) Discharge Capacity of a single battery - Amp-Hours

Step 163  Calculate Location of Selected Battery Design Capacity in Storage Cell Table

\( JBB = JMAX - J \)

Step 164  Calculate Estimate of Number of Batteries in Parallel

\[ XNBATT = \frac{CBDSTD}{CBAVAL(JBB)} \]
Step 165  Compare Estimate of Batteries Required With Reference

If:   XNBATT < 1.0
Then:  J = J + 1, AND,
Then:  RETURN TO STEP 162

Step 166  Compare Estimate of Batteries Required With Reference

If:   XNBATT < 10.0
Then:  GO TO STEP 172

Step 167  Increment Maximum Desired Battery Capacity Location in Storage Cell Table

JBMAX = JBMAX + 1

Step 168  Compare Maximum Desired Battery Capacity Location With Reference and Select Battery Attributes

If:   JBMAX > JBTOT,
Then:  NBATT = 10, AND,
Then:  CBDT = CBDSTD, AND,
Then:  CBD = CBDT/FLOAT(NBATT); AND,
Then:  GO TO STEP 174

Step 169  Calculate Location of Selected Battery Design Capacity in Storage Cell Table

JBB = JBMAX

Step 170  Calculate Estimate of Number of Batteries in Parallel

XNBATT = CBDSTD/CBAVAL(JBB)

Step 171  Compare Estimate of Batteries Required With Reference

If:   XNBATT > 10.0,
Then:  RETURN TO STEP 167
Step 172  Calculate Actual Number of Batteries in Parallel

\[\text{NBATT} = \text{IFIX}(\text{XNBATT})\]

\[\text{YNBATT} = \text{FLOAT}(\text{NBATT})\]

\[\text{DNBATT} = \text{XNBATT} - \text{YNBATT}\]

If: \[\text{DNBATT} \geq 0.5,\]
Then: \[\text{NBATT} = \text{NBATT} + 1\]

Step 173  Calculate Battery and ESG Storage Capacity

\[\text{CBD} = \text{CBAVAL}(\text{JBB})\]

\[\text{CBDT} = \text{CBD} \times \text{FLOAT}(\text{NBATT})\]

Step 174  Calculate Maximum Allowable Battery Charging Current

\[\text{EBDA} = \text{CBDT} \times \text{VCDAVG} \times \text{FLOAT}(\text{NCELL})\]

\[\text{DODA} = \frac{\text{EBDA}}{\text{VCDTH}}\]

\[\text{YICHMX} = \text{CBDT} \times \text{BRCHMX}\]

\[\text{ZICHMX} = \frac{\text{YICHMX}}{\text{FLOAT}(\text{NBATT})}\]

Where:

- \text{EBDA} = \text{Total Battery Energy Watt-Hours}
- \text{DODA} = \text{Maximum Battery Depth-of-Discharge}
- \text{YICHMX} = \text{Maximum Allowable Battery Charging Current for the ESG - Amperes}
- \text{ZICHMX} = \text{Maximum Allowable Charging Current for Single Battery - Amperes}
**Step 175** Calculate Battery Weight

\[ DWDE = DWDET(CBD) \]

\[ EBTOT = CBDT \times VCADE \times FLOAT(NCELL) \]

\[ WBATT = DWDE \times EBTOT \]

Where:
- **DWDE**: Battery Specific Weight - lbs/Watt-Hour
- **EBTOT**: Total Battery Energy in ESG - Watt-Hours
- **WBATT**: Battery Weight - Lbs
- **DWDET**: Input Table of DWDE as a function of CBD

**Step 176** Calculate Battery Cost

\[ DCDE = DCDET(CBD, NBATP) \]

\[ CBATT = DCDE \times EBTOT \]

Where:
- **DCDE**: Battery Specific Cost - $/Watt-Hour
- **NBATP**: Total Number of Batteries to be procured
- **CBATT**: Battery Cost - $
- **DCDET**: Input table of DCDE as a function of CBD and NBATP

**Step 177** Compare Battery Charger Type With Reference

If: \( ICHRT = 0 \), Then: \( PCHO = 0.0 \), AND, Then: \( WCHG = 0.0 \), AND, Then: \( CCNG = 0.0 \), AND, Then: GO TO STEP 181

Where:
- **PCHO**: Maximum Load for a Single Battery Charger - Watts
- **WCHG**: Weight of all chargers - Lbs
- **CCNG**: Cost of all chargers - $

3-44
Step 178  Calculate Single Charger Maximum Load

\[ PCHO = PBCHMx/FLOAT(NBATT) \]

Step 179  Calculate Battery Charger Weight

\[ DWDCH = DWDCHT(PCHO) \]

\[ WCHG = DWDCH \times PCHO \times FLOAT(NBATT) \]

Where:  
\[ DWDCH = \text{Battery Charger Specific Weight - Lb/Watt} \]

\[ DWDCHT = \text{Input Table of DWDCH as a function of PCHO} \]

Step 180  Calculate Battery Charger Cost

\[ DCDCH = DCDCHT(PCHO, NCHGP) \]

at:  
\[ NCHGP = NBATP \]

Where:  
\[ NCAGP = \text{Number of Battery Chargers Procured} \]

\[ DCDCH = \text{Battery Charger Specific Cost - $/Watt} \]

\[ DCDCHT = \text{Input Table of DCDCH as a Function of PCHO and NCHGP} \]

Step 181  Compare Shunt Limiter Type With Reference

If:  
\[ ISH = 0, \]
Then:  
\[ WSL = 0.0, \text{ AND,} \]
Then:  
\[ CSL = 0.0, \text{ AND,} \]
Then:  
\[ \text{GO TO STEP 215} \]

Where:  
\[ WSL = \text{Total Weight of Shunt Limiters - Lbs} \]

\[ CSL = \text{Total Cost of Shunt Limiters - $} \]
Step 182 Calculate Shunt Limiter Operating Point

VSLOP = VBCHMX

XISLOP = F(I2(L), V2(L))

at: V2(L) = VSLOP

Where: VSLOP = Shunt Limiter Operating Point Voltage - VDC

XISLOP = Shunt Limiter Operating Point Current - Amperes

Step 183 Compare Shunt Limiter Type With Reference

If: ISH > 2,

Then: GO TO STEP 208

Step 184 Calculate Power Source Group Type

IPSG = 1

Where: IPSG = Power Source Group Type

0 = One Shunt Limiter for the Solar Array

1 = One Shunt Limiter for each electrical section of the solar array

Step 185 Calculate Zener Diode Reference Power Level

PZRFP25 = HDER * HDZMX

Where: PZRFP25 = Single Zener Diode Reference Power Level at 25°C - Watts

Step 186 Calculate Estimate of Zener Diodes in a Single String

XNZS = PPSGMX/(PZRFP25 * FLOAT(NESP))

Where XNZS = Estimate of Zener Diodes in a Single String
Step 187 Calculate Actual No. of Zener Diodes in a Single String

\[ NZS = \text{IFIX}(XNZS) \]

\[ YNZS = \text{FLOAT}(NZS) \]

\[ DNZS = XNZS - YNZS \]

If: \( DNZS > 0.5 \),
Then: \( NZS = NZS + 1 \)

If: \( NZS < 1 \),
Then: \( NZS = 1 \)

Step 188 Calculate Zener Diode Operating Temperature

\[ TCZ = TSACMN \]

Where: \( TCZ = \) Zener Diode Operating Temperature - °C

Step 189 Calculate Single Zener Diode Operating Point

\[ VZOP = \frac{VSL0P}{\text{FLOAT}(NZS)} \]

\[ XIZOP = \frac{XISLOP}{\text{FLOAT}(NESP)} \]

Where: \( VZOP = \) Zener Diode Operating Point Voltage - VDC

\( XIZOP = \) Zener Diode Operating Point Current - Amperes

Step 190 Compare Shunt Limiter Type With Reference

If: \( ISH > 1 \),
Then: GO TO STEP 201

Step 191 Initialize Zener Diode Voltage Counter

\( LZ = 1 \)

Step 192 Initialize Zener Diode Breakdown Reference Voltage

\( VZB30 = VZOP \)

Where: \( VZB30 = \) Zener Diode Breakdown Voltage at 30°C - VDC
**Step 193** Compare Zener Diode Voltage Counter With Reference

If: \( LZ > 25 \)
Then: \( V_{ZBR} = V_{ZB}, \text{AND} \)
Then: GO TO STEP 205

Where: \( V_{ZBR} = \) Single Zener Diode Breakdown Voltage - VDC (at Operating Temperatures)
\( V_{ZB} = \) Estimate of Zener Diode Breakdown Voltage - VDC

**Step 194** Calculate Zener Diode Temperature Coefficient

\( TCO = Z_{TCOEF} (VZB30) \)

Where: \( TCO = \) Zener Diode Temperature Coefficient - \((\%/°C)\)
\( Z_{TCOEF} = \) Input Table of TCO as a function of VZB30

**Step 195** Calculate Zener Diode Dynamic Impedance

\( ZZ = Z_{DIMP} (TCZ, VZB30) \)

Where: \( ZZ = \) Zener Diode Impedance - Ohms
\( Z_{DIMP} = \) Input Table of ZZ as function of TCZ and VZB30

**Step 196** Calculate Estimate of Zener Diode Breakdown Voltage

\( V_{ZB} = V_{ZOP} - (X_{ZOP} * ZZ) \)

**Step 197** Calculate Estimate of Reference Temperature Zener Breakdown Voltage

\( V_{ZB301} = V_{ZB} \cdot \left[ 1.0 - \frac{TCO \cdot (TCZ - 30.0)}{100.0} \right] \)

Where: \( V_{ZB301} = \) Estimate of Zener Diode Breakdown Voltage at \( 30°C \) - VDC
Step 198  Calculate Breakdown Voltage Residual

\[ DVZB = \text{ABS}(\frac{VZB301 - VZB30}{VZB30}) \]

Where:  \( DVZB \) = Residual in Estimate of Zener Diode Breakdown Voltage at 30°C - VDC

Step 199  Compare Breakdown Voltage Residual With Reference

If:  \( DVZB < 0.01 \),
Then:  \( VZBR = VZB \), AND,
Then:  GO TO STEP 205

Step 200  Increment Zener Diode Voltage Counter and Adjust Reference Breakdown Voltage

\[ LZ = LZ + 1 \]
\[ VZB30 = VZB301 \]
RETURN TO STEP 193

Step 201  Calculate Temperature Compensated (TC) Zener Reference Current

\[ IZRF25 = \text{CURZ}(\text{HDZMX}) \]

Where:  \( IZRF25 \) = Zener Diode Reference Current at 25°C - Amperes

\text{CURZ} = \text{Input Table of } IZRF25 \text{ as a function of } \text{HDZMX}

Step 202  Calculate TC Zener Reference Voltage

\[ VZRF25 = \frac{PZRF25}{IZRF25} \]

Where:  \( VZRF25 \) = TC Zener Reference Voltage at 25°C - VDC
Step 203  Calculate TC Zener Breakdown Voltage Ratio

\[ RATVB = F (TCZ, RATI) \]

at: \( RATI = 0.0 \)

\[ RATI = TCZIV (RATV, TCZ) \]

Where:
- \( RATV = \) Zener Diode Voltage Ratio
- \( RATI = \) Zener Diode Current Ratio
- \( TCZIV = \) Input Table of RATI as a function of RATV and TCZ
- \( RATVB = \) Zener Breakdown Voltage Ratio

Step 204  Calculate TC Zener Breakdown Voltage

\[ VZBR = RATVB \times VRF25 \]

Step 205  Calculate Zener Diode Temperature at Breakdown

\[ TZBR = TCZ \]

Where: \( TZBR = \) Zener Diode Temperature at Breakdown Voltage - °C

Step 206  Calculate Total Weight of Shunt Limiter

\[ DWNZ = DWNZT (PRF25, ISH) \]

\[ NZTOT = NZS \times NESP \]

\[ WSL = DWNZ \times \text{FLOAT}(NZTOT) \]

Where:
- \( DWNZ = \) Zener Diode Specific Weight - Lbs/Zener
- \( NZTOT = \) Total Number of Zener Diodes
- \( DWNZT = \) Input Table of DWNZ as a function of PRF25 and ISH
Step 207  Calculate Total Cost of Shunt Limiter

\[NZTP = NZTOT \times NSAP\]

\[DCDNZ = DCDNZT (PRF25, NZTP, ISH)\]

\[CSL = DCDNZ \times \text{FLOAT}(NZTOT)\]

Where:  
\(NZTP\) = Total No. of Zener Diodes Procured

\(DCDNZ\) = Zener Diode Specific Cost - $/Zener

\(DCDNZT\) = Input Table of DCDNZ as a function of PRF25, NZTP and ISH

GO TO STEP 215

Step 208  Calculate Power Source Group Type

\[IPSG = 0\]

Step 209  Calculate Shunt Limiter Reference Temperature

\[TSHREF = TSACMN\]

Where:  
\(TSHREF\) = Shunt Limiter Reference Temperature

Step 210  Calculate Active Shunt Limiter Impedance

\[ZSH = ZSHTAB (TSH)\]

at:  
\(TSH = TSHREF\)

Where:  
\(ZSH\) = Active Shunt Limiter Dynamic Impedance - Ohms

\(ZSHTAB\) = Input Table of ZSH as a function of TSH

Step 211  Calculate Active Shunt Limiter Turn-On Voltage

\[VSHTOR = VSLOP - XISLOP \times ZSH\]

Where:  
\(VSHTOR\) = Shunt Limiter Turn-on Voltage - VDC at TSHREF
Step 212  Calculate Active Shunt Limiter Load

$$PSL = PPSGMX$$

Where:  $PSL = \text{Active Shunt Limiter Load - Watts}$

Step 213  Calculate Shunt Limiter Weight

$$DWDPS = DWDPS (PSL)$$

$$WSL = DWDPS \times PSL$$

Where:  $DWDPS = \text{Shunt Limiter Specific Weight - Lbs/Watt}$

Step 214  Calculate Total Cost of Shunt Limiter

$$NSLP = NSAP$$

$$DCDPS = DCDPS (PSL, NSLP)$$

$$CSL = DEDPS \times PSL$$

Where:  $NSLP = \text{No. of Active Shunt Limiters Procured}$

$$DCDPS = \text{Active Shunt Limiter Specific Cost - $/Watt}$$

$$DCDPST = \text{Input Table of DCDPS as a function of PSL and NSLP}$$

Step 215  Calculate Total Power System Weight

$$WPWR = WSA + WBATT + WCHG + WSL$$

Where:  $WPWR = \text{Total Power System Weight - lbs}$

Step 216  Calculate Total Power System Cost

$$CPWR = CSA + CBATT + CCHG + CSL$$

Where:  $CPWR = \text{Total Power System Cost - $}$
Step 217  Print Design Synthesis Output Information

Step 218  Set Performance Analysis Battery Parameters

   CB = CBD
   XN = FLOAT(NCELL)
   XICHMX = ZICHMX

RETURN TO MAIN PROGRAM
3.1 **Terminator Characteristics**

The Terminator Characteristics routine is used to calculate the sunrise and sunset times for a specific day of the year. The equations use solar vector location angles, time zone number, and buoy latitude and longitude to determine terminator hour angles and times.

### PROGRAM ALGORITHMS

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Obtain Exact Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATE = Date; Days from the start of the year (1,365)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2</th>
<th>Calculate Solar Vector Location in Equatorial Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPHEQ = OMEGA * DATE</td>
<td></td>
</tr>
<tr>
<td>Where: ALPHEQ = Solar Vector Location – Radians</td>
<td></td>
</tr>
<tr>
<td>OMEGA = (2 * π)/365.242</td>
<td></td>
</tr>
<tr>
<td>π = 3.14159</td>
<td></td>
</tr>
<tr>
<td>Note: There are 365.242 days per tropical year as measured from Vernal Equinox to Vernal Equinox</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 3</th>
<th>Calculate Solar Radiation Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>VAR(I) = FAO(I) + FA1(I) * COS(ALPHEQ) + ... + FA2(I) * COS(2.0 * ALPHEQ) + ... + FA3(I) * COS(3.0 * ALPHEQ) + ... + FB1(I) * SIN(ALPHEQ) + ... + FB2(I) * SIN(2.0 * ALPHEQ) + ... + FB3(I) * SIN(3.0 * ALPHEQ)</td>
<td></td>
</tr>
</tbody>
</table>

| DECL = VAR(1) * π/180.0 |
| ET = VAR(2) |
| Where: DECL = Solar Declination Angle – Radians |
| ET = Equation of Time Difference – Hours |
| FA, FB = Fourier Coefficients obtained from input data tables "Solar Radiation Fourier Coefficients" |
Step 3a Calculate Solar Radiation Variables

IF: ITAPE = 0,
THEN: APPSC = VAR(3) * 3.1524808, and,
THEN: ATMEXC = VAR(4), and,
THEN: SDF = VAR(5)

Where: APPSC = Apparent Solar Constant - Watts/Meter^2
(at AMO)
ATMEXC = Atmospheric Extinction Coefficient - Air Mass^{-1}
SDF = Sky Diffuse Factor

Step 4 Obtain Buoy Latitude

THELAD = Buoy latitude - degrees (+ North, - South)

Step 5 Convert Buoy Latitude

THETLA = THELAD * π/180.0

Where: THETLA = Buoy Latitude - Radians

Step 6 Calculate Terminator Hour Angle

IF: [THETLA > (π/2.0) - DECL],
THEN: HOURT = π, AND, Go to Step 7
HOURT = ARCCOS (-1.0 * TAN (THETLA) * TAN (DECL))

Where: HOURT = Terminator Hour Angle - Radians

Step 7 Convert Terminator Hour Angle

HOURA = HOURT * 12.0/π

Where: HOURA = Terminator Hour Angle - Hours

Step 8 Obtain Buoy Location Time Zone Number

TZN = Time Zone Number (Hours behind Greenwich Mean Time)
Step 2  Obtain Buoy Longitude

THELOD = Buoy Longitude - degrees \{ + West
\} - East

Step 10  Calculate Time of Sunrise and Sunset at Buoy Location

\[
\begin{align*}
SRT &= 12.0 - \text{HOURA} - \text{ET} - \text{TZN} + (\text{THELOD}/15.0) \\
SST &= 24.0 - SRT
\end{align*}
\]

Where: SRT = Sunrise Time - Hours

SST = Sunset Time - Hours

RETURN TO DESIGN SYNTHESIS DRIVER ROUTINE
3.2 Clear Day Solar Insolation

The Clear Day Solar Insolation routine is used to compute the intensity of solar radiation incident on the buoy solar array for a particular day and time. The insolation is calculated for a clear day (i.e., no cloud cover) using solar array tilt angles, buoy location hour angles, sky diffuse factor, clearness numbers, and surface reflectivity.

PROGRAM ALGORITHMS

<table>
<thead>
<tr>
<th>Step</th>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Obtain Geometrical and Temporal Information</td>
</tr>
<tr>
<td>TIMEH</td>
<td>Daily Time - Hours after Midnight - (0,24)</td>
</tr>
<tr>
<td>TZN</td>
<td>Buoy Location Time Zone Number - (Hours behind Greenwich Mean Time)</td>
</tr>
<tr>
<td>THELOD</td>
<td>Buoy Longitude - Degrees (+ West, - East)</td>
</tr>
<tr>
<td>HOURT</td>
<td>Terminator Hour Angle - Radians</td>
</tr>
<tr>
<td>DECL</td>
<td>Solar Declination Angle - Radians</td>
</tr>
<tr>
<td>THETLA</td>
<td>Buoy Latitude - Radians (+ North, - South)</td>
</tr>
</tbody>
</table>

Calculate Buoy Location Hour Angle

BHOURD = 15.0 * (TIMEH - 12.0 + TZN + ET) - THELOD
BHOUR = BHOURD * π/180.0

Where: BHOURD = Buoy Location Hour Angle - Degrees
BHOUR = Buoy Location Hour Angle - Radians

Step 3 Compare Buoy Location Hour Angle with Terminator Hour Angle (Test for Solar Occulation)

IF: ASB(BHOUR) > ABS(HOURT)
THEN: GO TO STEP 23

3-57
Step 4  Calculate Direction Cosines of Direct Solar Radiation

\[
\cos(\text{THETZS}) = \cos(\text{BHOUR}) \times \cos(\text{DECL}) \times \cos(\text{THETLA}) + \ldots
\]

\[
\ldots + \sin(\text{DECL}) \times \sin(\text{THETLA})
\]

\[
\cos(\text{THW}) = \cos(\text{DECL}) \times \sin(\text{BHOUR})
\]

IF: \( \cos(\text{BHOUR}) > \left( \frac{\tan(\text{DECL})}{\tan(\text{THETLA})} \right) \),
THEN: \( K_S = 1.0 \)

IF: \( \cos(\text{BHOUR}) < \left( \frac{\tan(\text{DECL})}{\tan(\text{THETLA})} \right) \),
THEN: \( K_S = -1.0 \)

\[
\cos(\text{THS}) = K_S \times \left( [1-\cos(\text{THETZS})]^2 - [\cos(\text{THW})]^2 \right)^{0.5}
\]

Where: \( \text{THETZS} \) = Angle between the local zenith and the solar Vector - Radians

\( \text{THW}, \text{THS} \) = Additional Direction Angles - Radians

Step 5  Calculate Solar Altitude

\( \text{SALT} = \arcsin(\cos(\text{THETZS})) \)

Where: \( \text{SALT} \) = Solar Altitude (Angle between the solar vector and the Horizontal, i.e., Earth's surface) - Radians

Step 6  Calculate Solar Azimuth

IF: \( \cos(\text{THS}) > 0 \),
THEN: \( \text{SAZM} = \arcsin(\cos(\text{THW})/\cos(\text{SALT})) \), AND GO TO STEP 7

IF: \( \cos(\text{THS}) < 0 \),
THEN: \( \text{SAZM} = \pi - \arcsin(\cos(\text{THW})/\cos(\text{SALT})) \)

Where: \( \text{SAZM} \) = Solar Azimuth (Angle between the Solar Vector Projected onto the Horizontal Surface and the South-Pointing Vector on the Horizontal Surface) - Radians

Step 7  Obtain Cleanness Number

\( \text{CN} = \text{Cleanness Number} \)

\[ = 0.7-9.9 \text{ for an industrial atmosphere} \]

\[ = 0.85-1.10 \text{ for non-industrial atmospheres} \]
### Step 8
**Obtain Solar Radiation Variables**

- **APPSC** = Apparent Solar Constant at AMO - Watts/Meter$^2$
- **ATMEXC** = Atmosphere Extinction Coefficient - Air Mass$^{-1}$
- **SDF** = Sky Diffuse Factor

### Step 9
**Calculate Intensity of Direct Normal Solar Radiation**

$$QDN = APPSC \times CN \times \exp(-ATMEXC \times \cos(THETZS))$$

Where: $QLN = Direct\ Normal\ Solar\ Radiation\ Intensity - Watts/\ Meter^2$

### Step 10
**Obtain Solar Array Pointing Angles**

- **PHIAID** = Surface Tilt Angle from Horizontal - Degrees
  (Angle between local Zenith and Solar Array Normal)
- **PHIAAD** = Surface Azimuth Angle from South - Degrees
  (Angle between South pointing vector and projection of array normal on horizontal surface)
  
  \[\text{if West of South}\]
  \[\text{- if East of South}\]

### Step 11
**Convert Solar Array Pointing Angles**

- **PHIAI** = PHIAID * π/180.0
- **PHIAA** = PHIAAD * π/180.0

Where: **PHIAI** = Surface Tilt Angle - Radians
  **PHIAA** = Surface Azimuth Angle - Radians

### Step 12
**Calculate Direction Cosines of Array Normal**

(Reference Axis: Vertical, Horizontal to West, Horizontal to South)

- **ETAA** = COS(PHIAI)
- **ETAB** = SIN(PHIAA) * SIN(PHIAI)
- **ETAC** = COS(PHIAA) * SIN(PHIAI)

Where: **ETAA, ETAB, ETAC** are Array Normal Direction Cosines
Step 13  Calculate Solar Array Tilt Angle

\[
\cos(TILT) = ETAA \cdot \cos(\theta_{TS}) + \ldots \\
+ ETAB \cdot \cos(\theta_{W}) + \ldots \\
+ ETAC \cdot \cos(\theta_{S})
\]

Where:  
- \( TILT \) = Solar Array Tilt Angle - Radians  
- (Angle between Solar Vector and Solar Array Normal)

Step 14  Calculate Intensity of Direct Solar Radiation Incident on the Solar Array

- IF: \( \cos(TILT) > 0.0 \),
- THEN: \( QD = QDN \cdot \cos(TILT) \)
- IF: \( \cos(TILT) \leq 0.0 \),
- THEN: \( QD = 0.0 \)

Where:  
- \( QD \) = Direct Solar Radiation Incident on Solar Array - Watts/Meter\(^2\)

Step 15  Calculate Sky Brightness

\[ BS = SDF \cdot QDN / (CN \cdot 2.0) \]

Where:  
- \( BS \) = Sky Brightness - Watts/Meter\(^2\)

Step 16  Obtain Horizontal Surface (Ground/Ocean) Reflectivity

\[ REFLH = \text{Horizontal Surface Reflectivity for Solar Radiation} \]

Step 17  Calculate Horizontal Surface Brightness

\[ BG = REFLH \cdot (BS + QDN \cdot \cos(\theta_{TS})) \]

Where:  
- \( BG \) = Horizontal Surface Brightness - Watts/Meter\(^2\)

Step 18  Calculate Intensity of Horizontal Surface Diffuse Radiation Incident on Solar Array

\[ QDG = BG \cdot ((1 - ETAA)/2.0) \]

Where:  
- \( QDG \) = Horizontal Surface Diffuse Radiation Incident on Solar Array - Watts/Meter\(^2\)
<table>
<thead>
<tr>
<th>Step 19</th>
<th>Calculate Intensity of Sky Diffuse Radiation Incident on a Horizontal Solar Array</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ Q_{DSH} = Q_{DN} \times SDF ]</td>
</tr>
<tr>
<td>Where:</td>
<td>( Q_{DSH} ) = Sky Diffuse Radiation Incident on a Horizontal Solar Array - Watts/Meter(^2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 20</th>
<th>Calculate Intensity of Sky Diffuse Radiation Incident on a Vertical Solar Array</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( Y_V = 0.45 )</td>
</tr>
<tr>
<td>IF:</td>
<td>( \cos(TILT) &gt; (-0.20) ), THEN: ( Y_V = 0.55 + 0.437 \times \cos(TILT) + 0.313 \times (\cos(TILT))^2.0 )</td>
</tr>
<tr>
<td></td>
<td>[ Q_{DSV} = Q_{DN} \times (SDF \times Y_V + (REFLH \times (SDF + \cos(THETZS)))/2.0) ]</td>
</tr>
<tr>
<td>Where:</td>
<td>( Q_{DSV} ) = Sky Diffuse Radiation Incident on a Vertical Solar Array - Watts/Meter(^2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 21</th>
<th>Calculate Intensity of Sky Diffuse Radiation Incident on Solar Array</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ Q_{DS} = Q_{DSV} + (Q_{DSH} - Q_{DSV}) \times \cos(SALT) ]</td>
</tr>
<tr>
<td>Where:</td>
<td>( Q_{DS} ) = Sky Diffuse Radiation Incident on Solar Array - Watts/Meter(^2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 22</th>
<th>Calculate Intensity of Total Clear Day Solar Insolation Incident on Solar Array</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[ Q_{DTC} = Q_D + Q_{DG} + Q_{DS} ]</td>
</tr>
<tr>
<td>Where:</td>
<td>( Q_{DTC} ) = Total Clear Day Solar Radiation Incident on Solar Array - Watts/Meter(^2)</td>
</tr>
<tr>
<td></td>
<td>Return to Design Synthesis Driver Routine</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 23</th>
<th>Calculate Occultation Conditions for Solar Insolation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( Q_{DN} = 0.0 )</td>
</tr>
<tr>
<td></td>
<td>( Q_D = 0.0 )</td>
</tr>
<tr>
<td></td>
<td>( Q_{DG} = 0.0 )</td>
</tr>
<tr>
<td></td>
<td>( Q_{DS} = 0.0 )</td>
</tr>
<tr>
<td></td>
<td>( Q_{DTC} = 0.0 )</td>
</tr>
<tr>
<td></td>
<td>Return to Design Synthesis Driver Routine</td>
</tr>
</tbody>
</table>
3.3 Solar Array Electrical Characteristics

The Solar Array Electrical Section is made up of the solar array, the solar array isolation diodes, and the power source series resistance. The characteristics of these elements are calculated for the environmental conditions in which the subsystem will operate and are then combined into a single solar array current-voltage curve. Performance data are stored for a single solar cell, for an isolation diode, and for the series resistance that is typical of those in the buoy solar array. The data are projected from the component level into the electrical configuration determined by the Design Synthesis driver program. Equations are also included to estimate performance when the array is mis-oriented from the sun vector and to estimate performance degradation due to cloud cover, temperature extremes, and environmental effects.

PROGRAM ALGORITHMS

<table>
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<tr>
<th>Step 1</th>
<th>Obtain Elapsed Time From Start of Mission</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DATEM = Elapsed time from start of mission - days</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2</th>
<th>Obtain Current Degradation Factors for Solar Array</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CDEGA = Solar Array Current Degradation Factor Due to Fabrication Losses - Percent (from zero)</td>
</tr>
<tr>
<td></td>
<td>CDEGB = Solar Array Current Degradation Factor Due to Terrestrial Performance Extrapolation Uncertainty - Percent (from zero)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 3</th>
<th>Calculate Current Degradation Factor Due to Environmental Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CDEGC = SADEGC(DATEM)</td>
</tr>
</tbody>
</table>

Where: CDEGC = Solar Array Current Degradation Factor Due to Environmental Effects - Percent (from zero)

SADEGC = Table of Solar Array Input Current Degradation Due to the Environment (in Percent from zero) as a Function of DATEM
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>Calculate Solar Array Current Degradation Factor</td>
</tr>
</tbody>
</table>
| \[
CDEG = \frac{1.0 \times 10^6 \times (100.0 - CDEG) \times (100.0 - CDEGB) \times (100.0 - CDEGC)}{1.0 \times 10^6}
\]

Where: CDEG = Solar Array Current Degradation Factor - Dimensionless

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Obtain Voltage Degradation Factor for Solar Array</td>
</tr>
<tr>
<td>VDEGA = Solar Array open circuit voltage degradation due to temperature uncertainty - Percent (from zero)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Calculate Voltage Degradation Factor Due to Environmental Effects</td>
</tr>
<tr>
<td>VDEGB = SADEGV(DATEM)</td>
<td></td>
</tr>
</tbody>
</table>

Where: VDEGB = Solar Array Open Circuit Voltage Degradation Factor due to Environmental Effects - Percent (from zero)

SADEGV = Table of Solar Array Open Circuit Voltage Degradation due to the Environment (in percent from zero) as a function of DATEM

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Calculate Solar Array Voltage Degradation Factor</td>
</tr>
</tbody>
</table>
| \[
VDEG = \frac{1.0 \times 10^4 \times (100.0 - VDEGA) \times (100.0 - VDEGB)}{1.0 \times 10^4}
\]

Where: VDEG = Solar Array Voltage Degradation Factor - Dimensionless

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Obtain Solar Cell Spectral Correction Factor</td>
</tr>
<tr>
<td>SPECOR = Solar Cell Spectral Correction Factor - Dimensionless (Corrects for differences between Spectrum of Solar Radiation Incident on Solar Cell and Spectral Response of Solar Cell)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Obtain Total Solar Radiation</td>
</tr>
<tr>
<td>QDT = Total Solar Radiation Incident on Solar Array - Watts/Meter^2</td>
<td></td>
</tr>
</tbody>
</table>
### Step 10: Calculate Effective Solar Insolation

\[ X = \text{SPECOR} \times \frac{QDT}{10.0} \]

Where: \( X = \text{Effective Solar Insolation Incident on Solar Cell - Milliwatts/cm}^2 \)

### Step 11: Calculate Modified Solar Insolation

\[ XX = X \times (1.0 - \text{CDEG}) \]

Where: \( XX = \text{Modified Solar Insolation - mw/cm}^2 \)

### Step 12: Obtain Single Solar Cell Area

\[ \text{ACELL} = \text{Single Solar Cell Area - cm}^2 \]

### Step 13: Obtain Solar Array Temperature

\[ \text{TSAC} = \text{Solar Array Temperature - °C} \]

### Step 14: Calculate Short Circuit Current Temperature Coefficient for a Single Solar Cell

\[ \text{ALPHAC} = (7.428 \times 10^{-7} - (1.83 \times 10^{-9}) \times \text{TSAC} \times (XX) \times \frac{\text{ACELL}}{4.0} \]

Where: \( \text{ALPHAC} = \text{Short Circuit Current Temperature Coefficient - Amperes/°C-cell} \)

### Step 15: Calculate Solar Cell Series Resistance

\[ \text{RCELLC} = P[\text{RSCELL, TEMTAB}] \text{ at TEMTAB = TSAC} \]

Where: \( \text{RCELLC} = \text{Solar Cell Series Resistance - Ohms} \)

\( \text{RSCELL} = \text{Internal Table of Solar Cell Series Resistance as a Function of Cell Temperature} \)

\( \text{ TEMTAB} = \text{Internal Table of Temperature Range Associated with RSCELL} \)
Step 16  Calculate Solar Cell I-V Curve Correction Factor

\[ \text{ROCELL} = F(\text{ROE, SUNLIT}) \text{ at SUNLIT} = XX \]

Where:  \( \text{ROCELL} = \) Solar Cell I-V Curve Correction factor at Solar Insolation Level:  \( XX \)

\( \text{ROE} = \) Internal Table of Solar Cell I-V Curve Correction Factor as a Function of Solar Insolation

\( \text{SUNLIT} = \) Internal Table of Solar Insolation Range Associated with ROE

Step 17  Calculate Open Circuit Voltage Temperature Coefficient for a Single Solar Cell

\[ \text{BETAA} = F(\text{BETAB (or BETAC or BETAD)}) \text{ at XX and TSAC} \]

\[ \text{BBETA} = \frac{\text{BETAA}}{1000.0} \]

Where:  \( \text{BBETA} = \) Open Circuit Voltage Temperature Coefficient - (Volts/°C) at XX and TSAC

\( \text{BETAA} = \) Open Circuit Voltage Temperature Coefficient - (mv/°C) at XX and TSAC

\( \text{BETAB, BETAC, BETAD} = \) Internal Tables of Solar Cell Open Circuit Voltage As a Function of Solar Insolation and Cell Temperatures

\( \text{SUNMW, SONMW, SENMW} = \) Internal Tables of Solar Insolation Ranges Associated with (BETAB) Tables

\( \text{BTEMP, CTEMP, DTEMP} = \) Internal Tables of Solar Cell Temperature Ranges Associated with (BETAA) Tables

Internal Tables BTEMP, SUNMW AND BETAB used when:

\[ (100 \leq XX \leq 540 \text{ mw/cm}^2) \text{ and } (-60 \leq TSAC \leq 160^\circ \text{C}) \]

Internal Tables CTEMP, SONMW, BETAC used when:

\[ (5 \leq XX \leq 253 \text{ mw/cm}^2) \text{ and } (-60 \leq TSAC \leq 60^\circ \text{C}) \]

Internal Tables DTEMP, SENMW, BETAD used when:

\[ (5 \leq XX \leq 100 \text{ mw/cm}^2) \text{ and } (-140 \leq TSAC \leq -40^\circ \text{C}) \]
Step 18 Obtain Single Cell ISC, VOC Data

IISC = Solar Cell Short Circuit Current - Amperes/cell
(at 145 mw/cm² Solar Insolation and 60°C)

VVOC = Solar Cell Open Circuit Voltage - Volts/cell
(at 145 mw/cm² Solar Insolation and 60°C)

Step 19 Calculate ISC, VOC Shift Due to Degradation

C1 = CDEG * IISC
C2 = VDEG * VVOC

Where: C1 = Solar Cell Short Circuit Current Shift - Amps/cell
C2 = Solar Cell Open Circuit Voltage Shift - Volts/cell

Step 20 Obtain Single Circuit (of Solar Cells) Arrangement

NS = No of Solar Cells in Series in Each Circuit
NP = No of Solar Cells in Parallel in Each Circuit

Step 21 Calculate Cell Electrical Circuit Parameters

ALPHA = ALPHAC * NP
BETA = BBETA * NS
RCELL = (0.114 + RCELLC) * NS/NP
RHO = ROCELL * NS/NP

Where: ALPHA = Short Circuit Current Temperature Coefficient for a Single Circuit - Amperes/°C-circuit
BETA = Open Circuit Voltage Temperature Coefficient for a Single Circuit - Volts/°C
RCELL = Single Circuit Series Resistance - Ohms
RHO = Series Resistance Temperature Correction Factor
Step 22 Calculate Modified Electrical Circuit Short Circuit Current

\[ ISC = IISC \times NP \times (1.0 - CDEG) \]

Where: ISC = Modified Electrical Circuit Short Circuit Current - Amperes/circuit

Step 23 Calculate Short Circuit Current Difference (for an Electrical Circuit)

\[ DISC = ISC \times ((X/145.0) - 1.0) + ALPHA \times (TSAC - 60.0) \]

Where: DISC = Short Circuit Current Difference due to current degradation, solar insolation changes and temperature changes - Amperes/circuit

Step 24 Calculate Electrical Circuit Voltage and Series Resistance Correction Factors

\[ C3 = BETA \times (TSAC - 60.0) + DISC \times RCELL \]

\[ C4 = RHO \times (TSAC - 60.0) \]

Where: C3 = Electrical Circuit Voltage Correction Factor - Volts/circuit

\[ C4 = Electrical Circuit Series Resistance Correction Factor - Ohms \]

Step 25 Obtain Reference Solar Cell Current-Voltage Characteristics

\[ II(J) = Reference Solar Cell Current Data point - Amperes \]

\[ VV(J) = Reference Solar Cell Voltage Data point - Volts \]

Where: J = 1,30

Step 26 Calculate Solar Cell Electrical Circuit Current-Voltage Characteristics

\[ I(J) = NP \times (II(J) - C1) + DISC \]

\[ V(J) = NS \times (VV(J) - C2) - C3 - (C4 \times I(J)) \]
Step 26 (contd)

Where:

\[ J = 1, 30 \]

\[ I(J) = \text{Electrical Circuit Current - Amperes at the given level of } V(J) \]

\[ V(J) = \text{Electrical Circuit Voltage - Volts} \]

Step 27 Obtain Solar Array Voltage Increment

\[ VSAINC = \text{Solar Array Voltage Increment - volts} \]

Step 28 Redefine Electrical Circuit Current - Voltage Array in Selected Voltage Increments as follows:

a) Set: Counter \( L = 1 \) and voltage \( V2(L) = 0.0 \)

b) Establish: Current \( I1(L) \) at \( V2(L) \)

\[ I1(L) = F \{I(J), V(J)\} \text{ at } V(J) = V2(L) \]

c) Increment: Counter \( L = L + 1 \) and voltage \( V2(L + 1) = V2(L) + VSAINC \) and Establish: Current \( I1(L + 1) \) at \( V2(L + 1) \),

Until: \( I1(L + 1) \leq 0.0 \)

d) Redefine: Last \( V2(L) \) at \( I1(L) = 0.0 \)

\[ V2(L) = F \{I(J), V(J)\} \text{ at } I(J) = 0.0 \]

e) Set: Current-Voltage Matrix Dimension to last counter value: \( MFINAL = L \)

Step 29 Obtain Number of Solar Cell Electrical Circuits in Solar Array

\[ NESP = \text{Number of Electrical Circuits in Solar Array} \]

(assumed in parallel)
Step 30  Calculate Solar Array Current-Voltage Characteristics

\[ I_2(L) = (I_1(L) \times \text{NESP}) \text{ at } V_2(L) \]

\[ L = 1, MF\text{FINAL} \]

Where:
- \(I_1(L)\) = Electrical Circuit Current - Amperes at \(V_2(L)\)
- \(I_2(L)\) = Solar Array Current - Amperes at \(V_2(L)\)
- \(V_2(L)\) = Circuit or Array Voltage - Volts

Step 31  Obtain Voltage Data for Calculation of Solar Array Maximum Power Point

\(X_V\) = Initial Voltage for Max Power Point Calculations - Volts

\(D_{XN}\) = Voltage Increment for Maximum Power Point Calculation - Volts

Step 32  Initialize Calculation Value of Solar Array Maximum Power

\(M_{\text{SAPWR}} = 0.0\)

Where: \(M_{\text{SAPWR}}\) = Solar Array Maximum Power - Watts

Step 33  Calculate Solar Array Power and Current

\[ X_I = F\{I_2(L), V_2(L)\} \text{ at } V_2(L) = X_V \]

\[ S_{\text{APWR}} = X_I \times X_V \]

Where:
- \(X_V\) = Solar Array Voltage - Volts
- \(X_I\) = Solar Array Current - Amperes
- \(S_{\text{APWR}}\) = Solar Array Power - Watts

Step 34  Compare Solar Array Power With Maximum Power

IF: \(S_{\text{APWR}} > M_{\text{SAPWR}}\)
THEN: \(M_{\text{SAPWR}} = S_{\text{APWR}}\)

\(X_V = X_V + D_{XV}\)

Repeat Step 33 until: \(S_{\text{APWR}} \leq M_{\text{SAPWR}}\)

3-69
Step 35  Recalculate Solar Array Current and Power

MSAPWR = 0.0

XV = XV - DXV

REPEAT STEP 33 ONLY

Step 36  Compare Solar Array Power With Maximum Power

IF: - SAPWR > MSAPWR,
    THEN:  MSAPWR = SAPWR

    DXV = DXV/10.0

    XV = XV + DXV

REPEAT STEP 33 ONLY UNTIL: SAPWR < MSAPWR

Step 37  Calculate Solar Array Maximum Power Point Characteristics

MAXV = XV - DXV

MAXI = MSAPWR/MAXV

Where: MAXV = Solar Array Voltage at Max Power Point - Volts

MAXI = Solar Array Current at Maximum Power Point - Amperes

RETURN TO DESIGN SYNTHESIS DRIVER ROUTINE
3.4 Power Conditioning and Distribution Group

The Power Conditioning and Distribution Group is made up of the lamp flasher and the housekeeping regulator. The characteristics of these two subassemblies are computed as a function of the selected lamp flasher pattern and the lamp flasher condition (on, off, or flashing). These characteristics are then shifted for the combined effects of wiring and connector series resistance to give a single set of current-voltage curves at the unregulated bus.

PROGRAM ALGORITHMS

<table>
<thead>
<tr>
<th>Step</th>
<th>Obtain Flasher Pattern Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF:</td>
<td>IFTYPE = 0.</td>
</tr>
<tr>
<td>THEN:</td>
<td>GO TO STEP 3</td>
</tr>
<tr>
<td>Where: IFTYPE is the type of flasher pattern</td>
<td></td>
</tr>
<tr>
<td>= 0: Non-Standard Pattern</td>
<td></td>
</tr>
<tr>
<td>&gt; 0: Standard Pattern</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2</th>
<th>Calculate Standard Flasher Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>TL1(J) = TLO (IFTYPE, J)</td>
<td></td>
</tr>
<tr>
<td>(1 &lt; IFTYPE &lt; 15) (1 ≤ J ≤ 16)</td>
<td></td>
</tr>
<tr>
<td>15 standard pattern types</td>
<td></td>
</tr>
<tr>
<td>Up to 16 steps per pattern</td>
<td></td>
</tr>
<tr>
<td>Alternate On/Off steps</td>
<td></td>
</tr>
<tr>
<td>GO TO STEP 4</td>
<td></td>
</tr>
<tr>
<td>Where: TLO is an input table containing TL1 as a function of IFTYPE and J</td>
<td></td>
</tr>
</tbody>
</table>

TL1 = Selected Lamp Flasher Pattern

<table>
<thead>
<tr>
<th>Step 3</th>
<th>Calculate Non-Standard Flasher Pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLL1(J) = TLL1(J) (1 ≤ J ≤ 16)</td>
<td></td>
</tr>
<tr>
<td>Where: TLL1(J) is the input data containing up to 16 alternate on-off steps for the Non-Standard Flasher Pattern</td>
<td></td>
</tr>
</tbody>
</table>
Step 4  Calculate Total Duration of Lamp Illumination and Lamp Shut-Off

\[ TLON = \sum_{J=1,3,5...}^{15} [TL1(J)] \]

\[ TLOFF = \sum_{J=2,4,6...}^{16} [TL1(J)] \]

Where:  
TLON = Total duration of lamp illumination in a single flasher period
TLOFF = Total duration of lamp shut-off

IF:  
TLON < 0, and; TLOFF < 0
THEN:  Stop program and
Print:  "No flasher pattern entries"

Step 5  Calculate Lamp Duty Cycle

\[ DL = \frac{TLON}{TLON + TLOFF} \]

Where:  DL = Lamp Duty Cycle

Step 6  Obtain Lamp Characteristics

VLR = Lamp Voltage Rating - VDC
ILR = Lamp Current Rating - Amperes
CLS = Cold-Filament Lamp Surge Coefficient

Step 7  Calculate Actual Lamp Current

\[ IL = CLS \cdot ILR \]

Where:  IL = Actual Lamp Current - Amperes

Note:  If DL = 1.0 then CLS = 1.0
If DL < 1.0 then CLS > 1.0
Step 8 Calculate Actual Lamp Resistance

\[ RL = \frac{V_{LR}}{I_L} \]

Where: \( RL \) = Actual Lamp Resistance - Ohms

Step 9 Calculate Average Lamp Current

\[ I_L' = I_L * D_L \]

Where: \( I_L' \) = Average Lamp Current - Amperes

Step 10 Calculate Effective Lamp Resistance

\[ RL = \frac{V_{LR}}{I_L} \]

Where: \( RL \) = Effective Lamp Resistance - Ohms

Step 11 Obtain Raw Power Bus Voltage Limits and User Load Cable Resistance

\[ V_{MIN} = \text{Minimum Raw Power Bus Voltage} - \text{VDC} \]
\[ V_{MAX} = \text{Maximum Raw Power Bus Voltage} - \text{VDC} \]
\[ R_{LL} = \text{User Load Cable Resistance} - \text{Ohms} \]

Step 12 Calculate PCD Group Voltage Increment

\[ V_{INC} = \frac{(V_{MAX} - V_{MIN})}{50.0} \]

Where: \( V_{INC} \) = PCD Group Voltage Increment - VDC

Step 13 Obtain PCD Equipment Temperature Characteristics

\[ T_{TAMB} = \text{Ambient Temperature} - ^\circ\text{F} \]
\[ D_{TTPCD} = \text{PCD Equipment Temperature Rise} - ^\circ\text{F} \]
Step 14 Calculate PCD Equipment Temperature

\[ T_{TTPCD} = T_{TAMB} + D_{TTPCD} \]

Where: \( T_{TTPCD} = \) PCD Equipment Temperature - °F

Step 15 Compare Raw Power Bus Minimum Voltage With Reference

\[ V_{RIO} = V_{RIOT}(T_{TTPCD}) \]

\[ V_{RISA} = V_{RISAT}(T_{TTPCD}) \]

IF: \( V_{MINIV} < V_{RIO} \), THEN: GO TO STEP 16

IF: \( (V_{MINIV} > V_{RIO}), \) And: \( (V_{MINIV} < V_{RISA}) \), THEN: Go to Step 24

IF: \( V_{MINIV} > V_{RISA} \), THEN: GO TO STEP 29

Where: \( V_{RIO} = \) Minimum (No Current) Voltage Drop - VDC Across Lamp Regulator in "Saturated" Condition

\[ V_{RISA} = \] Voltage level at which lamp regulator - VDC changes from "Saturated" condition operation to "Active" operation

\[ V_{RIOT} = \] Input Table of \( V_{RIO} \) as a function of \( T_{TTPCD} \)

\[ V_{RISAT} = \] Input Table of \( V_{RISA} \) as a function of \( T_{TTPCD} \)

Step 16 Initialize Counter and Lamp Regulator Voltage

\[ J = 1 \]

\[ VRI(J) = V_{MINIV} \]

Step 17 Calculate Lamp Regulator Current

\[ IRI(J,1) = 0.0 \]

\[ IRI(J,2) = 0.0 \]

\[ IRI(J,3) = 0.0 \]
Step 17 (Contd)

Where: \( VRI(J) \) = Lamp Regulator Input Voltage - VDC
\[ IRI(J,K) = \text{Lamp Regulator Input Current} \text{ - Volts} \]

When: 
- \( K=1 \) - Lamp Off
- \( K=2 \) - Lamp Flashing - Effective
- \( K=3 \) - Lamp On

Step 18
Increment Counter and Lamp Regulator Voltage and Compare With Reference

\[ J = J + 1 \]
\[ VRI(J) = VRI(J-1) + VINCIV \]

IF: 
- \( VRI(J) > VRIO \) And:
- \( VRI(J) < VMAXIV \)
THEN: GO TO STEP 20
IF: \( VRI(J) > VMAXIV \)
THEN: GO TO STEP 32

Step 19
Calculate Lamp Regulator Currents

\[ IRI(J,1) = 0.0 \]
\[ IRI(J,2) = 0.0 \]
\[ IRI(J,3) = 0.0 \]

REPEAT STEPS 18 AND 19

Step 20
Calculate Lamp Regulator Current

\[ IRI(J,1) = 0.0 \]
\[ IRI(J,2) = (VRI(J)-VRIO)/(RL + ZRS) \]
\[ IRI(J,3) = (VRI(J)-VRIO)/(RL + ZRS) \]

Where: 
- \( ZRS \) = Regulator Impedance in "Saturated" Condition - Ohms
- \( ZRS = ZRST \text{ (TTPCD)} \)
- \( ZRST \) = Input Table of ZRS as a function of TTPCD
**Step 21** Increment Counter and Lamp Regulator Voltage and Compare with Reference

\[ J = J + 1 \]

\[ V_{RI}(J) = V_{RI}(J - 1) + V_{INCIV} \]

**IF:** \((V_{RI}(J) > VRISA)\) AND:
**IF:** \((V_{RI}(J) < V_{MAXIV})\)

**THEN:** Go to Step 22

**IF:** \(V_{RI}(J) > V_{MAXIV}\)

**THEN:** Go to Step 32

REPEAT STEPS 20 AND 21

**Step 22** Calculate Lamp Regulator Currents

\[ V_{LB} = V_{LB} \left( V_{RI}, T_{TPCD} \right) \]

\[ Z_{RA} = Z_{RA} \left( T_{TPCD} \right) \]

\[ I_{RI}(J,1) = 0.0 \]

\[ I_{RI}(J,2) = \frac{V_{LB}}{(RL + Z_{RA})} \]

\[ I_{RI}(J,3) = \frac{V_{LB}}{(RL + Z_{RA})} \]

Where:
- \( V_{LB} \) = Regulator Output Voltage at Zero Current - Volts
- \( Z_{RA} \) = Regulator impedance in "Active" region - Ohms
- \( V_{LB} \) = Input Table of \( V_{LB} \) as a function of \( V_{RI} \) and \( T_{TPCD} \)
- \( Z_{RA} \) = Input Table of \( Z_{RA} \) as a function of \( T_{TPCD} \)

**Step 23** Increment Counter and Lamp Regulator Voltage and Compare With Reference

\[ J = J + 1 \]

\[ V_{RI}(J) = V_{RI}(J - 1) + V_{INCIV} \]

**IF:** \(V_{RI}(J) > V_{MAXIV}\)

**THEN:** Go to Step 32

REPEAT STEPS 22 AND 23
Step 24  Initialize Counter and Lamp Regulator Voltage

\[ J = 1 \]
\[ VRI(J) = VMINIV \]

Step 25  Calculate Lamp Regulator Currents

\[ IRI(J,1) = 0.0 \]
\[ IRI(J,2) = \frac{(VRI(J) - VRIO)}{(RL + ZRS)} \]
\[ IRI(J,3) = \frac{(VRI(J) - VRIO)}{(RL + ZRS)} \]

Step 26  Increment Counter and Lamp Regulator Voltage and Compare with Reference

\[ J = J + 1 \]
\[ VRI(J) = VRI(J - 1) + VINCIV \]

IF: \( VRI(J) > VRISA \), AND:

IF: \( VRI(J) < VMAXIV \)
THEN: GO TO STEP 27

IF: \( VRI(J) > VMAXIV \)
THEN: GO TO STEP 32

REPEAT STEPS 25 AND 26

Step 27  Calculate Lamp Regulator Currents

\[ IRI(J,1) = 0.0 \]
\[ IRI(J,2) = \frac{VLB}{\frac{RL}{ZRA}} \]
\[ IRI(J,3) = \frac{VLB}{\frac{RL + ZRA}{ZRA}} \]
<table>
<thead>
<tr>
<th>Step 28</th>
<th>Increment Counter and Lamp Regulator Voltage and Compare with Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( J = J + 1 )</td>
</tr>
<tr>
<td></td>
<td>( VRI(J) = VRI(J - 1) + VINCIV )</td>
</tr>
<tr>
<td></td>
<td><strong>IF:</strong> ( VRI(J) &gt; VMAXIV ) <strong>THEN:</strong> Go to Step 32</td>
</tr>
<tr>
<td></td>
<td><strong>REPEAT STEPS 27 AND 29</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 29</th>
<th>Initialize Counter and Lamp Regulator Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( J = 1 )</td>
</tr>
<tr>
<td></td>
<td>( VRI(J) = VMINIV )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 30</th>
<th>Calculate Lamp Regulator Currents</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( IRI(J,1) = 0.0 )</td>
</tr>
<tr>
<td></td>
<td>( IRI(J,2) = \frac{VLB}{(RL + ZRA)} )</td>
</tr>
<tr>
<td></td>
<td>( IRI(J,3) = \frac{VLB}{(RL + ZRA)} )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 31</th>
<th>Increment Counter and Lamp Regulator Voltage and Compare with Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( J = J + 1 )</td>
</tr>
<tr>
<td></td>
<td>( VRI(J) = VRI(J - 1) + VINCIV )</td>
</tr>
<tr>
<td></td>
<td><strong>IF:</strong> ( VRI(J) &gt; VMAXIV ) <strong>THEN:</strong> Go to Step 32</td>
</tr>
<tr>
<td></td>
<td><strong>REPEAT STEPS 30 AND 31</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 32</th>
<th>Calculate PCD Group Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( IHI(J) = \text{IHIT}(VRI(J), \text{TTPCD}) )</td>
</tr>
<tr>
<td></td>
<td>( XI(J,K) = IHI(J) + IRI(J,K) )</td>
</tr>
<tr>
<td></td>
<td>for: ( J = 1, 50; K = 1,3 )</td>
</tr>
</tbody>
</table>
Step 32 (contd)

Where: \( \text{XI}(J,K) = \text{PCD Group Current} = \text{Amperes} \)

\( \text{IHI}(J) = \text{Housekeeping Load Regulator Input Current} = \text{Amperes} \)

\( \text{IHIT} = \text{Input Table of IHI}(J) \text{ as a function of VRI}(J) \) and TTPCD

Step 33

Calculate PCD Group Voltage

\( \text{XX}(J,K) = \text{VRI}(J) + \text{XI}(J,K) \times \text{RLL} \)

for: \( J = 1,50; K = 1,3 \)

Where: \( \text{XX}(J,K) = \text{PCD Group Voltage} = \text{VDC} \)
4. PERFORMANCE ANALYSIS

The Performance Analysis segment of the DSPA program uses known power system arrangements, electrical sizes, and physical characteristics to determine the response (operational characteristics) of the equipment to a given stimulus (load and environmental profiles). A block diagram of the Performance Analysis driver program is shown in Figure 4.1. As shown, the object of the performance analysis methodology is to obtain the raw power bus operating point for each time increment during a mission period. Once this operating point is obtained, all power system operational characteristics are determinable.

To obtain the operating point, the power system is divided into groups. These groups and the equipment comprising them are:

a. Power Source Group:
   1) Solar Array.
   2) Shunt Limiter.
   3) Solar Array Isolation Diodes.
   4) Solar Array Cable.

b. Energy Storage Group:
   1) Batteries.
   2) Battery Chargers.
   3) Battery Isolation Diodes.
   4) Battery Cables.

c. Power Conditioning and Distribution Group:
   1) User Loads.
   2) Load Cable.

Current-voltage (I-V) characteristics are determined for each equipment group. The Power Conditioning and Distribution Group characteristics are then deducted from those of the Power Source Group to obtain a Difference Curve. The intersection of the Difference Curve with the
FIGURE 4.1: POWER SYSTEM PERFORMANCE ANALYSIS
Energy Storage Group characteristics is an estimate of the voltage and current on the raw power bus (operating point). During the time increment under examination, the battery is in a state-of-charge, discharge, or open-circuit depending on the value and sign of the operating point current.

After the operating point is obtained, the operational characteristics of the power system equipment are determined. The computer program is then ready for examination of power system response for the next time increment. The process is repeated until the end of the mission period.
PROGRAM ALGORITHMS

Step 1: Obtain Pertinent Mission and Equipment Information

- \( QON \) = Solar Insolation Level for Lamp Flasher Turn-On - Watts/Meter\(^2\)
- \( QOFF \) = Solar Insolation Level for Lamp Flasher Turn-Off - Watts/Meter\(^2\)
- \( ISH \) = Shunt Limiter Type

Where:  
- 0 = None
- 1 = Ordinary Zener Diode
- 2 = Temperature Compensated Zener Diode
- 3 = Active Shunt Limiter

- \( VBUSI \) = Initial Estimate of Power System Operating Point Voltage at Raw Power Bus - VDC

Step 2: Obtain Free Format Data Head-In Card Type

- \( NCTYPE \) = Free Format Card Type

Where:  
- 0 = Start-Up Data
- 1 = Time-Variant Data
- <0 = Termination Data

**IF:** \( NCTYPE = 0 \)  
**THEN:** GO TO STEP 3

**IF:** \( NCTYPE = 1 \)  
**THEN:** GO TO STEP 6

**IF:** \( NCTYPE < 0 \)  
**THEN:** Terminate Performance Analysis Calculations and return to main program

Step 3: Obtain Free Format Start-Up Data

- \( START \) = Starting "Time" of Computer Run - YYDDDHHMM

Where:  
- \( YY \) = Year (00-99)
- \( DDD \) = Date (001-365) days from beginning of the year
- \( HH \) = Hours (00-24) Hours after Midnight
- \( MM \) = Minutes (00-60) minutes after the hour
Step 3 (Contd)

HLLA = Nominal Time Increment for Performance Analysis Calculations - hours (Default value = 1.0 hours)

ACQB = Battery State-of-Charge Accuracy Requirement for the Predictor-Corrector Routine - (Default value = 0.01)

CT = Cloud Type (at Start-Up)
   0.0 = Cirrus or Cirrostratus Clouds
   1.0 = Stratus Clouds
   2.0 = Other Cloud Types

TC = Cloud Cover (at Start-Up)
   0.0 = No Cloud Cover
   (0.0 < TC ≤ 10.0) = Tenths of Sky Covered by Clouds

INDFIS = Lamp Flasher Condition Indicator
   0 = Lamp Flasher Off (Lamp Not Flashing)
   1 = Lamp Flasher On (Lamp Flashing)

Step 4 Calculate Starting "Time" Information for Computer Run

YEAR = YY (00-99) - Year

DATE = DDD {001-365} - Days from beginning of year

TIMEH = HH + \frac{MM}{60.0} - Hours after Midnight

DATEM = 0.0 - Elapsed Time Since "Start" of Computer run - days

Step 5 Initialize "Starting" Time Reference Data

YEAR1 = YEAR

DATE1 = DATE

DATEM1 = DATEM

Go To Step 10
Step 6 Obtain Free Format Time-Varying Data

DURA = Duration of a Significant Time Interval (\(=\) DDDHHMM)

Where: DDD = Days (\(\geq\) 000)

HH = Hours (\(\geq\) 00)

MM = Minutes (\(\geq\) 00)

NTS = Number of time steps during Significant Time Interval (DURA)
for printing out Performance Analysis Data

CT = Cloud Type (During Significant Time Interval)

TC = Cloud Cover (During Significant Time Interval)

Step 7 Initialize Time Step Counter and Durations of Various Intervals

LNTS = 1

DURAH = \((24.0) \times DDD + HH + \left(\frac{MM}{60.0}\right)\)

HINT = DURAH/NTS

Where: DURAH = Duration of a Significant time interval - Hours

HINT = Duration of a print-out time step - Hours

during a significant time interval

Step 7a Initialize Reference Value of Print-Out Time Step Duration

H2 = 0.0

Where: H2 = Reference Value of Print-Out Time Step Duration - Hours

Step 8 Calculate Performance Analysis Calculation Time Interval

H = AMIN (HLLA-H2, HINT)

Where: H = Performance Analysis Calculation Time Interval - Hours

Step 9 Calculate "Time" of Performance Analysis Calculation

DATEM = DATEM1 + (H/24.0)

DATE2 = DATE1 + (H/24.0)

TIMEH = (DATE2 - IFIX (DATE2)) \(\times\) 24.0

DATE = IFIX (DATE2)
Step 9 (Contd)

IF: DATE > 365.0
THEN: DATE = DATE - 365.0, AND,
THEN: YEAR = YEAR1 + 1.0

Step 9a Initialize Low Insolation Load Selector

KLL = 3

Where: KLL = Load Selector at Low Values of Solar Insolation

1 = Lamp Off
3 = Lamp On

Step 10 Obtain Power Sources Group Characteristics at the Raw Power Bus

NESP = Number of Electrical Circuits in Solar Array
RSA = Solar Array Electrical Circuit Cable Resistance - Ohms
MSAFWR = Solar Array Maximum Power - Watts
QDT = Total Solar Insolation Incident on Solar Array - Watts/Meter²
SX(I) = Power Source Group Voltage - VDC
SY(I) = Power Source Group Current at SX(I) - Amperes
I = 1, NAPSG

Where: IF: ISH = 0; THEN: NAPSG = MFINAL
IF: ISH > 0; THEN: NAPSG = NFINAL
IF: QDT < 0.0; THEN: NAPSG = KFINAL

MFINAL OR NFINAL are calculated as part of the Power Source Group current-voltage estimate

KFINAL is the maximum extent of the SX(I) and SY(I) arrays.

Step 11 Determine Lamp Flasher Condition

IF: QDT < 0.0
THEN: INDFLS = 1 AND: KL = 2

IF: (0.0 < QDT < QON)
THEN: INDFLS = 1 AND: FL = 3

IF: (QON < QDT < QOFF) AND: INDFLS = 0
THEN: INDFLS = 0 AND: KL = 1
Step 11 (Contd)

\[
\text{IF: } (QON < QDT < QOFF) \text{ AND: } \text{INDFLS} = 1 \\
\text{THEN: } \text{INDFLS} = 1 \text{ AND: } KL = 3
\]

\[
\text{IF: } QDT > QOFF \\
\text{THEN: } \text{INDFLS} = 0 \text{ AND: } KL = 1
\]

\[
\text{IF: } \text{NCTYPE} = 0 \text{ AND: } KL = 3 \\
\text{THEN: } KL = 2
\]

Where: KL = Load Selector Indicator

1 = Lamp Off (During Daylight)

2 = Lamp Flashing (At Night)

3 = Lamp Off/On (At Low Solar Insolation Levels)

Step 12  Determine Power Conditioning and Distribution Group Level Selector

\[
\text{IF: } KL = 1 \\
\text{THEN: } K = 1
\]

\[
\text{IF: } KL = 2 \\
\text{THEN: } K = 2
\]

\[
\text{IF: } KL = 3 \text{ AND: } \text{KLL} = 1 \\
\text{THEN: } K = 3
\]

Where: K = Power Conditioning/Distribution Group Load Selector

1 = Lamp Off

2 = Effective Load - Lamp Flashing

3 = Lamp On

Step 13  Obtain Power Conditioning and Distribution Group Characteristics at the Raw Power Bus

\[
XX(J) = \text{Power Conditioning and Distribution Group Voltage - VDC}
\]

\[
XI(J) = \text{Power Conditioning and Distribution Group Current at } XX(J) - \text{Ampere}
\]

J = 1,50 (Number of Data Points)

K = 1, 2, or 3 (See Above)

DL = Lamp Duty Cycle
Step 14 Rearrange Voltage Data into One Array in Ascending Order

\[ \text{DIFIV}(L,1) = \{F \cdot S(X(I)), \text{and } X(X(J))\} \]
(in ascending order)

\[ I = 1, \text{NAPSG} \]
\[ J = 1, 50 \]
\[ L = 1, (50 + \text{NAPSG}) \]

Where: \( \text{DIFIV}(L,1) \) = Difference Curve Voltages - VDC

Step 15 Calculate Difference Curve Current Values

\[ \text{DIFIV}(L,2) = S(Y(I)) - X(I(J)) \]

Where: \( \text{DIFIV}(L,2) \) = Difference Curve Current at Voltage Level

\( \text{DIFIV}(L,1) \) - Amperes

\( S(Y(I)) \) and \( X(I(J)) \) are selected at voltage \( \text{DIFIV}(L,1) \)

Note: If \( \text{DIFIV}(L,1) \) are beyond the limits of one of the current arrays, then use extrapolation methods based on existing current data.

Step 16 Obtain Energy Storage Group Characteristics at the Raw Power Bus

\( \text{ICHRT} \) = Battery Charger Type

\( 0 \) = No Charger

\( 1 \) = Constant Voltage Charger with Current Limit

\( \text{NBATT} \) = Number of Batteries in Parallel

\( \text{TRESLT}(L,1) \) = Energy Storage Group Voltage - VDC

\( \text{TRESLT}(L,2) \) = Energy Storage Group Current - Amperes at \( \text{TRESLT}(L,1) \)

IF: \( \text{ICHRT} = 0; \) THEN: \( \text{LY} = 1,9 \)

IF: \( \text{ICHRT} = 1; \) THEN: \( \text{LY} = 1,10 \)

\( \text{CB} \) = Maximum Discharge Capacity - Ampere-Hours
(for each Battery) at a standard discharge rate to a standard terminal voltage per cell at a standard temperature.
Step 16 (Contd)

<table>
<thead>
<tr>
<th>NiCd Batteries</th>
<th>Pb-Acid Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Discharge Rate</td>
<td>c/2</td>
</tr>
<tr>
<td>Standard Min Cell Terminal Voltage</td>
<td>0.5</td>
</tr>
<tr>
<td>Standard Temperature</td>
<td>70°F</td>
</tr>
</tbody>
</table>

TTEGG = Energy Storage Group Temperature - °F
QB = State of Charge of each battery - dimensionless

Step 17
Initialize Power System Operating Point

IF: NCTYPE = 0,
THEN: VBUS = VBUSI

Where: VBUS = Power System Voltage at Operating Point - VDC
(at Raw Power Bus)

Step 18
Calculate Current Difference

DELCUR = DIFIV(M,2) - TRESLT(M,2)

Where: DIFIV(M,2) = P(DIFIV(L,2), DIFIV(L,1)) at DIFIV(L,1) = VBUS
TRESLT(M,2) = F(TRESLT(LY,2), TRESLT(LY,1))
at TRESLT(LY,1) = VBUS

DELCUR = Difference in current level between difference curve and energy storage group - Amperes

Step 19
Compare Current Difference with Reference and Calculate New Operating Point Voltage

IF: DELCUR ≤ 0.0005 (Amperes)
THEN: Go to Step 20

VBUS2 = VBUS

VBUS = VBUS + DVBUS

VBUS3 = VBUS

Where: DVBUS = Increment added to operating point voltage estimate by Newton-Raphson closure routine - VDC

VBUS2, VBUS3 = Estimates of VBUS

REPEAT STEPS 18 AND 19
Step 20  Determine Operating Point Stability

IF:    SDIF < SESG
THEN:  GO TO STEP 21

Where:  SESG = Slope of the Energy Storage Group Current-Voltage Characteristics (TRESLT) at VBUS - Amperes/VDC

SDIF = Slope of the Difference curve (DIFIV) Current-Voltage Characteristics at VBUS - Amperes/VDC

VBSAVE = VBUS

Compare VBUS3 to VBUS2 and continue in the same general "direction" (from VBUS2 to VBUS3) with respect to voltage (by repeating steps 18, 19, 20) until a stable point is found or until the appropriate lower or upper voltage limits (based on Difference Curve Voltages) are reached. If no stable point is obtained, set VBUS = VBSAVE and repeat steps 18, 19, 20 in the opposite direction (relative to voltage) until a stable point is obtained or until the appropriate lower or upper voltage is reached.

If no stable operating point is estimated, then terminate run and print out the following information:

DIAGNOSTIC:
"RUN TERMINATED - NO STABLE OPERATING POINT"

"TRESLT(LY,1) ="
"TRESLT(LY,2) ="
LY = 1, 10 to (10 * NBATT)

"DIFIV(L,1) ="
"DIFIV(L,2) ="
L = 1, (50 + NAPSG)

Step 21  Calculate Energy Storage Group Current

XITT = DIFIV(M,2) at DIFIV(M,1) = VBUS

Where:  XITT = Energy Storage Group Current - Amperes at VBUS

Step 22  Obtain Energy Storage Unit Current-Voltage Characteristics

TRESV(LY) = Energy Storage Unit Voltage - VDC
TRESI(LY) = Energy Storage Unit Current - Amperes at TRESV(LY)

IF:  ICHR = 0; THEN:  LY = 1, 9

IF:  ICHR = 1; THEN:  LY = 1, 10
Step 23 Calculate Battery Current

\[ BCUR = F(\text{TRESI}(LY), \text{TRESV}(LY)) \text{ at } \text{TRESV}(LY) = \text{VBUS} \]

Where: \( BCUR \) = Current for each Battery - Amperes

\(+\) = Battery Charging

\(0\) = Battery Open Circuit

\(-\) = Battery Discharging

Step 24 Obtain Battery Current-Voltage Characteristics

\( \text{VG}(LJ) = \text{Battery Potential} - \text{VDC} \)

\( \text{XIB}(LJ) = \text{Battery Current} - \text{Amperes} \)

\( \text{at } \text{VB}(LJ) \)

\( LJ = 1, 9 \) (Number of data points)

Step 25 Calculate Battery Potential

\[ \text{VBAT} = F(\text{VB}(LJ), \text{XIB}(LJ)) \text{ at } \text{XIB}(LJ) = \text{BCUR} \]

Where: \( \text{VBAT} \) = Potential of each battery - VDC

Step 26 Calculate Power Conditioning and Distribution Group Current

\[ \text{XIPCD} = F(\text{XI}(J), \text{XX}(J)) \text{ at } \text{XX}(J) = \text{VBUS} \]

\( J = 1, 50 \) (data points)

\( K = 1, 2 \) or \( 3 \) (from Step 12)

Where: \( \text{XIPCD} \) = Input Current to Power Conditioning and Distribution Group - Amperes

Step 27 Calculate Power Sources Group Current

\[ \text{XIPSG} = F(\text{SY}(I), \text{SX}(I)) \text{ at } \text{SX}(I) = \text{VBUS} \]

\( I = 1, \text{NAPSG} \)

Where: \( \text{XIPSG} \) = Power Sources Group Output Current - Amperes

at the Operating Point
<table>
<thead>
<tr>
<th>Step 28</th>
<th>Obtain Shunt-Limiter Current-Voltage Characteristics at the Raw Power Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$ZV(IZ) =$ Shunt Limiter Voltage - VDC</td>
</tr>
<tr>
<td></td>
<td>$ZI(IZ) =$ Shunt Limiter Current - Amperes at $ZV(IZ)$</td>
</tr>
<tr>
<td></td>
<td>$IZ = 1, 20$ (data points)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 29</th>
<th>Calculate Shunt Limiter Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$XIZ = F(ZI(IZ), ZV(IZ))$ at $ZV(IIZ) = VBUS$</td>
</tr>
<tr>
<td></td>
<td>Where: $XIZ =$ Shunt Limiter Current at the operating point - Amperes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 30</th>
<th>Calculate Solar Array Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$XISA = XIZ + XIPSG$</td>
</tr>
<tr>
<td></td>
<td>Where: $XISA =$ Solar Array Current - Amperes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 31</th>
<th>Calculate Solar Array Electrical Circuit Current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$XIEC = XISA/NESP$</td>
</tr>
<tr>
<td></td>
<td>Where: $XIEC =$ Solar Array Electrical Circuit Current - Amperes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 32</th>
<th>Calculate Solar Array Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$VDIODE = AD1(XIEC)$</td>
</tr>
<tr>
<td></td>
<td>$VSA = VBUS + VDIODE + (XIEC \cdot RSA)$</td>
</tr>
<tr>
<td></td>
<td>Where: $VDIODE =$ Electrical Section Blocking Diode Voltage Drop at $XIEC - VDC$</td>
</tr>
<tr>
<td></td>
<td>$VSA =$ Solar Array Potential - VDC</td>
</tr>
<tr>
<td></td>
<td>$AD1 =$ Input Table of $VDIODE$ as a function of $XIEC$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 33</th>
<th>Calculate Equipment Power Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$PESG =</td>
</tr>
<tr>
<td></td>
<td>$PBATT =</td>
</tr>
<tr>
<td></td>
<td>$PPCD = VBUS \cdot XIPCD$</td>
</tr>
<tr>
<td></td>
<td>$PPSG = VBUS \cdot XIPSG$</td>
</tr>
<tr>
<td></td>
<td>$PSL = VBUS \cdot XIZ$</td>
</tr>
<tr>
<td></td>
<td>$PSA = VSA \cdot XISA$</td>
</tr>
</tbody>
</table>
Step 33 (Contd)

Where:  PESG = Energy Storage Group Power - Watts
        PBATT = Power Level of each Battery - Watts
        PPCD = Power Conditioning and Distribution Group Power - Watts
        PPSG = Power Source Group Power - Watts
        PSL = Shunt Limiter Power - Watts
        PSA = Solar Array Power - Watts

Step 34 Calculate Equipment Power Margins

MARSA = MSAPWR - PSA

Where:  MARSA = Solar Array Power Margin - Watts

Step 36 Initialize Battery Charge Efficiency

IF:  NCTYPE = 0; THEN:  ETA = 1.0

Where:  ETA = Instantaneous Charge Efficiency for each Battery - dimensionless

Step 37 Compare Battery Charge Efficiency With Reference

IF:  ETA < 0.0; THEN:  ETA = 0.00001; AND:  Go To Step 42

Step 38 Compare Battery Current With Reference

IF:  BCUR < 0.0; THEN:  ETA = 1.0; AND:  Go To Step 42

Step 39 Calculate Normalized Battery Charge Rate

CHRN = BCUR/CB

Where:  CHRN = Normalized Battery Charge Rate - Hour⁻¹

Step 40 Calculate Instantaneous Battery Charge Efficiency

ETA = A(TTESG, CHRN, QB)

Where:  A = A series of Input Data Tables (A1, A2, A3, A4, A5, A6) giving instantaneous charge efficiency as a function of battery temperature, normalized battery charge rate and battery state-of-charge
Step 41. Compare Battery Charge Efficiency With Reference
   IF: ETA < 0.0, THEN: ETA = 0.00001

Step 42. Calculate Rate of Charge of Battery State-of-Charge With Time
   \[ D_{QBDT} = \frac{BCUR \cdot ETA}{CB} \]
   Where: \( D_{QBDT} \) = Rate of Charge of each Battery State-of-Charge with Time - Hours^-1

Step 44. Compare Card Type with Reference
   IF: NCTYPE = 0;
   THEN: H = 0; AND, 
   THEN: GO TO STEP 49

Step 45. Compare Load Selection Indicator With Reference and Determine Reference Calculation Interval
   IF: KL = 1, OR,
   IF: KL = 2,
   THEN: GO TO STEP 49
   IF: KLL = 3,
   THEN: H1 = H

   Where: H1 = Performance Analysis Reference Calculation Interval - Hours

Step 46. Compare Low Insolation Load Selector With Reference and Calculate Performance Analysis Calculation Interval
   IF: KLL = 1
   THEN: GO TO STEP 47
   H = DL \cdot H1
   GO TO STEP 49

Step 47. Calculate Performance Analysis Calculation Interval
   \[ H = (1.0 - DL) \cdot H1 \]

Step 49. Calculate Battery State-of-Charge Increment
   \[ DELQB = H \cdot DQBDT \]
   Where: \( DELQB \) = State-of-Charge Increment for each Battery
### Step 51
Compare Card Type and Low Insolation Load Selector With References

**IF:** NCTYPE = 1, AND,
**IF:** KLL = 3,
**THEN:** GO TO Step 57

### Step 53
Calculate New Battery State-of-Charge

\[ QB = QB + DELQB \]

### Step 54
Calculate Battery Electrolyte Freezing Temperature

1. \[ SPGR = SPGR1 (QB) \]
2. \[ TBFRZ = TBFRZ1 (SPGR) \]

Where:
- \( SPGR \) = Electrolyte Specific Gravity for each Battery
- \( TBFRZ \) = Electrolyte Freezing Temperature for each Battery - °F
- \( SPGR1 \) = Input Table of SPGR as a function of \( QB \)
- \( TBFRZ1 \) = Input Table of \( TBFRZ \) as a function of \( SPGR \)

### Step 56
Compare Card Type With Reference

**IF:** NCTYPE = 0
**THEN:** GO TO Step 2

GO TO Step 63

### Step 57
Calculate Battery State-of-Charge Relative Increment

\[ DQB = ABS(DELQB/QB) \]

Where: \( DQB \) = State-of-Charge Relative Increment for each Battery

### Step 59
Compare Battery SOC Relative Increment With Reference

1. **IF:** \( (H \cdot ACCQB/DQB) > (HINT - H2 - 0.01) \)
   **THEN:** Go To Step 60
2. **IF:** \( (DQB) < (0.7 \cdot ACCQB) \), OR:
   **IF:** \( (DQB) > (ACCQB) \)
   **THEN:** \( h = (H \cdot ACCQB/DQB) \), AND:
   **THEN:** RETURN TO Step 9
**Step 60** Calculate New Battery State-of-Charge

\[ QB = QB + \Delta QB \]

**Step 61** Calculate Battery Electrolyte Freezing Temperature

\[ SPGR = SPGR(qb) \]

\[ TBFRZ = TBFRZ(qb) \]

**Step 62** Compare Load Selection Indicator and Low Insolation Load Selection With Reference and Calculate Low Insolation Load Selector

IF: \[ KL = 3, \text{ AND} \]

IF: \[ KLL = 3, \text{ AND} \]

THEN: \[ KLL = 1, \text{ AND} \]

THEN: \[ \text{GO TO STEP 12} \]

**Step 62a** IF: \[ QB = 0 \]

THEN: \[ \text{Print Error Message, AND} \]

THEN: \[ \text{Return to Main Program} \]

**Step 63** Calculate Time Reference Data

\[ DATEM1 = DATEM \]

\[ DATE1 = DATE \]

\[ TIMEH = 24.0 \times (DATE1 - IFIX(DATE)) \]

\[ YEAR1 = YEAR \]

**Step 64** Calculate Time Elapsed Since Last Print-Out

\[ H2 = H2 + H \]

**Step 65** Compare Elapsed Time With Duration of Time Until Next Print-Out

IF: \[ H2 > HINT \]

THEN: \[ \text{Print Performance Analysis Output Information} \]

THEN: \[ \text{GO TO STEP 66} \]

RETURN TO STEP 8

**Step 66** Increment Time Step Counter and Compare With Reference

\[ LNTS = LNTS + 1 \]

IF: \[ LNTS > NTS \]

THEN: \[ \text{GO TO STEP 2} \]

RETURN TO STEP 7a
4.1 Power Sources Group

The Power Source Group is made up of the solar array, the shunt limiter, the solar array isolation diodes, and the power source series resistance. The characteristics of these elements are calculated for the environmental conditions in which the subsystem is operated and are then combined into a single power source current-voltage curve at the unregulated bus. Performance data are stored for a single solar cell, for an isolation diode, for the specific shunting device to be used, and for the series resistance that are typical of those in the buoy solar array. The data are projected from the component level into the electrical configuration of the buoy solar array, and the program solves sets of equations that are designed to predict solar array/shunt limiter I-V characteristics at the unregulated bus. The Power Source Group program also includes equations to estimate the array performance when the array is misoriented from the sun vector and to estimate performance degradation due to cloud cover, temperature, and environmental effects.

PROGRAM ALGORITHMS

Step 1  Obtain the exact date and time of year

TIMEH = Daily Time - Hours after Midnight
Range of values: 0-24

DATE = Date - Days from start of the year
Range of Values: 1-365

Step 1a IF: ITAPE ≠ 0 THEN: Obtain TTAMB from 'MERGE' file
THEN: GO TO STEP 5

Step 2 Obtain the Average Yearly Temperature

TTAVE = Average Yearly temperature in selected location - °F
Step 3  Calculate Average Daily Temperature
TTA = TTAVE + DTTA
Where: TTA = Average Daily Temperature - °F
       DTTA = Average Daily Temperature Increment - °F
DTTA is obtained from input data in a table of average daily
temperature increment as a function of the date, ie.,
DTTA = DTTA1(DATE)

Step 4  Calculate Ambient Temperature
TTAMB = TTA + DTTAMB
Where: TTAMB = Ambient Temperature at selected location - °F
       DTTAMB = Average hourly temperature increment at
                selected location - °F
       DTTAMB is obtained from a table of Average hourly temperature increment as a function of the time, ie.,
       DTTAMB = DTAMB1(TIMEH)

Step 5  Obtain Power Source Group Equipment Temperature Characteristics
DTTPSG = Power Source Group Equipment Temperature Rise - °F

Step 6  Calculate Solar Array Temperature
TSAF = TTAMB + DTTPSG
Where: TSAF = Solar Array Temperature - °F
Step 7

Convert Solar Array Temperature

\[ TSAR = TSAF + 459.67 \]

\[ TSAK = \frac{5.0}{9.0} \cdot TSAR \]

\[ TSAC = TSAK - 273.15 \]

Where:

- \( TSAR \) = Solar Array Temperature - °R
- \( TSAK \) = Solar Array Temperature - °K
- \( TSAC \) = Solar Array Temperature - °C

Step 8

Calculate Solar Vector Location in Equatorial Plane

\[ ALPHEQ = OMEGA \cdot DATE \]

Where:

- \( ALPHEQ \) = Solar Vector Location - Radians
- \( OMEGA = \frac{(2 \cdot \pi)}{365.242} \)
- \( \pi = 3.14159 \)

Note: There are 365.242 days per tropical year as measured from Vernal Equinox to Vernal Equinox

Step 9

Calculate Solar Radiation Variables

\[ VAR(I) = FAO(I) + FA1(I) \cdot \cos(ALPHEQ) + \ldots \]

\[ + FA2(I) \cdot \cos(2.0 \cdot ALPHEQ) + \ldots \]

\[ + FA3(I) \cdot \cos(3.0 \cdot ALPHEQ) + \ldots \]

\[ + FB1(I) \cdot \sin(ALPHEQ) + \ldots \]

\[ + FB2(I) \cdot \sin(2.0 \cdot ALPHEQ) + \ldots \]

\[ + FB3(I) \cdot \sin(3.0 \cdot ALPHEQ) \]
Step 9 (contd)

\[
\begin{align*}
\text{DECL} &= \text{VAR (1)} \cdot \pi/180.0 \\
\text{ET} &= \text{VAR (2)} \\
\text{APPSC} &= \text{VAR (3)} \cdot 3.1524808 \\
\text{ATMEXC} &= \text{VAR (4)} \\
\text{SDF} &= \text{VAR (5)}
\end{align*}
\]

Where:
- DECL = Solar Declination Angle - Radians
- ET = Equation of Time Difference - Hours
- APPSC = Apparent Solar Constant - Watts/Meter\(^2\) (at AMO)
- ATMEXC = Atmosphere Extinction Coefficient - Air Mass\(^{-1}\)
- SDF = Sky Diffuse Factor
- FA, FB = Fourier Coefficients obtained from input data tables "Solar Radiation Fourier Coefficients"

Step 10 Obtain Buoy Latitude

\[
\begin{align*}
\text{THELAD} &= \text{Buoy latitude - degrees} \\
&\quad \{+ \text{North} \} \\
&\quad \{- \text{South} \}
\end{align*}
\]

Step 11 Convert Buoy Latitude

\[
\begin{align*}
\text{THETLA} &= \text{THELAD} \cdot \pi/180.0 \\
\text{Where:} \quad \text{THETLA} &= \text{Buoy Latitude - Radians}
\end{align*}
\]

Step 12 Calculate Terminator Hour Angle

\[
\begin{align*}
\text{IF:} \quad \text{THETLA} &> \left(\pi/2.0 \right) - \text{DECL} \\
\text{THEN:} \quad \text{HOURT} &= n
\end{align*}
\]

Go to Step 13

\[
\begin{align*}
\text{HOURT} &= \text{ARCCOS} \left(-1.0 \cdot \text{TAN (THETLA)} \cdot \text{TAN (DECL)}\right) \\
\text{Where:} \quad \text{HOURT} &= \text{ Terminator Hour Angle - Radians}
\end{align*}
\]
Step 13  Convert Terminator Hour Angle

\[ \text{HOURA} = \text{HOURT} \times \frac{12.0}{\pi} \]

Where: \( \text{HOURA} \) = Terminator Hour Angle - Hours

Step 14  Obtain Buoy Location Time Zone Number

\( \text{TZN} = \text{Time Zone Number (Hours behind Greenwich Mean Time)} \)

Step 15  Obtain Buoy Longitude

\( \text{THELOD} = \text{Buoy Longitude - degrees} \)

\( \{ + \text{West} \}

\( \{ - \text{East} \}

Step 16  Calculate Time of Sunrise and Sunset at Buoy Location

\( \text{SRT} = 12.0 - \text{HOURA - ET - TZN} \times \left( \frac{\text{THELOD}}{15.0} \right) \)

\( \text{SST} = 24.0 - \text{SRT} \)

Where: \( \text{SRT} = \text{Sunrise time - Hours} \)

\( \text{SST} = \text{Sunset time - Hours} \)

Step 17  Calculate Buoy Location Hour Angle

\( \text{BHOURD} = 15.0 \times \left( \text{TIMEH} - 12.0 + \text{TZN} + \text{ET} \right) - \text{THELOD} \)

\( \text{BHOUR} = \frac{\text{BHOURD}}{\pi/180.0} \)

Where: \( \text{BHOURD} = \text{Buoy Location Hour Angle - Degrees} \)

\( \text{BHOUR} = \text{Buoy Location Hour Angle - Radians} \)

Step 18  Test for Solar Occultation

\( \text{IF}: \ \text{ABS (BHOUR)} > \text{ABS (HOURT)} \)

Go to Step 118

Step 19  Calculate Direction Cosines of Direct Solar Radiation

\[ \text{COS (THETZS)} = \text{COS (BHOUR)} \times \text{COS (DECL)} \times \text{COS (THETLA)} + \ldots \]

\[ + \text{SIN (DECL)} \times \text{SIN (THETLA)} \]
Step 19 (contd)

Where: \( \text{THETZS} \) = Angle between the local zenith and the solar vector - radians

\[
\text{COS (THW)} = \text{COS (DECL)} \times \text{SIN (BHOUR)}
\]

**IF**: \( \text{COS (BHOUR)} > \left| \frac{\text{TAN (DECL)}}{\text{TAN (THETLA)}} \right| \)

**THEN**: \( KS = 1.0 \)

**IF**: \( \text{COS (BHOUR)} < \left| \frac{\text{TAN (DECL)}}{\text{TAN (THETLA)}} \right| \)

**THEN**: \( KS = -1.0 \)

\[
\text{COS (THS)} = KS \times \left[ (1 - \text{COS (THETZS)})^2 - (\text{COS (THW)})^2 \right]^{0.5}
\]

Where: \( THW, THS = \) Additional Direction Angles - Radians

Step 20
Calculate Solar Altitude

\[
\text{SALT} = \text{ARCSIN (COS (THETZS))}
\]

Where: \( \text{SALT} = \) Solar Altitude (Angle between the solar vector and the Horizontal, i.e.. Earth's surface) - Radians

Step 21
Calculate Solar Azimuth

**IF**: \( \text{COS (THS)} > 0 \)

**THEN**: \( \text{SAZM} = \text{ARCSIN} \left[ \frac{\text{COS (THW)}}{\text{COS (SALT)}} \right] \)

GO TO STEP 22

**IF**: \( \text{COS (THS)} < 0 \)

**THEN**: \( \text{SAZM} = \pi - \text{ARCSIN} \left[ \frac{\text{COS (THW)}}{\text{COS (SALT)}} \right] \)

Where: \( \text{SAZM} = \) Solar Azimuth (Angle between the Solar Vector, Projected onto the Horizontal Surface and the South-Pointing Vector on the Horizontal Surface) - Radians
Step 22  Obtain Cloud Cover Conditions

CT = Cloud Type

0.0 = Cirrus or Cirrostratus Clouds
1.0 = Stratus Clouds
2.0 = Other Cloud Types

TC = Total cloud Cover

1.0 = 1/10 of sky covered
2.0 = 2/10 of sky covered

...  
9.0 = 9/10 of sky covered
10.0 = 10/10 of sky covered

ICT = 1 + IFIX (CT)

Where: ICT = Cloud Type indicator

1 = Cirrus of Cirrostratus Clouds
2 = Stratus Clouds
3 = Other Cloud Types

Step 23  Calculate Cloud Cover Modifier

IF:   TC = 0.0,  
THEN:  CCM = 1.0 and go to Step 24

IF:   SALT ≤ π/4.0;  
THEN:  ISALT = 1

IF:   SALT > π/4.0;  
THEN:  ISALT = 2

Where: ISALT = Solar Altitude Indicator

CCM = PO (ICT,ISALT) + P1 (ICT,ISALT) * TC + ...  
+ P2 (ICT,ISALT) * (TC^2.0) + ...  
+ P3 (ICT,ISALT) * (TC^3.0)
Step 23 (contd)

Where:

\[ CCM = \text{Cloud Cover Modifier} \]

\[ P_0, P_1, P_2, P_3 = \text{Polynomial Coefficients obtained from input data tables "Cloud Cover Modifier Polynomial Coefficients"} \]

Step 24

Obtain Clearness Number

\[ CN = \text{Clearness Number} \]

- 0.7-0.9 for an industrial atmosphere
- 0.85-1.0 for non-industrial atmospheres

Step 25

Calculate Intensity of Direct Normal Solar Radiation

\[ QDN = \text{APPSC} \times CN \times CCM \times \exp \left( \frac{-ATMEXC}{\cos(\text{THETZS})} \right) \]

Where: \( QDN = \text{Direct Normal Solar Radiation Intensity} \) - Watts/Meter\(^2\)

Step 26

Obtain Solar Array Pointing Angles

\[ \text{PHIAID} = \text{Surface Tilt Angle from Horizontal} = \text{Degrees} \]

(Angle between local Zenith and Solar Array Normal)

\[ \text{PHIAAD} = \text{Surface Azimuth Angle from South} = \text{Degrees} \]

(Angle between South pointing vector and projection of array normal on horizontal surface)

- + if West of South
- - if East of South

Step 27

Convert Solar Array Pointing Angles

\[ \text{PHIA} = \text{PHIAID} \times \pi/180.0 \]

\[ \text{PHIAA} = \text{PHIAAD} \times \pi/180.0 \]

Where: \( \text{PHIA} = \text{Surface Tilt Angle} \) - Radians

\( \text{PHIAA} = \text{Surface Azimuth Angle} \) - Radians
Step 28  Calculate Direction Cosines of Array Normal
(Reference Axis: Vertical, Horizontal to West, Horizontal to South)
ETAA = \cos (PHIA1)
ETAB = \sin (PHIA1) \times \sin (PHIA1)
ETAC = \cos (PHIA1) \times \sin (PHIA1)
Where: ETAA, ETAB, ETAC = Array Normal Direction Cosines

Step 29  Calculate Solar Array Tilt Angle
\cos (TILT) = ETAA \times \cos (THETZS) + ...
+ ETAB \times \cos (THW) + ...
+ ETAC \times \cos (THS)
Where: TILT = Solar Array Tilt Angle - Radians
(Angle between Solar Vector and Solar Array Normal)

Step 30  Calculate Intensity of Direct Solar Radiation Incident on the Solar Array
IF: \cos (TILT) > 0.0
THEN: QD = QDN \times \cos (TILT)
IF: \cos (TILT) \leq 0.0
THEN: QD = 0.0
Where: QD = Direct Solar Radiation Incident on Solar Array - Watts/Meter²

Step 31  Calculate Sky Brightness
BS = SDF \times QDN/(CN**2.0)
Where: BS = Sky Brightness - Watts/Meter²

Step 32  Obtain Horizontal Surface (Ground/Ocean) Reflectivity
REFLH = Horizontal Surface Reflectivity for Solar Radiation
Step 33 Calculate Horizontal Surface Brightness

\[ BG = \text{REFLH} \times (BS + QDN \times \cos(\text{THETZS})) \]

Where: \( BG \) = Horizontal Surface Brightness - Watts/Meter\(^2\)

Step 34 Calculate Intensity of Horizontal Surface Diffuse Radiation Incident on Solar Array

\[ QDG = \frac{BG \times ((1 - ETAA)/2.0)}{2} \]

Where: \( QDG \) = Horizontal Surface Diffuse Radiation Incident on Solar Array - Watts/Meter\(^2\)

Step 35 Calculate Intensity of Sky Diffuse Radiation Incident on a Horizontal Solar Array

\[ QUSH = QDN \times SDF \]

Where: \( QUSH \) = Sky Diffuse Radiation Incident on a Horizontal Solar Array - Watts/Meter\(^2\)

Step 36 Calculate Intensity of Sky Diffuse Radiation Incident on a Vertical Solar Array

\[ YV = 0.45 \]

IF: \( \cos(\text{TILT}) > (-0.2); \)
THEN: \( YV = 0.55 \times 0.437 \times \cos(\text{TILT}) + 0.313 \times ((\cos(\text{TILT})^2 \times 2.0) \]

\[ QDSV = QDN \times (SDF \times YV \times (\text{REFLH} \times (SDF \times \cos(\text{THETZS}))))/2.0) \]

Where: \( QDSV \) = Sky Diffuse Radiation Incident on a Vertical Solar Array - Watts/Meter\(^2\)

Step 37 Calculate Intensity of Sky Diffuse Radiation Incident on Solar Array

\[ QDS = QDSV \times (QUSH - QDSV) \times \cos(SALT) \]

Where: \( QDS \) = Sky Diffuse Radiation Incident on Solar Array - Watts/Meter\(^2\)
Step 38  Calculate Intensity of Total Solar Insolation Incident on Solar Array

\[ Q_{DT} = Q_D + Q_{DG} + Q_{DS} \]

Where:  \( Q_{DT} = \text{Total Solar Radiation Incident on Solar Array} \) - Watts/Meter$^2$

Step 39  Obtain Elapsed Time From Start of Mission

\[ \text{DATEM} = \text{Elapsed time from start of mission} \] - days

Step 40  Obtain Current Degradation Factors for Solar Array

\[ \text{CDEGA} = \text{Solar Array Current Degradation Factor Due to Fabrication Losses} \] - Percent (from zero)

\[ \text{CDEGB} = \text{Solar Array Current Degradation Factor Due to Terrestrial Performance Extrapolation Uncertainty} \] - Percent (from zero)

Step 41  Calculate Current Degradation Factor Due to Environmental Effects

\[ \text{CDEGC} = \text{SADEGC (DATEM)} \]

Where:  \( \text{CDEGC} = \text{Solar Array Current Degradation Factor Due to Environmental Effects} \) - Percent (from zero)

\[ \text{SADEGC} = \text{Table of Solar Array Input Current Degradation Due to the Environment (in Percent from Zero) as a function of DATEM} \]

Step 42  Calculate Solar Array Current Degradation Factor

\[ \text{CDEG} = \frac{1.0 \times 10^6 - (100.0 - \text{CDEGA}) \times (100.0 - \text{CDEGR}) \times (100.0 - \text{CDEGC})}{1.0 \times 10^6} \]

Where:  \( \text{CDEG} = \text{Solar Array Current Degradation Factor} \) - Dimensionless
Step 43 Obtain Voltage Degradation Factor for Solar Array

\[ V_{DEGA} = \text{Solar Array open circuit voltage degradation due to temperature uncertainty} \quad \text{Percent (from zero)} \]

Step 44 Calculate Voltage Degradation Factor Due to Environmental Effects

\[ V_{DEGB} = \text{SADEGV (DATEM)} \]

Where: \( V_{DEGB} = \text{Solar Array Open Circuit Voltage Degradation Factor due to Environmental Effects - Percent (from zero)} \)

\[ \text{SADEGV} = \text{Table of Solar Array Open Circuit Voltage Degradation due to the Environment (in percent from zero) as a function of DATEM} \]

Step 45 Calculate Solar Array Voltage Degradation Factor

\[ V_{DEG} = \frac{1.0 \times 10^{10} - (100.0 - V_{DEGA}) \times (100.0 - V_{DEGB})}{1.0 \times 10^{10}} \]

Where: \( V_{DEG} = \text{Solar Array Voltage Degradation Factor - Dimensionless} \)

Step 46 Obtain Solar Cell Spectral Correction Factor

\[ \text{SPECOR} = \text{Solar Cell Spectral Correction Factor - Dimensionless} \]

(Corrects for differences between Spectrum of Solar Radiation Incident on Solar Cell and Spectral Response of Solar Cell)

Step 47 Calculate Effective Solar Insolation

\[ X = \text{SPECOR} \times \frac{QDT}{10.0} \]

Where: \( X = \text{Effective Solar Insolation Incident on Solar Cell - Milliwatts/\text{cm}^2} \)
Step 58: Calculate Modified Solar Insolation

\[ XX = X \times (1.0 - CDEG) \]

Where: \( XX \) = Modified Solar Insolation - \( \text{W/m}^2 \)

Step 49: Obtain Single Solar Cell Area

\( ACELL = \text{Single Solar Cell Area} - \text{cm}^2 \)

Step 50: Calculate Short Circuit Current Temperature Coefficient for a Single Solar Cell

\[ ALPHAC = \left( (7.428 \times 10^{-7}) - (1.83 \times 10^{-9}) \times TSAC \right) \times (XX) \times ACELL/4.0 \]

Where: \( ALPHAC \) = Short Circuit Current Temperature Coefficient - Amperes/°C-cell

Step 51: Calculate Solar Cell Series Resistance

\[ RCELLC = F(RSCELL, TEMTAB) \text{ at } TSAC \]

Where: \( RCELLC \) = Solar Cell Series Resistance - Ohms (at Temperature TSAC)

\( RSCELL = \text{Internal Table of Solar Cell Series Resistance as a function of Cell Temperature} \)

\( TEMTAB = \text{Internal Table of Temperature Range Associated with RCELL} \)

Step 51A: Calculate Solar Cell I-V Curve Correction Factor

\[ ROCELL = F(ROE, SUNLIT) \text{ at } XX \]

Where: \( ROCELL \) = Solar Cell I-V Curve Correction Factor at Solar Insolation Level: \( XX \)

\( ROE = \text{Internal Table of Solar Cell I-V Curve Correction Factor as a Function of Solar Insolation} \)

\( SUNLIT = \text{Internal Table of Solar Insolation Range Associated with ROE} \)
Step 52 Calculate Open Circuit Voltage Temperature Coefficient for a Single Solar Cell

\[ \text{BBETA} = \frac{\text{BBETA}}{1000.0} \]

Where:

\[ \text{BBETA} = \text{Open Circuit Voltage Temperature Coefficient} \quad \text{(Volts/°C)} \]

\[ \text{BETAA} = \text{Open Circuit Voltage Temperature Coefficient} \quad \text{(Mv/°C)} \]

\[ \text{BETAB, BETAC, BETAD} = \text{Internal Tables of Solar Cell Open Circuit Voltage as a Function of Solar Insolation and Cell Temperature} \]

\[ \text{SUNMW, SONMW, SENMW} = \text{Internal Tables of Solar Insolation Ranges Associated with (BETA) Tables} \]

\[ \text{BTEMP, CTEMP, DTEMP} = \text{Internal Tables of Solar Cell Temperature Ranges Associated with (BETA..) Tables} \]

Internal Tables BTEMP, SUNMW AND BETAB used when:

\[ (100 < XX < 540 \text{ Mw/Cm}^2) \text{ and } (-60 < TSAC < 160°C) \]

Internal Tables CTEMP, SONMW, BETAC used when:

\[ (5 < XX < 253 \text{ Mw/Cm}^2) \text{ and } (-40 < TSAC < 60°C) \]

Internal Tables DTEMP, SENMW, BETAD used when:

\[ (5 < XX < 100 \text{ Mw/Cm}^2) \text{ and } (-140 < TSAC < -40°C) \]

Step 53 Obtain Single Cell ISC, VOC Data

\[ \text{IISC} = \text{Solar Cell Short Circuit Current} \quad \text{Ampere/Cel} \]

\[ \text{at 145 Mw/Cm}^2 \text{ Solar Insolation and 60°C} \]

\[ \text{VVOC} = \text{Solar Cell Open Circuit Voltage} \quad \text{Volts/Cell} \]

\[ \text{at 145 Mw/Cm}^2 \text{ Solar Insolation and 60°C} \]
Step 54  Calculate ISC, VOC Shift Due to Degradation

\[ C_1 = C_{DEG} \times I_{ISC} \]
\[ C_2 = V_{DEG} \times V_{VOC} \]

\( C_1 \) = Solar Cell Short Circuit Current Shift - Amps/Cell

\( C_2 \) = Solar Cell Open Circuit Voltage Shift - Volts/Cell

Step 55  Obtain Single Circuit (of Solar Cells) Arrangement

\( NS \) = No. of Solar Cells in Series in Each Circuit

\( NF \) = No. of Solar Cells in Parallel in Each Circuit

Step 56  Calculate Cell Electrical Circuit Parameters

\[ \text{ALPHA} = \text{ALPHAC} \times NF \]
\[ \text{BETA} = \text{BBETA} \times NS \]
\[ R_{CELL} = (0.11 + R_{CELLC}) \times NS/NF \]
\[ RHO = R_{CELL} \times NS/NF \]

Where:  
\( \text{ALPHA} \) = Short Circuit Current Temperature Coefficient for a Single Circuit - Amperes/°C-circuit

\( \text{BETA} \) = Open Circuit Voltage Temperature Coefficient for a Single Circuit - Volts/°C

\( R_{CELL} \) = Single Circuit Series Resistance - Ohms

\( RHO \) = Series Resistance Temperature Correction Factor

Step 57  Calculate Modified Electrical Circuit Short Circuit Current

\[ ISC = I_{ISC} \times NF \times (1.0 - C_{DEG}) \]

Where:  
\( ISC \) = Modified Electrical Circuit Short Circuit Current - Amperes/Circuit
Step 58  Calculate Short Circuit Current Differences (for an Electrical Circuit)

\[ \text{DISC} = \text{ISC} \times \left( \frac{(X/145.0) - 1.0}{\text{ALPHA} \times (TSAC - 60.0)} \right) \]

Where: DISC = Short Circuit Current Difference due to current degradation, solar insolation changes and temperature changes - Amperes/Circuit

Step 59  Calculate Electrical Circuit Voltage and Series Resistance Correction Factors

\[ \begin{align*}
C_3 &= \text{BETA} \times (TSAC - 60.0) + \text{DISC} \times \text{RCELL} \\
C_4 &= \text{RHO} \times (TSAC - 60.0)
\end{align*} \]

Where: \( C_3 \) = Electrical Circuit Voltage Correction Factor - Volts/Circuit
\( C_4 \) = Electrical Circuit Series Resistance Correction Factor - Ohms

Step 60  Obtain Reference Solar Cell Current-Voltage Characteristics

\[ \begin{align*}
\text{II}(J) &= \text{Reference Solar Cell Current Data Point - Amperes (Internal Tables)} \\
\text{VV}(J) &= \text{Reference Solar Cell Voltage Data Point - Volts (Internal Tables)}
\end{align*} \]

\( J = 1, 30 \)

Step 61  Calculate Solar Cell Electrical Circuit Current-Voltage Characteristics

\[ \begin{align*}
I(J) &= \text{NF} \times (\text{II}(J) - C_1) + \text{DISC} \\
V(J) &= \text{NC} \times (\text{VV}(J) - C_2) - C_3 - (C_4 \times I(J))
\end{align*} \]

\( J = 1, 30 \)

Where: \( I(J) \) = Electrical Circuit Current - Amperes at the given level of \( V(J) \)
\( V(J) \) = Electrical Circuit Voltage - Volts
Step 62
Obtain Solar Array Voltage Increment

\[ \text{VSAINC} = \text{Solar Array Voltage Increment - Volts} \]

Step 63
Redefine Electrical Circuit Current-Voltage Array in Selected Voltage Increments as follows:

a) Set: Counter \( L=1 \) and voltage \( V2(L) = 0.0 \)

b) Establish: Current \( I1(L) \) at \( V2(L) \)

\[ I1(L) = F(I(J), V(J)) \text{ at } I(J) = 0.0 \]

c) Increment: Counter \( L = L + 1 \) and voltage \( V2(L + 1) = V2(L) + \text{VSAINC} \) and Establish: Current \( I1(L + 1) \) at \( V2(L + 1) \). Until: \( I1(L + 1) \leq 0.0 \)

d) Redefine: Last \( V2(L) \) at \( I1(L) = 0.0 \)

\[ V2(L) = F(I(J), V(J)) \text{ at } I(J) = 0.0 \]

e) Set: Current-Voltage Matrix Dimension to last counter value \( MFINAL = L \)

Step 64
Obtain Number of Solar Cell Electrical Circuits in Solar Array

\( NESP = \text{Number of Electrical Circuits in Solar Array (assumed in parallel)} \)

Step 65
Calculate Solar Array Current-Voltage Characteristics

\[ I2(L) = I1(L) \times NESP \text{ at } V2(L) \]

\( L = 1, MFINAL \)

Where: \( I1(L) = \text{Electrical Circuit Current - Amperes at } V2(L) \)

\( I2(L) = \text{Solar Array Current - Amperes at } V2(L) \)

\( V2(L) = \text{Circuit or Array Voltage - Volts} \)

Step 66
Obtain Voltage Data for Calculation of Solar Array Maximum Power Plant

\( XV = \text{Initial Voltage for Max Power Point Calculations - Volts} \)

\( DXN = \text{Voltage Increment for Max Power Point Calculation - Volts} \)
Step 67  Initialize Calculation Value of Solar Array Maximum Power

\[ MSAPWR = 0.0 \]

Where:  \( MSAPWR = \text{Solar Array Maximum Power - Watts} \)

Step 68  Calculate Solar Array Power and Current

\[ XI = F(I_2(L), V_2(L)) \text{ at } V_2(L) = XV \]

\[ SAPWR = XI \times XV \]

Where:  \( XV = \text{Solar Array Voltage - Volts} \)

\( XI = \text{Solar Array Current - Amperes} \)

\( SAPWR = \text{Solar Array Power - Watts} \)

Step 69  Compare Solar Array Power With Maximum Power

IF:  \( SAPWR > MSAPWR \)

THEN:  \( MSAPWR = SAPWR \)

\( I_XV = XV + DXV \)

REPEAT STEP 68 UNTIL:  \( SAPWR \leq MSAPWR \)

Step 70  Recalculate Solar Array Current and Power

\[ MSAPWR = 0.0 \]

\[ XV = XV - DXV \]

REPEAT STEP 68 ONLY

Step 71  Compare Solar Array Power With Maximum Power

IF:  \( SAPWR \geq MSAPWR \)

THEN:  \[ \begin{cases} DXV = DXV/10.0 \\ XV = XV + DXV \end{cases} \]

REPEAT STEP 68 ONLY UNTIL:  \( SAPWR < MSAPWR \)
Step 72  Calculate Solar Array Maximum Power Point Characteristics

\[
\text{MAXV} = \text{XV} - \text{DXV} \\
\text{MAXI} = \frac{\text{MSAPWR}}{\text{MAXV}}
\]

Where:  \text{MAXV} = \text{Solar Array Voltage at Max Power Point} \ - \ \text{Volts} \\
\text{MAXI} = \text{Solar Array Current at Max Power Point} \ - \ \text{Amperes}

Step 73  Obtain Solar Array Electrical Section Cable Resistance

\[\text{RSA} = \text{Series resistance of cable for an electrical section of the solar array} \ - \ \text{Ohms}\]

Step 74  Calculate Voltage Shift in Electrical Section Voltage Due to Cable Resistance and Blocking Diodes

\[
\text{VDIODE} = \text{AD1 \{I1(L)\}} \\
V2(L) = V2(L) - (I1(L) \times \text{RSA}) - \text{VDIODE} \\
L = 1, \text{ MFINAL}
\]

Where:  \text{VDIODE} = \text{Electrical Section Blocking Diode} \ - \ \text{Volts} \\
\text{Voltage Drop at Current Level I1(L)} \\
\text{AD1} = \text{Table (Input Data) of Electrical Section Blocking Diode as a function of current}

Step 75  Obtain Shunt Limiter Type

\[\text{ISH} = \text{Shunt Limiter Type}\]

0 = None \\
1 = Ordinary Zener Diode \\
2 = Temperature Compensated Zener Diode \\
3 = Active Shunt Limiter

Step 76  Obtain Shunt Limiter Current Voltage Characteristics

\[
\text{ZI(I)} = \text{Shunt Limiter Current at ZV(I) - Amperes} \\
\text{ZV(I)} = \text{Shunt Limiter Voltage - Volts} \\
I = 1, 20
\]
**Step 77**
Obtain Power Source Group Type

\[ IPSG = \text{Power Source Group Type} \]

\[ 0 = \text{One Shunt Limiter for the Solar Array} \]

\[ 1 = \text{One Shunt Limiter for each Electrical Section of the Solar Array} \]

**Step 78**
Select Power Source Group Current-Voltage Calculation and Calculate Significant Voltages

\[ VZSB = ZV(2) \]

\[ SAOCV = V2(MFINAL) \]

**IF:** ISH = 0; GO TO STEP 79

**IF:** ISH = 1; GO TO STEP 80

**IF:** ISH = 2; GO TO STEP 98

**IF:** ISH = 3; GO TO STEP 80

Where:

\[ VZSB = \text{Shunt-Limiter Turn-On Voltage} - \text{Volts} \]

\[ SAOCV = \text{Solar Array Open Circuit Voltage} - \text{Volts} \]

**Step 79**
Calculate Power Source Group Current-Voltage Characteristics (With No Shunt-Limiter)

\[ XZI(L) = ZI(L) \]

\[ SY(L) = I2(L) - XZI(L) \]

\[ SX(L) = V2(L) \]

\[ L = 1, MFINAL \]

Where:

\[ XZI(L) = \text{Shunt Limiter Current at } SX(L) - \text{Amperes} \]

\[ SY(L) = \text{Power Source Group Current at } SY(L) - \text{Amperes} \]

\[ SX(L) = \text{Power Source Group Voltage} - \text{Volts} \]

Return to Performance Analysis Routine
Step 80
Select PSG Current-Voltage Calculation Based on PSG Type

IF: IPSG = 0; GO TO STEP 81
IF: IPSG = 1; GO TO STEP 89

Step 81
Initialize Index Counter and PSG Voltage and Current

LL = 1
SY(1) = 0.0
SX(1) = F(I2(L), V2(L)) at V2(L) = SX(1)
XZI(1) = 0.0

Step 82
Compare Voltage and Current to Reference Levels

IF: SY(LL) < 0.0: and
IF: SX(LL) > SAOCV
THEN: GO TO STEP 88

Step 83
Increment Index Counter and Calculate PSG Voltage and Current

LL = LL + 1
SX(LL) = SX(LL - 1) + VSAINC
SY(LL) = F(I2(L), V2(L)) at V2(L) = SX(LL)
XZI(LL) = 0.0

Step 84
Compare PSG Voltage with Shunt-Limiter Turn-On Voltage

IF: SX(LL) < VZSB:
THEN: REPEAT STEPS 82 AND 83
Step 85  Calculate PSG Current at Shunt Limiter Turn-On

\[ SX(\text{LL}) = VZSB \]
\[ SY(\text{LL}) = F(I2(L), V2(L)) \text{ at } V2(L) = SX(\text{LL}) \]
\[ XZI(\text{LL}) = F(ZI(I), ZV(I)) \text{ at } ZV(I) = SX(\text{LL}) \]
\[ SY(\text{LL}) = SY(\text{LL}) - XZI(\text{LL}) \]

Step 86  Compare PSG Current With Reference

IF:  \[ SY(\text{LL}) < 0.0 \]
THEN:  GO TO STEP 88

Step 87  Increment Index Counter and Calculate PSG Voltage and Current

\[ \text{LL} = \text{LL} + 1 \]
\[ SX(\text{LL}) = SX(\text{LL} - 1) + 0.01 \]
\[ SY(\text{LL}) = F(I2(L), V2(L)) \text{ at } V2(L) = SX(\text{LL}) \]
\[ XZI(\text{LL}) = F(ZI(I), ZV(I)) \text{ at } ZV(I) = SX(\text{LL}) \]
\[ SY(\text{LL}) = SY(\text{LL}) - XZI(\text{LL}) \]
REPEAT STEPS 86 AND 87

Step 88  Calculate Maximum PSG Voltage

Perform a Straight-Line Interpolation between the last two sets of PSG current-voltage values to predict the voltage at which the PSG current is equal to zero (VZCR)

\[ SX(\text{LL}) = VZCR \]
\[ SY(\text{LL}) = 0.0 \]
\[ XZI(\text{LL}) = F(ZI(I), ZV(I)) \text{ at } ZV(I) = SX(\text{LL}) \]
\[ \text{NFINAL} = \text{LL} \]

RETURN TO PERFORMANCE ANALYSIS ROUTINE
Step 89  
Initialize Index Counter and Section Voltage and Current

\[ LL = 1 \]
\[ VSECT(1) = 0.0 \]
\[ ISECT(1) = F(I1(L), V2(L)) \text{ at } V2(L) = VSECT(1) \]
\[ XZIS = 0.0 \]

Where: \( ISECT(LL) = \) Electrical Section Composite Current - Amperes at \( VSECT(LL) \)
\( VSECT(LL) = \) Electrical Section Voltage - Volts
\( XZIS(LL) = \) Shunt Limiter Section Current - Amperes

Step 90  
Compare Voltage and Current to Reference Levels

IF: \( ISECT(LL) \leq 0.0 \) and
IF: \( VSECT(LL) > SAGOV \);
THEN: GO TO STEP 96

Step 91  
Increment Index Counter and Calculate Section Composite Voltage and Current

\[ LL = LL + 1 \]
\[ VSECT(LL) = VSECT(LL - 1) + VSAINC \]
\[ ISECT(LL) = F(I1(L), V2(L)) \text{ at } V2(L) = VSECT(LL) \]
\[ XZIS(LL) = 0.0 \]

Step 92  
Compare Section Voltage with Shunt Limiter Turn-On Voltage

IF: \( VSECT(LL) < VZSB \);
THEN: REPEAT STEPS 90 AND 91
Step 93 Calculate Section Current at Shunt Limiter Turn-On

\[
VSECT(LL) = VZSB
\]
\[
ISECT(LL) = F(I1(L), V2(L)) \text{ at } V2(L) = VSECT(LL)
\]
\[
XZIS(LL) = F(ZI(I), ZV(I)) \text{ at } ZV(I) = VSECT(LL)
\]
\[
ISECT(LL) = ISECT(LL) - XZIS(LL)
\]

Step 94 Compare Section Current With Reference

\[
\text{IF: } ISECT(LL) \leq 0.0
\]
\[
\text{THEN: GO TO STEP 96}
\]

Step 95 Increment Index Counter and Calculate Section Voltage and Current

\[
LL = LL + 1
\]
\[
VSECT(LL) = VSECT(LL - 1) + 0.01
\]
\[
ISECT(LL) = F(I1(L), V2(L)) \text{ at } V2(L) = VSECT(LL)
\]
\[
XZIS(LL) = F(ZI(I), ZV(I)) \text{ at } ZV(I) = VSECT(LL)
\]
\[
ISECT(LL) = ISECT(LL) - XZIS(LL)
\]
\[
\text{REPEAT STEPS 94 AND 95}
\]

Step 96 Calculate Maximum Section Voltage

Perform a straight-line interpolation between the last two sets of section current-voltage values to predict the voltage at which the section current is equal to zero (VZCR)

\[
VSECT(LL) = VZCR
\]
\[
ISECT(LL) = 0.0
\]
\[
XZIS(LL) = F(ZI(I), ZV(I)) \text{ at } ZV(I) = VSECT(LL)
\]
\[
\text{NFINAL} = LL
\]
Step 97  Calculate PSG Current Voltage Characteristics

\[
\begin{align*}
SY(\text{LL}) &= ISECT(\text{LL}) \times NESP \\
XZI(\text{LL}) &= XZIS(\text{LL}) \times NESP \\
SX(\text{LL}) &= VSECT(\text{LL}) \\
\text{LL} &= 1, NFINAL \\
\end{align*}
\]

RETURN TO PERFORMANCE ANALYSIS ROUTINE

Step 98  Select PSG Current Voltage Type Based on PSG Type

IF:  IPSG = 0; GO TO STEP 99
IF:  IPSG = 1; GO TO STEP 108

Step 99  Initialize Index Counter and PSG Voltage and Current

\[
\begin{align*}
\text{LL} &= 1 \\
SX(1) &= 0.0 \\
SY(1) &= F(I2(L), V2(L)) \text{ at } V2(L) = SX(1) \\
XZI(1) &= 0.0 \\
\end{align*}
\]

Step 100  Compare Voltage and Current to Reference Levels

IF:  SY(\text{LL}) < 0.0; \text{ and} \\
IF:  SX(\text{LL}) > SAOCV; \\
THEN:  GO TO STEP 107

Step 101  Increment Index Counter and Calculate PSG Voltage and Current

\[
\begin{align*}
\text{LL} &= \text{LL} + 1 \\
SX(\text{LL}) &= SX(\text{LL} - 1) + VSAIMC \\
SY(\text{LL}) &= F(I2(L), V2(L)) \text{ at } V2(L) = SX(\text{LL}) \\
XZI(\text{LL}) &= 0.0 \\
\end{align*}
\]
Step 102 Compare PSG Voltage With Shunt-Limiter Turn-On Voltage

IF: \( SX(LL) < VZSB; \)
THEN: REPEAT STEPS 100 AND 101

Step 103 Calculate PSG Current at Shunt-Limiter Turn-On

\[
\begin{align*}
SX(LL) &= VZSB \\
SY(LL) &= F(I2(L), V2(L)) \text{ at } V2(L) = SX(LL) \\
XZI(LL) &= F(ZI(I), ZV(I)) \text{ at } ZV(I) = SX(LL) \\
SY(LL) &= SY(LL) - XZI(LL)
\end{align*}
\]

Step 104 Compare PSG Current with Reference

IF: \( SY(LL) < 0.0 \)
THEN: GO TO STEP 107

Step 105 Calculate Zener String Voltage Increment

\[
VZINC = ZV(4) - ZV(3)
\]

VZINC = Zener String Voltage Increment - Volts beyond Zener Breakdown Voltage

Step 106 Increment Index Counter and Calculate PSG Voltage and Current

\[
LL = LL + 1
\]

\[
\begin{align*}
SX(LL) &= SX(LL - 1) + VZINC \\
SY(LL) &= F(I2(L), V2(L)) \text{ at } V2(L) = SX(LL) \\
XZI(LL) &= F(ZI(I), ZV(I)) \text{ at } ZV(I) = SX(LL) \\
SY(LL) &= SY(LL) - XZI(LL)
\end{align*}
\]

REPEAT STEPS 104, 105 AND 106
Step 107  Calculate Maximum PSG Voltage

Perform a straight-line interpolation between the last two sets of PSG Current-Voltage values to predict the voltage at which the PSG current is equal to zero (VZCR)

\[ SX(LL) = VZCR \]
\[ SY(LL) = 0.0 \]
\[ XZI(LL) = F(ZI(1), ZV(1)) \text{ at } ZV(1) = SY(LL) \]
\[ NFINAL = LL \]
RETURN TO PERFORMANCE ANALYSIS ROUTINE

Step 108  Initialize Index Counter and Section Voltage and Current

\[ LL = 1 \]
\[ VSECT(1) = 0.0 \]
\[ ISECT(1) = F(11(L), V2(L)) \text{ at } V2(L) = VSECT(1) \]
\[ XZIS(1) = 0.0 \]

Step 109  Compare Voltage and Current to Reference Levels

IF: \[ ISECT(LL) < 0.0; \text{ and} \]
IF: \[ VSECT(LL) > SAOCV; \]
THEN: GO TO STEP 116

Step 110  Increment Index Counter and Calculate Section Composite Voltage and Current

\[ LL = LL + 1 \]
\[ VSECT(LL) = VSECT(LL - 1) \ast VSAINC \]
\[ ISECT(LL) = F(11(L), V2(L)) \text{ at } V2(L) \ast VSECT(LL) \]
\[ XZIS(LL) = 0.0 \]
**Step 111**

Compare Section Voltage With Shunt Limiter Turn-On Voltage

IF:  \( \text{VSECT}(\text{LL}) < \text{VZSB} \);  
THEN:  REPEAT STEPS 109 AND 110

**Step 112**

Calculate Section Current at Shunt Limiter Turn-On

\( \text{VSECT}(\text{LL}) = \text{VZSB} \)

\( \text{ISECT}(\text{LL}) = f(I_1(\text{L}), V_2(\text{L})) \text{ at } V_2(\text{L}) = \text{VSECT}(\text{LL}) \)

\( \text{XZIS}(\text{LL}) = f(Z_1(\text{I}), Z_2(\text{I})) \text{ at } Z_2(\text{I}) = \text{VSECT}(\text{LL}) \)

\( \text{ISECT}(\text{LL}) = \text{ISECT}(\text{LL}) - \text{XZIS}(\text{LL}) \)

**Step 113**

Compare Section Current With Reference

IF:  \( \text{ISECT}(\text{LL}) < 0.0 \)
THEN:  GO TO STEP 116

**Step 114**

Calculate Zener String Voltage Increment

\( \text{VZINC} = Z_2(4) - Z_2(\text{L}) \)

**Step 115**

Increment Index Counter and Calculate Section Voltage and Current

\( \text{LL} = \text{LL} + 1 \)

\( \text{VSECT}(\text{LL}) = \text{VSECT}(\text{LL} - 1) + \text{VZINC} \)

\( \text{ISECT}(\text{LL}) = f(I_1(\text{L}), V_2(\text{L})) \text{ at } V_2(\text{L}) = \text{VSECT}(\text{LL}) \)

\( \text{XZIS}(\text{LL}) = f(Z_1(\text{I}), Z_2(\text{I})) \text{ at } Z_2(\text{I}) = \text{VSECT}(\text{LL}) \)

\( \text{ISECT}(\text{LL}) = \text{ISECT}(\text{LL}) - \text{XZIS}(\text{LL}) \)

REPEAT STEPS 113, 114 AND 115
Step 116 Calculate Maximum Section Voltage

Perform a straight-line interpolation between the last two sets of section current-voltage values to predict the voltage at which section current is equal to zero (VZCR)

\[ V_{SECT}(LL) = VZCR \]
\[ ISECT(LL) = 0.0 \]
\[ XZIS(LL) = f(ZI(I), ZV(I)) \text{ at } ZV(I) = V_{SECT}(LL) \]
\[ NF\text{FINAL} = LL \]

Step 117 Calculate PSC Current Voltage Characteristics

\[ SY(LL) = I_{SECT}(LL) \times NESP \]
\[ XZI(LL) = XZIS(LL) \times NESP \]
\[ SX(LL) = V_{SECT}(LL) \]

\[ LL = 1, \text{ NF\text{FINAL}} \]

Return to Performance Analysis Routine

Step 118 Calculate Oscillation Conditions for Solar Insolation

\[ QDN = 0.0 \]
\[ QD = 0.0 \]
\[ QDG = 0.0 \]
\[ QDS = 0.0 \]
\[ QDT = 0.0 \]

Where:  
\[ QDN = \text{Direct, Normal Solar Insolation at Buoy Location} - \text{Watts/M}^2 \]
\[ QD = \text{Direct Solar Insolation Incident on Solar Array} - \text{Watts/M}^2 \]
\[ QDG = \text{Horizontal Surface Diffuse Insolation Incident on Solar Array} - \text{Watts/M}^2 \]
\[ QDS = \text{Sky Diffuse Insolation Incident on Solar Array} - \text{Watts/M}^2 \]
\[ QDT = \text{Total Solar Insolation Incident on Solar Array} - \text{Watts/M}^2 \]
Step 118a  Calculate Solar Array Maximum Power

\[ \text{MSAFWR} = 0.0 \]

Step 119  Obtain Solar Array Parameters

\[ \text{VSAINC} = \text{Solar Array Voltage Increment - Volts} \]

\[ \text{KFFINAL} = \text{Maximum extent of PSG group Current-Voltage Characteristics Matrix} \]

Step 120  Calculate PSG Current-Voltage Characteristics

\[ \begin{align*}
\text{SY}(1) &= 0.0 \\
\text{XZI}(1) &= 0.0 \\
\text{SX}(1) &= 0.0 \quad \text{(INITIALIZATION)}
\end{align*} \]

\[ \begin{align*}
\text{SY}(LL) &= 0.0 \\
\text{XZI}(LL) &= 0.0 \\
\text{SX}(LL) &= \text{SX}(LL - 1) + \text{VSAINC} \\
& \text{LL = 1, KFINAL}
\end{align*} \]

RETURN TO PERFORMANCE ANALYSIS ROUTINE
4.1.1 Shunt Limiters

The Shunt Limiter routine allows the user to specify whether an active shunt limiter, an ordinary zener diode, a temperature-compensated zener diode, or no shunting device will be used in conjunction with the solar array. The shunt device selected will not influence the solar array performance until prevailing conditions require the limiting of the array voltage. The array voltage is then clamped at a maximum potential, altering the Power Source Group current-voltage characteristics. The combined solar array/shunt limiter performance curve is the algebraic difference between the solar array and the array limiter characteristics.

PROGRAM ALGORITHMS

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Obtain Shunt Limiter Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISH</td>
<td>Shunt Limiter Type</td>
</tr>
<tr>
<td>0</td>
<td>No Shunt Limiter</td>
</tr>
<tr>
<td>1</td>
<td>Ordinary Zener Diode</td>
</tr>
<tr>
<td>2</td>
<td>Temperature Compensated Zener Diode</td>
</tr>
<tr>
<td>3</td>
<td>Active Shunt Limiter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Step 2</th>
<th>Select Shunt Limiter Current-Voltage Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>If: ISH = 0; GO TO STEP 3</td>
<td></td>
</tr>
<tr>
<td>If: ISH = 1; GO TO STEP 4</td>
<td></td>
</tr>
<tr>
<td>If: ISH = 2; GO TO STEP 5</td>
<td></td>
</tr>
<tr>
<td>If: ISH = 3; GO TO STEP 6</td>
<td></td>
</tr>
</tbody>
</table>
Step 3 Calculate No-Shunt Limiter Current Voltage Characteristics

FOR I = 1, 20

ZI(I) = 0.0
ZV(I) = 0.0

Where: ZI(I) = Shunt Limiter Current at ZV(I) - Amperes
ZV(I) = Shunt Limiter Voltage - Volts

RETURN TO POWER SOURCES GROUP ROUTINE

Step 4 Obtain Ordinary Zener Diode Current-Voltage Characteristics

ZI(I); ZV(I)

For I = 1, 20

RETURN TO POWER SOURCES GROUP ROUTINE

Step 5 Obtain Temperature Compensated Zener Diode Current-Voltage Characteristics

For I = 1, 20:

ZI(I); ZV(I)

RETURN TO POWER SOURCES GROUP ROUTINE

Step 6 Obtain Active Shunt Limiter Current-Voltage Characteristics

For I = 1, 20:

ZI(I); ZV(I)

RETURN TO POWER SOURCES GROUP ROUTINE
ORDINARY ZENER DIODE

For the Initial Load Line Analysis Calculation go to Step 1

For Subsequent Load Line Analysis Calculations go to Step 3

Step 1

Obtain Zener Diode Operational Requirements

\[ V_{ZBR} = \text{Breakdown Voltage of a Single Zener Diode - Volts} \text{ (at } T_{ZBR}) \]

\[ T_{ZBR} = \text{Temperature of Zener Diode - } {^\circ}\text{C} \text{ (at Breakdown Voltage)} \]

Step 2

Calculate Zener Diode Breakdown Voltage at Reference Temperature

Iterate the following equations until the change in Zener breakdown voltage at reference temperature is less than 0.1 volts. The number of iterations shall not exceed 15.

\[ V_{ZB3C} = V_{ZBR} \times \left[ 1.0 - \frac{TC \times (T_{ZBR} - 30.0)}{100} \right] \]

\[ TC = ZTCOF (V_{ZB30}) \]

Where: \[ V_{ZB30} = \text{Zener diode breakdown voltage at } 30{^\circ}\text{C - Volts} \]

\[ TC = \text{Zener diode temperature coefficient (}/^\circ\text{C) as a function of } V_{ZB30} \]

\[ ZTCOF = \text{Input table of } TC \text{ as a function of } V_{ZB30} \]

Step 3

Obtain Solar Array Temperature

\[ T_{SAC} = \text{Solar Array Temperature - } {^\circ}\text{Centigrade} \]
Step 4 Calculate Zener Diode Operating Temperature

\[ TJZ1 = TSAC \]

Where: \( TJZ1 = \) Zener Diode Operating Temperature - °C

Step 5 Calculate Zener Diode Breakdown Voltage

\[ VZB = VZB30 \times \left[ 1.0 + \frac{TC \times (TJZ1 - 30.0)}{100.0} \right] \]

Where: \( VZB = \) Single Zener Diode Breakdown Voltage - Volts at \( TJZI \)

Step 6 Obtain Number of Zener Diodes in a String

\( NZS = \) Number of Zener Diodes in Series

Step 7 Calculate Zener String Breakdown Voltage

\[ VZSB = VZB \times NZS \]

Where: \( VZSB = \) Zener String Breakdown Voltage - Volts

Step 8 Calculate Zener Diode Dynamic Impedance

\[ ZZ = ZDIMP \{ TJZ1, VZB30 \} \]

Where: \( ZDIMP = \) Input Table of ZZ as a function of \( TJZ1 \) and \( VZB30 \)

Step 9 Calculate Zener Diode Current-Voltage Characteristics

\[ ZI(I) = Zener \ Diode \ Current \ - \ Amperes \]
\[ ZV(I) = Zener \ Diode \ Voltage \ - \ Volts \]
\[ I = 1, 20 \]
Step 9 (contd)
as follows:
a) For I = 1
   \( ZI(I) = 0.0 \)
   \( ZV(I) = 0.0 \)
b) For I = 2
   \( ZI(2) = 0.0 \)
   \( ZV(2) = VZSB \)
c) For I = 3
   \( ZI(3) = 100.0 \)
   \( ZV(3) = VZSB + ZI(3) \times ZZ \times NZS \)
d) For I = 4, 20
   \( ZI(I) = 0.0 \)
   \( ZV(I) = 0.0 \)

Step 10 RETURN TO GENERAL SHUNT LIMITER ROUTINE
TEMPERATURE COMPENSATED ZENER DIODE

<table>
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<th>Step</th>
<th>Description</th>
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</thead>
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<td>Step 1</td>
<td>Obtain Zener Diode Operational Requirements</td>
</tr>
<tr>
<td></td>
<td>NZS = Number of Zener diodes in series in a string</td>
</tr>
<tr>
<td></td>
<td>HDZMX = Maximum Heat Dissipation of a single zener diode - Watts</td>
</tr>
<tr>
<td></td>
<td>HDER = Heat Dissipation Derating Factor for a single zener diode</td>
</tr>
<tr>
<td>Step 2</td>
<td>Calculate Reference Zener Power</td>
</tr>
<tr>
<td></td>
<td>PZRF25 = HDER * HDZMX</td>
</tr>
<tr>
<td></td>
<td>Where: PZRF25 = Zener diode power at 25°C - Watts</td>
</tr>
<tr>
<td>Step 3</td>
<td>Calculate Reference Zener Current</td>
</tr>
<tr>
<td></td>
<td>IZRF25 = CURZ (HDZMX)</td>
</tr>
<tr>
<td></td>
<td>Where: IZRF25 = Zener Diode Current at 25°C - Watts</td>
</tr>
<tr>
<td></td>
<td>CURZ = Input Table of IZRF25 as a function of HDZMX</td>
</tr>
<tr>
<td>Step 4</td>
<td>Calculate Reference Zener Voltage</td>
</tr>
<tr>
<td></td>
<td>VZRF25 = PZRF25/IZRF25</td>
</tr>
<tr>
<td></td>
<td>Where: VZRF25 = Zener Diode Voltage at 25°C - Volts</td>
</tr>
<tr>
<td>Step 5</td>
<td>Obtain Solar Array Temperature</td>
</tr>
<tr>
<td></td>
<td>TSAC = Solar Array Temperature - °C</td>
</tr>
</tbody>
</table>
Step 6  Calculate Zener Diode Operating Temperature

\[ TCZ = TSAC \]

Where: \( TCZ = \text{Zener Diode Operating Temperature} \cdot ^\circ \text{C} \)

Step 7  Calculate Zener Diode Breakdown Voltage Ratio as follows:

a). Given the formulation:

\[ \text{RATI} = \text{TCZIV(RATV, TCZ)} \]

Where:
- \( \text{RATI} = \text{Zener Diode Current Ratio at RATV and TCV} \)
- \( \text{RATV} = \text{Zener Diode Voltage Ratio} \)
- \( \text{TCZIV} = \text{Input table of Zener diode current-voltage characteristics (RATI, RATV) as a function of TCV} \)

b) Then:

\[ \text{RATVB} = \text{RATV: when; RATI} = 0.0 \]

Where: \( \text{RATVB} = \text{Zener Diode Breakdown Voltage Ratio} \)

Step 8  Calculate Voltage Ratio Increment Size

\[ \text{RTVINC} = 1.05 - \frac{\text{RATVB}}{18.0} \]

Step 9  Calculate Zener Diode Current Ratio-Voltage Ratio Characteristics

\[ \text{RIZ(J)} = \text{Zener Diode Current Ratio at RVZ(J)} \]

\[ \text{RVZ(J)} = \text{Zener Diode Voltage Ratio} \]

\( J = 1, 20 \)

as follows:

a) For \( J = 1 \)

\[ \text{RIZ(1)} = 0.0 \]

\[ \text{RVZ(1)} = 0.0 \]
Step 9 (contd)

b) For J = 2

\[ RIZ(2) = 0.0 \]
\[ RVZ(2) = RATVB \]

c) For J = 3, 20: Repeat Step 80; 18 times

\[ RVZ(J) = RVZ(J - 1) + RTVINC \]
\[ RATV = RVZ(J) \]
\[ RATI = TCZIV(RATV, TCZ) \]
\[ RIZ(J) = RATI \]
\[ J = J + 1 \]

Step 10

Calculate Zener Diode String Current Voltage Characteristics

\[ ZI(J) = \text{Zener Diode Current at } ZV(J) \text{ - Amperes} \]
\[ ZV(J) = \text{Zener Diode String Voltage - Volts} \]

J = 1, 20

as follows:

\[ ZI(J) = IZRF25 \times RIZ(J) \]
\[ ZV(J) = NZS \times VZRF25 \times RVZ(J) \]

Step 11

RETURN TO GENERAL SHUNT LIMITER ROUTINE
# ACTIVE SHUNT LIMITER

## Step 1
Obtain Shunt Limiter Operational Requirements

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSAC</td>
<td>Solar Array Temperature - °C</td>
</tr>
<tr>
<td>VSHTOR</td>
<td>Required Shunt Limiter Turn-On Voltage - Volts at TSHREF</td>
</tr>
<tr>
<td>TSHREF</td>
<td>Shunt-Limiter Reference Temperature - °C</td>
</tr>
<tr>
<td>CSH</td>
<td>Shunt-Limiter Turn-On Voltage Coefficient - %/°C</td>
</tr>
</tbody>
</table>

## Step 2
Calculate Shunt Limiter Operating Temperature

\[ TSH = TSAC \]

Where: \( TSH \) = Shunt Limiter Operating Temperature

## Step 3
Calculate Shunt Limiter Turn-On Voltage

\[ VSHTO = VSHTOR \left[ 1.0 + \frac{CSH \times (TSH - TSHREF)}{100.0} \right] \]

Where: \( VSHTO \) = Shunt Limiter Turn-On Voltage - Volts \( (\text{at TSH}) \)

## Step 4
Calculate Shunt Limiter Dynamic Impedance

\[ ZSH = ZSHTAB(TSH) \]

Where: \( ZSH \) = Shunt Limiter Dynamic Impedance - Ohms

\( ZSHTAB \) = Input Table of \( ZSH \) as a function of \( TSH \)
Step 5  Calculate Shunt Limiter Current Voltage Characteristics

ZI(I) = Shunt Limiter Current - Amperes

ZV(I) = Shunt Limiter Voltage - Volts

I = 1, 3

as follows:

a) For I = 1

ZI(1) = 0.0
ZV(1) = 0.0

b) For I = 2

ZI(2) = 0.0
ZV(2) = VSHTO

c) For I = 3

ZI(3) = 100.0
ZV(3) = VSHTO + ZI(3) * ZSH

d) For I = 4, 20

ZI(I) = 0.0
ZV(I) = 0.0

Step 6  RETURN TO GENERAL SHUNT LIMITER ROUTINE
4.2 Energy Storage Group

The Energy Storage Group is made up of the buoy batteries, the battery cables, the battery chargers and the battery discharge diodes. The characteristics of these elements are consolidated as a function of the battery states-of-charge, temperature, number of series cells, cable resistance, and battery charge rate and are then expressed as a single set of current-voltage characteristics at the unregulated bus operating point.

The Energy Storage Group algorithms access a comprehensive set of battery charge and discharge data that are ordered in specific battery operating states and temperatures. The battery data are in the form of current-voltage curves at specified temperatures and depths of discharge. A total of 21 curves are available for each of six temperatures, 126 curves in all.

PROGRAM ALGORITHMS

Step 1  Obtain Battery Charger Type

ICHRT = Battery Charger Type

0 = No Charger
1 = Constant Voltage Charger with Current Limit

IF:    This is Initial Load Line Analysis:
THEN:  GO TO STEP 2

IF:    This is Subsequent Load Line Analysis:
THEN:  GO TO STEP 3
Step 2 Obtain Battery Characteristics

\[ DT T E S G = \text{Energy Storage Group Temperature Rise - } ^\circ F \]

\[ NB A T T = \text{Number of Batteries in Parallel} \]

\[ CB = \text{Capacity of each Battery - ampere-hours} \]

\[ X N = \text{Number of Cells in series in each Battery} \]

\[ RL = \text{Resistance of Cable Connected to each Battery - Ohms} \]

\[ X I C H M X = \text{Maximum Allowable Battery Charge Current - Ampere} \]

Step 3 Obtain Ambient Temperature

\[ TT A M B = \text{Ambient Temperature at Selected Location - } ^\circ F \]

Step 4 Calculate Energy Storage Group Temperature

\[ TT E S G = TT A M B + DT T E S G \]

Where: \( TT E S G = \text{Energy Storage Group Temperature - } ^\circ F \)

Step 5 Obtain Battery State-of-Charge

\[ Q B = \text{State of Charge of each Battery} \]

Step 6 Calculate Battery Current-Voltage Characteristics

\[ B R R ( J , K , L ) = B C Q T ( V C C ( J , K , L ) , Q B B ( K ) , T B R ( L ) ) \]

\[ V C ( J ) = V C C ( J , K , L ) \text{ at } Q B B = Q B \text{ and } T B B = T T E S G \]

\[ B R ( J ) = B R R ( J , K , L ) \text{ at } V C C = V C ( J ) , Q B B = Q B , \text{ and } T B R = T T E S G \]

\[ V B ( J ) = V C ( J ) \times X N \]
Step 6 (Contd)

\[ X_{IB}(J) = B_{R}(J) \cdot C_{B} \]

\[ J = 1, 9 \text{ (Data Points)} \]

\[ K = 1, N_{QBB} \]

\[ L = 1, N_{TBB} \]

Where:  
- BRR = Normalized Battery Current Rate (expressed as ratio of battery current (amperes) to battery capacity (ampere-hours)) - Hours
- VCC = Cell Voltage - VDC
- QBB = Battery State-of-Charge
- TBB = Battery Temperature - °F
- BCQT = Input Table of BRR as a function of VCC, QBB and TBB
- NQBB = Number of QBB entries in BCQT
- NTBB = Number of TBB entries in BCQT
- VC(J) = Cell Voltage for each Battery - VDC
- VB(J) = Battery Voltage for each battery - VDC
- BR(J) = Normalized Battery Current for each Battery - Hours\(^{-1}\)
- XIB(J) = Battery Current for each Battery - Hours\(^{-1}\)

Step 7  Calculate Effect of Parasitic Losses

IF: \[ X_{IB}(J) \geq 0.0 \]
THEN: \[ V_{BM}(J) = V_{B}(J) + R_{L} \cdot X_{IB}(J) \]

IF: \[ X_{IB}(J) < 0.0 \]
THEN: \[ \begin{align*}
V_{BM}(J) &= V_{B}(J) - V_{DIODE} - R_{L} \cdot |X_{IB}(J)| \\
V_{DIODE} &= AD2(\{|X_{IB}(J)|\})
\end{align*} \]

Where:  
- VBM = Modified Battery Voltage for each Battery - VDC
- VDIODE = Battery Discharge Blocking Diode Voltage Drop - VDC
- AD2 = Input Table of VDIODE as a function of battery discharge current

\[ J = 1, 9 \]
### Step 7 (Contd)

**IF:** \( \text{ICHRT} = 1 \)

**THEN:** GO TO STEP 17

### Step 8
Rearrange Modified Battery Voltage Data into One Array in Ascending Order

\[
\text{TRESLT}(J,1) = F(VBM(J)) \text{ (in ascending order)}
\]

\( J = 1, 9 \)

Where: \( \text{TRESLT}(J,1) = \) Energy Storage Group Voltage - VDC

### Step 9
Initialize Counter and Special Voltage Array

\( LL = 1 \)

\( LY = 1 \)

\( \text{TRESVT}(LY) = \text{TRESLT}(LL,1) \)

Where: \( \text{TRESVT} = \) Special Voltage Array for ES Group - VDC

\( LY = \) Remaining Number of Modified Voltage Points

### Step 10
Index Counter and Compare Voltage Differences

\( LL = LL + 1 \)

**IF:** \( |(\text{TRESLT}(LL,1) - \text{TRESLT}((LL-1),1)| < 0.01 \)

**THEN:** REPEAT STEP 10

### Step 11
Index Counter and Calculate Values in Special Voltage Array

\( LY = LY + 1 \)

\( \text{TRESVT}(LY) = \text{TRESLT}(LL,1) \)

**IF:** \( LL > 9 \)

**THEN:** GO TO STEP 12

REPEAT STEPS 10 AND 11

### Step 12
Calculate Revisions to Energy Storage Group Voltage

\( \text{TRESLT}(LL,1) = 0.0 \)

\( LL = 1,9 \)

\( \text{TRESLT}(LY,1) = \text{TRESVT}(LY) \)

\( LY = 1,9 \)
Step 13 Calculate Individual Battery Voltage

\[ \text{TRESV}(LY) = \text{TRESLT}(LY,1) \]

\[ LY = 1,9 \]

Where: \( \text{TRESV} = \) Individual Battery Voltage - VDC

Step 14 Calculate Average Battery Cell Voltages

\[ \text{VCM}(J) = \text{VCM}(J)/XN \]

\[ J = 1,9 \]

Where: \( \text{VCM} = \) Modified Average Cell Voltage - VDC

Step 15 Calculate Individual Battery Current

\[ \text{TRESI}(J) = F(XIB(J),\text{VCM}(J)) \text{ at values of } \text{VCM}(J) = \text{TRESV}(J)/XN \]

\[ J = 1,9 \]

Where: \( \text{TRESI} = \) Individual Battery Current - Amperes

Step 16 Calculate Total Battery Current

\[ \text{TRESLT}(LY,2) = \text{TRESI}(LY) \cdot \text{NBATT} \]

\[ LY = 1,9 \]

Where: \( \text{TRESLT}(LY,2) = \) Energy Storage Group Current - Amperes

\( \text{at TRESLT}(LY,1) \)

\( \text{TRESLT}(LY,1) = \) Energy Storage Group Voltage - VDC

RETURN TO PERFORMANCE ANALYSIS ROUTINE

Step 17 Enlarge Modified Current-Voltage Characteristic Array

\[ \text{XIBBM}(JJ) = \text{XIB}(J) \]

\[ \text{VBBM}(JJ) = \text{VBM}(J) \]

\[ JJ = J \]

\[ J = 1,9 \]

But, allow for an extra location so that \( (JJ)_{\text{maximum}} = 10 \)
Step 18  Insert Battery Voltage Corresponding to Maximum Allowable Battery Current (XICHMX) into Modified Current-Voltage Characteristic Array such that the array contains I-V data for that point.

Thus,

\[ \text{VBBM(JJ)} = \text{Modified Battery Voltage for each Battery} \ - \ VDC \]

\[ \text{XIBBM(JJ)} = \text{Battery Current for each Battery} \ - \ \text{Ampere} \]

\[ \text{Corresponding to VBBM(JJ)} \]

\[ JJ = 1,10 \]

Step 19  Obtain Battery Charger Reference Voltages

\[ \text{VCHIO} = \text{VCHIOT(TTESG)} \]

\[ \text{VCHISA} = \text{VCHIST(TTESG)} \]

Where:

\[ \text{VCHIO} = \text{Battery Charger Input Voltage at Turn-On} \ - \ VDC \]

\[ (\text{Minimum Voltage Drop at Zero Current Level}) \]

\[ \text{VCHISA} = \text{Battery Charger Input Voltage} \ - \ VDC \]

\[ \text{at which operation changes from "saturated" to "active" conditions} \]

\[ \text{VCHIOT} = \text{Input table of VCHIO as a function of TTESG} \]

\[ \text{VCHIST} = \text{Input table of VCHISA as a function of TTESG} \]

Step 20  Obtain Battery Charger Impedance

\[ \text{ZCHRS} = \text{ZCHRST(TTESG)} \]

\[ \text{ZCHRA} = \text{ZCHRSA(TTESG)} \]

Where:

\[ \text{ZCHRS} = \text{Output Impedance of Battery Charger in "saturated" condition} \ - \ \text{Ohms} \]

\[ \text{ZCHRA} = \text{Output Impedance of Battery Charger in "active" condition} \ - \ \text{Ohms} \]

\[ \text{ZCHRST} = \text{Input Table of ZCHRS as a function of TTESG} \]

\[ \text{ZCHRAT} = \text{Input Table of ZCHRA as a function of TTESG} \]

Step 21  Obtain Battery Charger Impedance

\[ \text{ZCHRS} = \text{ZCHRST(TTESG)} \]

\[ \text{ZCHRA} = \text{ZCHRSA(TTESG)} \]
Step 21 (Cont)

Where:  
\[ Z_{CHR5} \] = Output Impedance of Battery Charger in "saturated" condition - Ohms

\[ Z_{CHRA} \] = Output Impedance of Battery Charger in "active" condition - Ohms

\[ Z_{CHRST} \] = Input Table of \[ Z_{CHR5} \] as a function of TTESG

\[ Z_{CHRAT} \] = Input Table of \[ Z_{CHRA} \] as a function of TTESG

Step 23
Initialize Counter

\[ JJ = 1 \]

Step 24
Calculate Energy Storage Unit Discharge I-V Characteristics and Then Increment Counter

\[ \text{IF: } XIBBM(JJ) > 0.0 \]
\[ \text{THEN: GO TO STEP 25} \]

\[ VESI(JJ) = VBBM(JJ) \]

\[ XIESI(JJ) = XIBBM(JJ) \]

\[ JJ = JJ + 1 \]

Where:  
\[ VESI(JJ) \] = Energy Storage Unit Input Voltage - VDC

\[ XIESI(JJ) \] = Energy Storage Unit Input Current (Corresponding to \[ VESI(JJ) \]) - Amperes

Repeat Step 24

Step 25
Compare Power Sources Group Maximum Voltage with Reference Voltages

\[ \text{IF: } (VPSGMX) > (VCHI0 + VBBM(JJ)) \]
\[ \text{THEN: GO TO STEP 28} \]

Step 26
Calculate Energy Storage Unit Charge I-V Characteristics and Increment Counter

\[ \text{IF: } JJ > 10 \]
\[ \text{THEN: GO TO STEP 27} \]

\[ VESI(JJ) = VBBM(JJ) \]

\[ XIESI(JJ) = 0.0 \]

\[ \text{REPEAT STEP 26} \]
### Step 28
Calculate Estimate of Charger Input Voltage

\[
V_{CHOOS} = V_{BBM(JJ)} + X_{IBBM(JJ)} \times ZCHRS
\]

\[
V_{ESS} = V_{CHOOS} + V_{CHIO}
\]

**IF:** \( V_{ESS} > V_{CHISA} \)

**THEN:** GO TO STEP 30

Where:  
- \( V_{CHOOS} = \) Battery Charger Output Voltage (in "saturated" condition) at zero current - VDC
- \( V_{ESS} = \) Estimate of Battery Charger Input Voltage in "saturated" condition - VDC

### Step 29
Calculate Energy Storage Unit Charge I-V Characteristics and Increment Counter

**IF:** \( JJ > 10 \)

**THEN:** GO TO STEP 27

\[
X_{IESI(JJ)} = X_{IBBM(JJ)}
\]

\[
V_{ESI(JJ)} = V_{ESS(JJ)}
\]

\[
JJ = JJ + 1
\]

RETURN TO STEP 28

### Step 30
Calculate Estimate of Charger Input Voltage

\[
V_{CHOOA} = V_{BBM(JJ)} + X_{IBBM(JJ)} \times ZCHRA
\]

\[
V_{ESA} = VCHIT\{V_{CHOOA},TTESG\}
\]

Where:  
- \( V_{CHOOA} = \) Battery Charger Output Voltage (in "active" condition) at zero current - VDC
- \( V_{ESA} = \) Estimate of Battery Charger Input Voltage in "active" condition - VDC
- \( VCHIT = \) Input Table of \( V_{ESA} \) as a function of \( V_{CHOOA} \) and \( TTESG \)

### Step 31
Calculate Energy Storage Unit Charge I-V Characteristics and Increment Counter

**IF:** \( JJ > 10 \)

**THEN:** GO TO STEP 27
Step 31 (Contd)

\[ X \text{IESI}(JJ) = X \text{IBBM}(JJ) \]
\[ V \text{ESI}(JJ) = V \text{ESA} \]
\[ JJ = JJ + 1 \]

RETURN TO STEP 30

Step 32

Compare Battery Charger Input Current with Reference Current Limit

\[ \text{IF: } X \text{IESI}(JJ) > X \text{ICBMX} \]
\[ \text{THEN: } X \text{IESI}(JJ) = X \text{ICBMX} \]
\[ JJ = 1, 10 \]

Step 33

Rearrange Energy Storage Unit Voltage Data into One Array in Ascending Order

\[ T \text{RESLT}(JJ,1) = f(V \text{ESI}(JJ)) \text{ (in ascending order)} \]
\[ JJ = 1, 10 \]

Step 34

Initialize Counter and Special Voltage Array

\[ LL = 1 \]
\[ LY = 1 \]

\[ T \text{RESVT}(LY) = T \text{RESLT}(LL,1) \]

Step 35

Index Counter and Compare Voltage Differences

\[ LL = LL + 1 \]

\[ \text{IF: } |(T \text{RESLT}(LL,1) - T \text{RESLT}((LL - 1),1)| < 0.01 \]
\[ \text{THEN: } \text{REPEAT STEP 35} \]

Step 36

Index Counter and Calculate Values in Special Voltage Array

\[ LY = LY + 1 \]

\[ T \text{RESVT}(LY) = T \text{RESLT}(LL,1) \]

\[ \text{IF: } LL > 10 \]
\[ \text{THEN: } \text{GO TO STEP 37} \]

\[ \text{REPEAT STEPS 35 AND 36} \]
Step 37  Calculate Revisions to Energy Storage Group Voltage

TRESLT(\(LL,1\)) = 0.0

\(LL = 1.10\)

TRESLT(\(LY,1\)) = TRESVT(\(LY\))

\(LY = 1.10\)

Step 38  Calculate Individual Energy Storage Unit Voltage

TRESV(\(LY\)) = TRESLT(\(LY,1\))

\(LY = 1.10\)

Step 39  Calculate Energy Storage Unit Equivalent Single Cell Voltage

VESIC(\(JJ\)) = VESI(\(JJ\))/XN

\(JJ = 1.10\)

Where:  VESIC = Equivalent Single Cell Voltage of an Energy Storage Unit - VDC

Step 40  Calculate Energy Storage Unit Current

TRESI(\(LY\)) = F(XIESI(\(JJ\)),VESIC(\(JJ\)))

At values of:  VESIC(\(JJ\)) = TRESV(\(LY\))/XN

\(JJ = 1.10\)

\(LY = 1.10\)

Step 41  Calculate Total Energy Storage Group Current

TRESLT(\(LY,2\)) = TRESI(\(LY\)) \* HBATT

\(LY = 1.10\)

RETURN TO PERFORMANCE ANALYSIS ROUTINE
4.3 Power Conditioning and Distribution Group

The Power Conditioning and Distribution Group is made up of two subassemblies: the Lamp Flasher and the Housekeeping Regulator. The characteristics of the subassemblies are computed as a function of the lamp flasher pattern and the lamp flasher condition (on, off, or flashing). These characteristics are then shifted for the combined effects of wiring and connector series resistance to give a single set of current-voltage curves at the unregulated bus.

PROGRAM ALGORITHMS

For the Initial Load Line Analysis, GO TO STEP 1
For Subsequent Load Line Analysis, GO TO STEP 13

Step 1 Obtain Flasher Pattern Type
IF:  IFTYPE = 0, GO TO STEP 3
Where: IFTYPE = Type of flasher pattern
IFTYPE = 0: Non-Standard Pattern
IFTYPE > 0: Standard Pattern

Calculate Standard Flasher Pattern
TL1(J) = TLO(IFTYPE,J)
(1 ≤ IFTYPE ≤ 15) (15 standard pattern types)
(1 ≤ J ≤ 16) (Up to 16 steps per pattern)
Alternate On/Off

Where: TLO(IFTYPE,J) = Input table containing the patterns exhibited by the Standard Lamp Flashers
TL1 = Selected Lamp Flasher Pattern

GO TO STEP 4

Step 3 Calculate Non-Standard Flasher Pattern
TL1(J) = TLL1(J) (1 ≤ J ≤ 16)

Where: TLL1(J) = Input data containing up to 16 alternate on-off steps for the Non-Standard Flasher Pattern
Step 4  Calculate Total Duration of Lamp Illumination and Lamp Shut-Off

\[ T_{LON} = \sum_{J=1,3,5...}^{15} T_{L1}(J) \]
\[ T_{LOFF} = \sum_{J=2,4,6...}^{16} T_{L1}(J) \]

Where:  \( T_{LON} = \) Total duration of lamp illumination  
\( T_{LOFF} = \) Total duration of lamp shut-off

IF:  \( T_{LON} \leq 0 \) and \( T_{LOFF} \leq 0 \) stop program and
Print:  "No flasher pattern entries"

Step 5  Calculate Lamp Duty Cycle

\[ DL = T_{LON}/(T_{LON} + T_{LOFF}) \]

Where:  \( DL = \) Lamp Duty Cycle

Step 6  Obtain Lamp Characteristics

\( V_{LR} = \) Lamp Voltage Rating - VDC  
\( C_{LR} = \) Lamp Current Rating - Amperes  
\( C_{LS} = \) Cold-Filament Lamp Surge Coefficient

Step 7  Calculate Actual Lamp Current

\[ I_{L} = C_{LS} \times C_{LR} \]

Where:  \( I_{L} = \) Actual Lamp Current - Amperes

Note:  IF:  \( DL = 1.0 \)  
THEN:  \( C_{LS} = 1.0 \)

IF:  \( DL < 1.0 \)  
THEN:  \( C_{LS} > 1.0 \)
Step 8  Calculate Actual Lamp Resistance

\[ RL = \frac{V_L}{I_L} \]

Where:  \( RL \) = Actual Lamp Resistance - Ohms

Step 9  Calculate Average Lamp Current

\[ \overline{I_L} = I_L \times D_L \]

Where:  \( \overline{I_L} \) = Average Lamp Current - Amperes

Step 10  Calculate Effective Lamp Resistance

\[ RL = \frac{V_L}{I_L} \]

Where:  \( RL \) = Effective Lamp Resistance - Ohms

Step 11  Obtain Raw Power Bus Voltage Limits and User Load Cable Resistance

\[ V_{MINIV} = \text{Minimum Raw Power Bus Voltage} - \text{VDC} \]
\[ V_{MAXIV} = \text{Maximum Raw Power Bus Voltage} - \text{VDC} \]
\[ R_{LL} = \text{User Load Cable Resistance} - \text{Ohms} \]

Step 12  Calculate PCD Group Voltage Increment

\[ V_{INCIV} = \frac{(V_{MAXIV} - V_{MINIV})}{50.0} \]

Where:  \( V_{INCIV} \) = PCD Group Voltage Increment - VDC

Step 13  Obtain PCD Equipment Temperature Characteristics

\[ T_{TAMB} = \text{Ambient Temperature} - °F \]
\[ D_{TTPCD} = \text{PCD Equipment Temperature Rise} - °F \]
Step 14 Calculate PCD Equipment Temperature

\[ T_{TPCD} = T_{TAMB} + DT_{TPCD} \]

Where: \( T_{TPCD} = \text{PCD Equipment Temperature} - ^\circ\text{F} \)

Step 15 Compare Raw Power Bus Minimum Voltage With Reference

IF: \( V_{MINIV} < V_{RIO} \)
THEN: GO TO STEP 16

IF: \((V_{MINIV} > V_{RIO}) \text{ and } (V_{MINIV} < V_{RISA})\)
THEN: GO TO STEP 24

IF: \( V_{MINIV} > V_{RISA} \)
THEN: GO TO STEP 29

Where: \( V_{RIO} = \text{Minimum (No Current) Voltage Drop - VDC} \)
Across Lamp Regulator in "Saturated" Condition

\( V_{RISA} = \text{Voltage level at which lamp regulator - VDC} \)
changes from "Saturated" condition operation
to "Active" operation

\( V_{RIO} = V_{RIOT}(T_{TPCD}) \)

\( V_{RISA} = V_{RISAT}(T_{TPCD}) \)

Step 16 Initialize Counter and Lamp Regulator Voltage

\[ J = 1 \]

\[ V_{RI}(J) = V_{MINIV} \]

Step 17 Calculate Lamp Regulator Current

\[ I_{RI}(J,1) = 0.0 \]

\[ I_{RI}(J,2) = 0.0 \]

\[ I_{RI}(J,3) = 0.0 \]

Where: \( V_{RI}(J) = \text{Lamp Regulator Input Voltage - VDC} \)

\[ I_{RI}(J,K) = \text{Lamp Regulator Input Current - Volts} \]

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Step 17 (contd)

When:  
K = 1 - Lamp Off

K = 2 - Lamp Flashing - Effective

K = 3 - Lamp On

Step 18 Increment Counter and Lamp Regulator Voltage and Compare With Reference

J = J + 1

VRI(J) = VRI(J - 1) + VINCIV

IF:  (VRI(J) > VRIO) and

IF:  (VRI(J) < VMAXIV)

THEN:  GO TO STEP 20

IF:  VRI(J) > VMAXIV

THEN:  GO TO STEP 32

Step 19 Calculate Lamp Regulator Currents

IRI(J,1) = 0.0

IRI(J,2) = 0.0

IRI(J,3) = 0.0

REPEAT STEPS 18 AND 19

Step 20 Calculate Lamp Regulator Current

IRI(J,1) = 0.0

IRI(J,2) = (VRI(J) - VRIO)/(IR + ZRS)

IRI(J,3) = (VRI(J) - VRIO)/(IR + ZRS)

Where:  ZRS = Regulator Impedance in "Saturated" Condition - Ohms

ZRS = ZRST(TTPCD)

ZRST = Input Table of ZRS as a function of TTPCD
Step 21  Increment Counter and Lamp Regulator Voltage and Compare with Reference

\[ J = J + 1 \]
\[ VRI(J) = VRI(J - 1) + VINCIV \]

**IF:** \((VRI(J) > VRISA) \) and

**IF:** \((VRI(J) < VMAXIV)\)

**THEN:** Go to Step 22

**IF:** \(VRI(J) > VMAXIV\)

**THEN:** Go to Step 32

REPEAT STEPS 20 AND 21

---

Step 22  Calculate Lamp Regulator Currents

\[ IRI(J,1) = 0.0 \]
\[ IRI(J,2) = \frac{VLB}{(RL + ZRA)} \]
\[ IRI(J,3) = \frac{VLB}{(RL + ZRA)} \]

**Where:**
- \(VLB\) = Regulator Output Voltage at Zero Current - Volts
- \(ZRA\) = Regulator impedance in "Active" region - Ohms
- \(VLB = VLBT(VRI, TTPCD)\)
- \(ZRA = ZRAT(TTPCD)\)

**Where:**
- \(VLBT\) = Input Table of \(VLB\) as a function of \(VRI\) and \(TTPCD\)
- \(ZRAT\) = Input Table of \(ZRA\) as a function of \(TTPCD\)

---

Step 23  Increment Counter and Lamp Regulator Voltage and Compare with Reference

\[ J = J + 1 \]
\[ VRI(J) = VRI(J - 1) + VINCIV \]

**IF:** \(VRI(J) > VMAXIV\)

**THEN:** Go to Step 32

REPEAT STEPS 22 AND 23
Step 24 Initialize Counter and Lamp Regulator Voltage

\[ J = 1 \]

\[ VRI(J) = VMINIV \]

Step 25 Calculate Lamp Regulator Currents

\[ IRI(J,1) = 0.0 \]

\[ IRI(J,2) = \frac{(VRI(J) - VR10)}{(RL + ZRS)} \]

\[ IRI(J,3) = \frac{(VRI(J) - VR10)}{(KL + ZRA)} \]

Step 26 Increment Counter and Lamp Regulator Voltage and Compare with Reference

\[ J = J + 1 \]

\[ VRI(J) = VRI(J - 1) + VINCIV \]

IF: \( VRI(J) > VRISA \) and

IF: \( VRI(J) < VMAXIV \)

THEN: GO TO STEP 27

IF: \( VRI(J) > VMAXIV \)

THEN GO TO STEP 32

REPEAT STEPS 25 AND 26

Step 27 Calculate Lamp Regulator Currents

\[ IRI(J,1) = 0.0 \]

\[ IRI(J,2) = \frac{VLB}{(RL + ZRA)} \]

\[ IRI(J,3) = \frac{VLB}{(KL + ZRA)} \]
**Step 28** Increment Counter and Lamp Regulator Voltage and Compare with Reference

\[ J = J + 1 \]

\[ VRI(J) = VRI(J - 1) + VINCIV \]

IF: \[ VRI(J) > VMAXIV \]

THEN: GO TO STEP 32

REPEAT STEPS 27 AND 28

**Step 29** Initialize Counter and Lamp Regulator Voltage

\[ J = 1 \]

\[ VRI(J) = VMINIV \]

**Step 30** Calculate Lamp Regulator Currents

\[ IRI(J,1) = 0.0 \]

\[ IRI(J,2) = \frac{VLB}{(RL + ZRA)} \]

\[ IRI(J,3) = \frac{VLB}{(RL + ZRA)} \]

**Step 31** Increment Counter and Lamp Regulator Voltage and Compare with Reference

\[ J = J + 1 \]

\[ VRI(J) = VRI(J - 1) + VINCIV \]

IF: \[ VRI(J) > VMAXIV \]

THEN: GO TO STEP 32

REPEAT STEPS 30 AND 31
Step 32  Calculate PCD Group Current

\[ X_{I}(J,K) = I_{HI}(J) + I_{RI}(J,K) \]
\[ I_{HI}(J) = I_{HIT}(V_{RI}(J), T_{TPCD}) \]

\[ J = 1, 50 \]
\[ K = 1, 3 \]

Where: \( X_{I}(J,K) = \) PCD Group Current - Amperes
\( I_{HI}(J) = \) Housekeeping Load Regulator Input Current - Amperes
\( I_{HIT} = \) Input Table of \( I_{HI}(J) \) as a function of \( V_{RI}(J) \) and \( T_{TPCD} \)

Step 33  Calculate PCD Group Voltage

\[ X_{V}(J,K) = V_{RI}(J) + X_{I}(J,K) \times R_{LL} \]

\[ J = 1, 50 \]
\[ K = 1, 3 \]

Where: \( X_{V}(J,K) = \) PCD Group Voltage - VDC
5. **MERGE**

The MERGE program set is a group of computer programs (TDF14, DECK280, and LISTMERGE) which provide a support function to the DSPA program. The purpose of the MERGE package is to provide a means for extracting actual weather information from NOAA data tapes and using it as input to the DSPA program. The three MERGE programs and their functions are described below.

![Diagram of MERGE program flow](image)

**FIGURE 5-1. MERGE COMPUTER PROGRAMS OVERVIEW**

5.1. **Creation of a MERGE File (TDF14)**

The building of the skeletal MERGE file is controlled by the TDF14 program. The user requests the creation of a MERGE file to span a particular period of years for a selected location from a NOAA TDF-14 weather tape. The TDF14 program then extracts the date, temperature, and wind velocity data from the NOAA tape, builds a one-day record consisting of 24 hourly observations of temperature and wind velocity and space for solar insolation, and sequentially writes the day's information to a MERGE file.
FIGURE 5-2. TDF14 COMPUTER PROGRAM

PROGRAM ALGORITHMS

Step 1  Obtain one day's weather data from TDF-14 input tape

Step 2  Convert TDF-14 data to numerics (DECODE)

Step 3  Write MERGE file record

Step 4  If: end of TDF-14 tape,
          Then: Stop Program
          Otherwise: Go TO STEP 1

5.2 Addition of Solar Insolation Data to MERGE File (DECK280)

The addition of solar insolation data to a MERGE file created by TDF14 is performed by the DECK280 program. The user requests that, for a particular MERGE location, NOAA DECK-280 tape data from a specified location be inserted into the file. The DECK280 program extracts the solar radiation data (in Langley's) from the NOAA tape, converts the data to watts/square meter, and adds the data to the appropriate day and hour position in the MERGE file.
FIGURE 5-3. DECK280 COMPUTER PROGRAM

PROGRAM ALGORITHMS

Step 1 Obtain solar radiation data from DECK-280 input tape

Step 2 Convert DECK-280 data to numerics (DECODE)

Step 3 Convert DECK-280 data to watts/square meter

\[
Q = S \times \frac{41.82}{3.6}
\]

where: \( S = \) Solar Insolation - Langleys

\( Q = \) Solar Insolation - watts/meter^2

Step 4 Add solar insolation data to appropriate day and hour in MERGE file

Step 5 If: end of Deck-280 tape,
Then: Stop Program
Otherwise: GO TO STEP 1

5.3 Displaying MERGE File Data (LISTMERGE)

The average MERGE file consists of from 10 to 12 years of hourly temperature, wind velocity, and solar insolation data recordings. The LISTMERGE program permits the user to randomly view any number of sequential days within the file beginning at any date contained in the file.
**FIGURE 5-1. LISTMERGE COMPUTER PROGRAM**

**PROGRAM ALGORITHMS**

- **Step 1**: Obtain user request date (YYDDD) and number of days to be displayed (N)
- **Step 2**: Initialize day counter
  \[ I = 1 \]
- **Step 3**: Obtain MERGE record for day YYDDD
- **Step 4**: Print MERGE record information
- **Step 5**: If: last day of MERGE file,
  Then: Stop Program
  Otherwise, if: \( I > N \),
  Then: Go to Step 1
  Otherwise: \( I = I + 1 \)
- **Step 6**: Increment request date
  \[ YYDDD = YYDDD + 1 \]
Step 7  If:  DDD > 366
       Then:  YY = YY + 1
       Then:  DDD = 1

Step 8  GO TO STEP 3
6. **STAT**

The STAT program set is a group of computer programs (STATS and PROFILE) which provide a support function to the DSPA program. The purpose of the STAT package is to provide a means of producing a single year of statistical data from a MERGE file, and using it as input to the DSPA program. The two STAT programs and their functions are described below.

![FIGURE 6-1. STAT COMPUTER PROGRAMS OVERVIEW](image)

6.1 **Statistical Analysis of MERGE File Data (STATS)**

The STATS program uses the 10 to 12 years of MERGE file weather data to produce a one-year statistical file. The procedure involves the averaging of data for a given hour of a given day of each of the years contained in the MERGE file. The statistical data is then written to a STATS file which is used as input to the PROFILE program (see Section 6.2 below). Specifically, the STATS program computes and outputs (both to the STATS file and to a printer) the following statistics:

1a) Average temperature for each hour of one year.
1b) Average wind velocity for each hour of one year.
1c) Average solar insolation for each hour of one year.
2a) Average wind velocity for each day of each data year.
2b) Average solar insolation for each day of each data year.
3a) Average wind velocity for each day of one year.
3b) Average solar insolation for each day of one year.
4a) Average temperature for each month of each data year.
4b) Average wind velocity for each month of each data year.
4c) Average solar insolation for each month of each data year.
5a) Average temperature for each month of one year.
5b) Average wind velocity for each month of one year.
5c) Average solar insolation for each month of one year.
6a) Standard deviation of statistics gathered in 4a.
6b) Standard deviation of statistics gathered in 4b.
6c) Standard deviation of statistics gathered in 4c.
7a) Maximum temperature for each year.
7b) Minimum temperature for each year.
8a) Mean and standard deviation of statistics gathered in 7a.
8b) Mean and standard deviation of statistics gathered in 7b.

PROGRAM ALGORITHMS

**Step 1** Initialize yearly minimum and maximum temperatures

\[
\text{TMIN}(J) = 1000.0 \\
\text{TMAX}(J) = -1000.0 \\
\text{for } J = 1, 12
\]

**Step 2** Initialize monthly sums for each year

\[
\text{MTSUM}(J) = 0.0 \\
\text{MVSUM}(J) = 0.0 \\
\text{MQSUM}(J) = 0.0 \\
\text{for } J = 1, 12
\]

*where:* \(\text{MTSUM}(J)\) = monthly temperature total for year \(J\)
\(\text{MVSUM}(J)\) = monthly wind velocity total for year \(J\)
\(\text{MQSUM}(J)\) = monthly solar insolation total for year \(J\)
Figures 6-2 and 6-3
Step 3  Initialize daily sums for each year

\[
\begin{align*}
DVSUM(J) &= 0.0 \\
DQSUM(J) &= 0.0 \\
\text{for } J=1, 12 \\
\text{where: } DVSUM(J) &= \text{daily wind velocity total for year } J \\
DQSUM(J) &= \text{daily solar insolation total for year } J
\end{align*}
\]

Step 4  Obtain hourly temperature, wind velocity, and solar insolation data for same day of each MERGE year \((\text{NYRS} \leq 12)\)

\[
\begin{align*}
T(I,J) &= \text{temperature for hour } I \text{ of year } J \\
V(I,J) &= \text{wind velocity for hour } I \text{ of year } J \\
Q(I,J) &= \text{solar insolation for hour } I \text{ of year } J
\end{align*}
\]

Step 5  Initialize hour counter

\[ I = 1 \]

Step 6  Initialize hourly sums

\[
\begin{align*}
TSUM &= 0.0 \\
VSUM &= 0.0 \\
QSUM &= 0.0 \\
\text{where: } TSUM &= \text{hourly temperature total over all years} \\
VSUM &= \text{hourly wind velocity total over all years} \\
QSUM &= \text{hourly solar insolation total over all years}
\end{align*}
\]

Step 7  Initialize year counter

\[ J = 1 \]

Step 8  Add hour's data to sums

\[
\begin{align*}
TSUM &= TSUM + T(I,J) \\
VSUM &= VSUM + V(I,J) \\
QSUM &= QSUM + (Q(I,J) \\
DVSUM(J) &= DVSUM(J) + V(I,J) \\
DQSUM(J) &= DQSUM(J) + Q(I,J) \\
MTSUM(J) &= MTSUM(J) + T(I,J) \\
MVSUM(J) &= MVSUM(J) + V(I,J) \\
MQSUM(J) &= MQSUM(J) + Q(I,J)
\end{align*}
\]
<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
</table>
| 9    | Select minimum and maximum temperatures  

\[
\text{TMIN}(J) = \text{AMIN1}(\text{TMIN}(J), T(I,J)) \\
\text{TMAX}(J) = \text{AMAX1}(\text{TMAX}(J), T(I,J))
\]  

| Step 10 | If: J = NYRS  
Then: GO TO STEP 11  
Otherwise: J = J + 1  
And: GO TO STEP 8 |

| Step 11 | Compute hourly statistics  
TOUT(I) = TSUM/NYRS  
VOUT(I) = VSUM/NYRS  
QOUT(I) = QSUM/NYRS  
where: TOUT(I) = average temperature for hour I  
VOUT(I) = average wind velocity for hour I  
QOUT(I) = average solar insolation for hour I |

| Step 12 | If: I = 24  
Then: GO TO 13  
Otherwise: I = I + 1  
And: GO TO STEP 6 |

| Step 13 | Compute daily statistics for each year  
VDAY(J) = DVSUM(J)/(24 * NYRS)  
QDAY(J) = DQSUM(J)/(24 * NYRS)  
for J = 1, NYRS  
where: VDAY(J) = average wind velocity for given day of year J  
QDAY(J) = average solar insolation for given day of year J |

| Step 14 | Write statistical day record to STATS file |

| Step 15 | If: last day of month  
Then: GO TO STEP 16  
Otherwise: GO TO STEP 3 |
Step 16  Compute monthly statistics for each year

\[
\begin{align*}
TOUT(J) &= \frac{MTSUM(J)}{(24 \cdot NYRS \cdot NDYS)} \\
YOUT(J) &= \frac{MVSUM(J)}{(24 \cdot NYRS \cdot NDYS)} \\
QOUT(J) &= \frac{MQSUM(J)}{(24 \cdot NYRS \cdot NDYS)} \\
\end{align*}
\]

for \( J = 1, NYRS \)

where:  
\( TOUT(J) = \) average temperature for given month of year \( J \)  
\( YOUT(J) = \) average wind velocity for given month of year \( J \)  
\( QOUT(J) = \) average solar insolation for given month of year \( J \)  
\( NDYS = \) number of days in current month

Step 17  Compute mean monthly statistics and standard deviations

\[
\begin{align*}
XOUT(13) &= \frac{\sum_{J=1}^{NYRS} \frac{XOUT(J)}{NYRS}}{NYRS} \\
XOUT(14) &= \sqrt{\left( \frac{\sum_{J=1}^{NYRS} XOUT(J)^2}{NYRS} - \frac{NYRS \left( \sum_{J=1}^{NYRS} XOUT(J) \right)^2}{NYRS^2} \right) / (NYRS - 1)} \\
\end{align*}
\]

where:  
\( XOUT \) is used to represent each of the \( TOUT, YOUT, \) and \( QOUT \) variables since the equations are of the same form for each

Step 18  Write statistical month record to STATS file

Step 19  If:  last day of year  
Then:  GO TO STEP 20  
Otherwise:  GO TO STEP 2
Step 20  Compute mean TMIN and TMAX and standard deviations

\[ TOUT(1) = \sum_{J=1}^{NYRS} \frac{TMIN(J)}{NYRS} \]

\[ TOUT(2) = \sqrt{\left( \sum_{J=1}^{NYRS} TMIN(J)^2 - NYRS \left( \sum_{J=1}^{NYRS} TMIN(J) \right)^2 \right)} / (NYRS-1) \]

\[ TOUT(3) = \sum_{J=1}^{NYRS} \frac{TMAX(J)}{NYRS} \]

\[ TOUT(4) = \sqrt{\left( \sum_{J=1}^{NYRS} TMAX(J)^2 - NYRS \left( \sum_{J=1}^{NYRS} TMAX(J) \right)^2 \right)} / (NYRS-1) \]

Step 21  Write yearly statistical data to STATS file

Step 22  Stop Program
6.2 Environmental Profiling of STATS Data (PROFILE)

The PROFILE program uses the one year of statistically prepared STATS data to produce a modified statistical file for use with the DSPA program. The procedure involves the scaling of the STATS file data, on a monthly basis, by factors computed from user-specified proportions and confidence levels. In addition, the PROFILE program will, upon request, perform a worst case analysis for low solar insolation, low wind, or high wind periods. The revised weather data is written to a STAT file for subsequent use as input to the DSPA program.

![Flowchart of PROFILE Computer Program]

**FIGURE 6-3. PROFILE COMPUTER PROGRAM**
PROGRAM ALGORITHMS

Step 1 Read monthly user input request

ALPHAQ = confidence level (0 to 1) for solar insolation data
ALPHAT = confidence level (0 to 1) for temperature data
ALPHAV = confidence level (0 to 1) for wind velocity data
ALPHHV = confidence level (0 to 1) for high wind worst case
ALPHLQ = confidence level (0 to 1) for low insolation worst case
ALPHLV = confidence level (0 to 1) for low wind worst case
LH(1) = temperature flag: -1 = low profile
        0 = means profile
        +1 = high profile
LH(2) = wind velocity flag (-1, 0, or +1)
LH(3) = solar insolation flag (-1, 0, or +1)
LH(4) = low insolation flag: 0 = no worst case analysis
        +1 = worst case analysis
LH(5) = low wind flag (0 or +1)
LH(6) = high wind flag (0 or +1)
PHV = scale factor (>1) for high wind worst case
PLQ = scale factor (0 to 1) for low insolation worst case
PLV = scale factor (0 to 1) for low wind worst case
PQ = proportion (0 to 1) for solar insolation data
PT = proportion (0 to 1) for temperature data
PV = proportion (0 to 1) for wind velocity data

Step 2 Compute tolerance limit factors
ZA = F(A,ZTABLE)
ZP = F(P,ZTABLE)
AL = 1.0 - ZA**2/(2.0*(NYRS - 1))
BL = ZP**2 - ZA**2/NYRS
CL = (ZP + SQRT(ZP**2 - AL*BL))/AL
for each of CLT, CLV, and CLQ
where:  
A = specified confidence level  
P = specified proportion  
ZTABLE = table of inverse error function vs. percent  
CLT = temperature tolerance limit factor  
CLV = wind velocity tolerance limit factor  
CLQ = solar insolation tolerance limit factor

Step 3  
Compute low/high delta/scale factors

DLHT = LH(1) * CLT * TM(2)  
RLHV = 1.0 + LH(2) * CLV * VM(2)/VM(1)  
RLHQ = 1.0 + LH(3) * CLQ * QM(2)/QM(1)  

where:  
DLHT = temperature delta factor  
RLHV = wind velocity scale factor  
RLHQ = solar insolation scale factor  
TM(2) = monthly temperature standard deviation  
VM(1) = average monthly wind velocity  
VM(2) = monthly wind velocity standard deviation  
QM(1) = average monthly solar insolation  
QM(2) = monthly solar insolation standard deviation

Step 4  
Read next STATS file day

T(I) = temperature for hour I  
V(I) = wind velocity for hour I  
Q(I) = solar insolation for hour I  
for I = 1,24

Step 5  
Modify STATS data

T(I) = DLHT + T(I)  
V(I) = RLHV * V(I)  
Q(I) = RLHQ * Q(I)

Step 6  
Write modified day's data to STAT file
Step 7  
If: last day of month  
Then: GO TO STEP 8  
Otherwise: GO TO STEP 4

Step 8  
If: worst case analysis requested  
Then: GO TO STEP 9  
Otherwise: GO TO STEP 13

Step 9  
Compute Poisson maximum likelihood estimate  
\[ \Lambda = \frac{\text{SUM} - \text{CNT}}{\text{CNT}} \]  
for each of high wind, low wind, and low insolation

where: \( \Lambda \) = maximum likelihood estimate  
SUM = total number of bad* days for current month  
CNT = number of strings of bad days for current month

Step 10  
Compute number of sequential worst case days for current month

\[ \sum_{J=1}^{\Lambda} \frac{\Lambda^J}{J!} \]  
NR such that \( \frac{\sum_{J=1}^{\Lambda} \frac{\Lambda^J}{J!}}{\text{NDYS}} \geq \text{confidence level} \]

for each NRHV, NRLQ, NRLV

where: NDYS = number of days in current month  
NRHV = number of sequential high wind worst case days to be centered about the 20th day  
NRLQ = number of sequential low insolation worst case days to be centered about the 15th day  
NRLV = number of sequential low wind worst case days to be centered about the 10th day

*A bad day is a day for which \((Q < PLQ^* \ Q_{avg. \ for \ month})\)
Step 11  Modify worst case day's data for appropriate days of current month.

\[ V(I) = PLV \times V(I) \] for low wind period
\[ Q(I) = PLQ \times Q(I) \] for low insolation period
\[ V(I) PHV \times V(I) \] for high wind period

Step 12  Re-write worst case days to STAT file

Step 13  If: last day of year
Then:  GO TO STEP 14
Otherwise: TO TO STEP 1

Step 14  Stop Program