5.1. Power Subsystem.

The power subsystem on the IUE spacecraft is a direct energy transfer (DET) system. The primary source of power is the spacecraft solar array which consists of two deployable paddles mounted to the spacecraft structure. Power from the solar paddles is transferred directly to the spacecraft bus which is regulated at +28.0 volts ±2%. The lack of any series elements between the solar array and the spacecraft loads provides for a transfer of array power to the loads at nearly 100 percent efficiency. Power during solar eclipses and other periods when demand exceeds solar array output is provided by two 6 ampere-hour nickel-cadmium batteries through a boost regulator. The power supply electronics (PSE) is of modular design and consists of two power modules operating in unison through a mission adapter module (MAM). The PSE conditions the outputs from the two power sources, the solar array and the batteries, at +28.0 volts ±2%.

Three modes of operation had been defined, depending on the available solar array power and the spacecraft load requirements, which are referred to as power positive, power negative and power neutral.

- Power positive. The solar array power is greater than the spacecraft load. In this case, the PSE will first provide battery charge current and then dump the excess array power through the use of dump resistors attached to shear panels that are located on the antisun side of the spacecraft.

- Power negative. The spacecraft load exceeds the solar array output, so the difference in power will be supplied by discharging the batteries through the boost regulator.

- Power neutral. The spacecraft load is equal to the solar array power. In this case, the PSE will be in a non desirable mode called dead-band.

The IUE power subsystem was designed to support transfer and mission orbit operations during three years with a five year design goal. In order to assure this objective, the design was influenced by the following basic requirements: use of conventional solar conversion/energy storage system with proven design techniques, use of redundant units where necessary to assure maximum confidence in achieving design goal, standardization of basic subsystem functions for maximum commonality with other spacecraft design were required and inhibition of automatic switch over to redundant units because of reliability considerations.

5.1.1. Solar array.

The solar array was supplied by ESA with the design and development under the cognizance of the European Space and Technology Center (ESTEC). It is comprised of two rigid solar cell paddles with tree panels on each (one central panel, 70.5 cm X 54.8 cm, and two lateral panels, each 70.5 cm X 67.8 cm). The lateral panels are attached to opposite sides of the central panel with each lateral panel plane making a 45° angle with the central panel plane. In the launch configuration, the solar paddles were stowed wrapped around the spacecraft body. After IUE was transferred into geosynchronous orbit, they were deployed along the pitch (Y) axis, rotated, and locked at a 22.5° angle with respect to the spacecraft roll (X) axis. The plane of each array is perpendicular to the XZ plane of the spacecraft. The orientation of the spacecraft is controlled such that the sun is always in the XZ plane.

Each array panel has a honeycomb-type construction. There are 4980 2 cm x 2 cm silicon solar cells bonded to the array structure with silicon adhesive. The cells are 0.02 cm thick and have a resistivity of 1 ohm per centimetre. The cover glasses are 0.01 cm thick cerium-doped microsheet and provided protection for the cells against immediate catastrophic radiation damage. To improve wiring reliability and reduce the risk of a short circuit on the 28-volt main bus, it was found preferable to mount blocking diodes in the spacecraft. Multiple wires link the diode board to all subpanels, ensuring current equalization in the pins of the connectors. One single connector is used per paddle. Each paddle is also equipped with temperature sensors, although four of them failed soon after launch. This had no effect on spacecraft operations.

The current generated by the solar cells is affected on a temporary basis by solar illumination and temperature and, in a permanent way, by radiation damage.

- **Solar Illumination.**
  The illumination of the solar array is most directly influenced by the angle beta (angle between the sunline and the roll axis). So, the maximum output is at beta equal to 67.5° where the sunline is normal to the surface of the central panels.

  Also influencing the solar illumination of the array is the solar intensity, which follows a $1/r^2$ law based on the distance between the earth and the sun. The solar intensity is greatest in January when the earth is closest to the sun and least in July when the earth is farthest from the sun, as shown the figure 5-1.

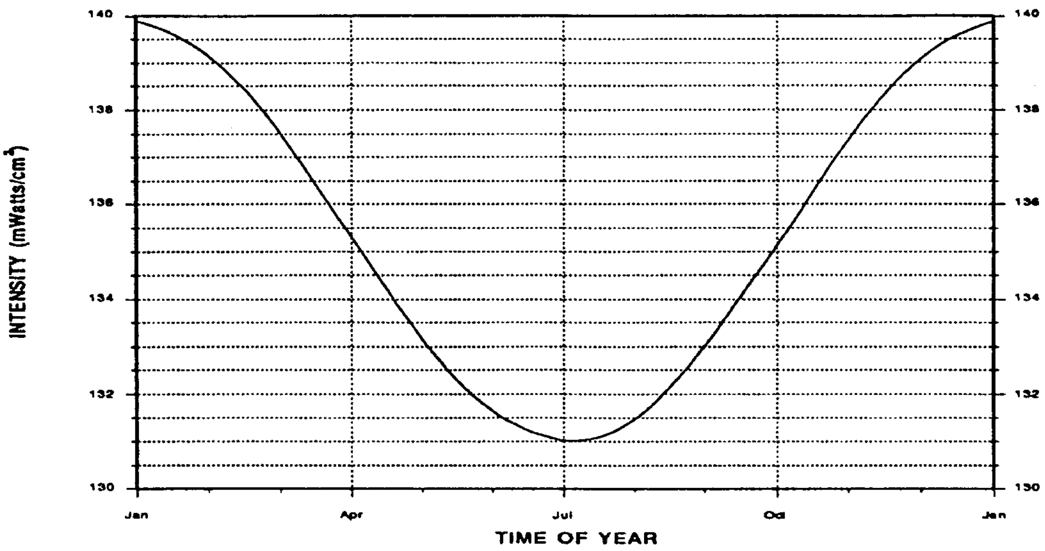

Figure 5-1. Solar Intensity vs. Time of Year.

- **Temperature.**
  The current and voltage characteristics of the solar array are influenced by temperature.

An increase in temperature causes a slight increase in cell current but a significant decrease in the voltage.

The figure 5-2 shows the data gathered while the temperature sensors were operational.

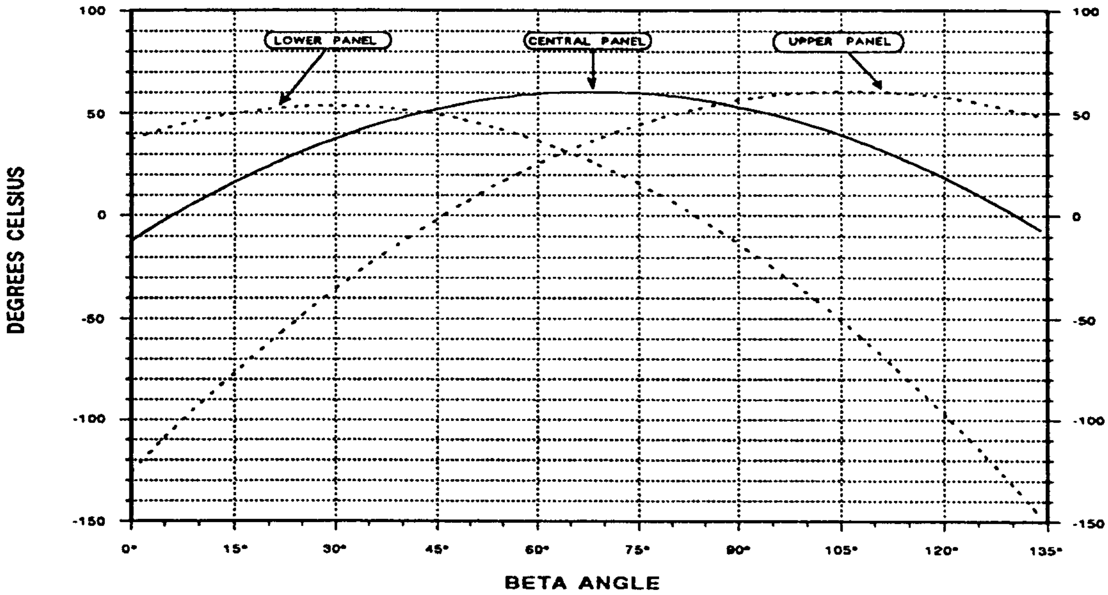

Figure 5-2. Solar Panel Temperatures.

Radiation Damage.

Solar radiation varies from year to year and has a great influence on the level of solar array degradation. For example, the solar cycle maximum around 1989 produced a 9.74% reduction in power output capability, measured from February 1990 to February 1989, while the average degradation produced between consecutive years until this date had been 2.8%.

The figure 5-3 shows a history of the solar array output from launch to the end of life. Raw data was collected in the allowable beta range for each year. An equation designed to take the geometrical design of the solar array into account was used to produce best fit values from the collected data, as the raw telemetry values had been proven to be inaccurate.

$$I_{SA} = I_t + s + v + 0.0086\,(I_s + s + v)$$

Where,

I_{SA} is the actual solar array output
I_t is the solar array current as read from telemetry
I_s is the spacecraft current as read from telemetry
s is 0, 0.014 or 0.028 amps depending on whether 0, 1, or 2 s-band transmitters are on
v is 0, 0.023 or 0.046 amps depending on whether 0, 1, or 2 transmitters are on

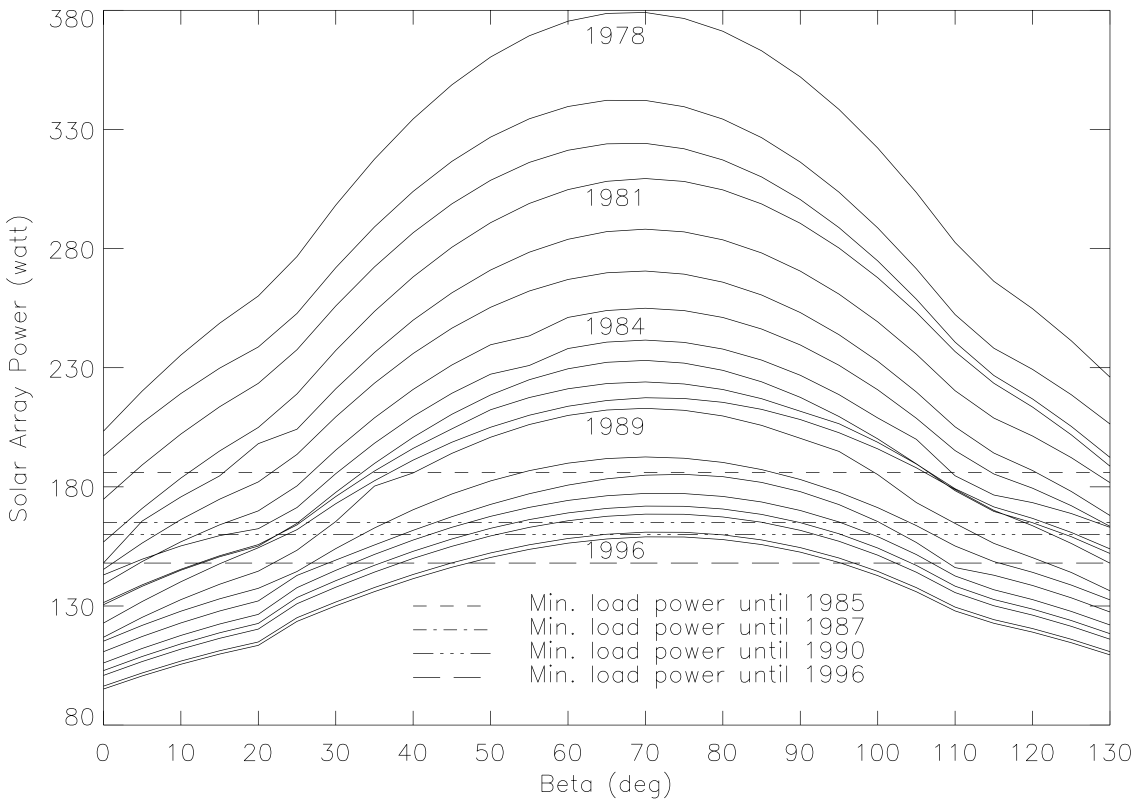

Figure 5-3. History of average solar array output.

The annual degradation computed at beta 67° is shown in the figure 5-4. The degradation has always been under the pre-launch expected value of 10% per year.

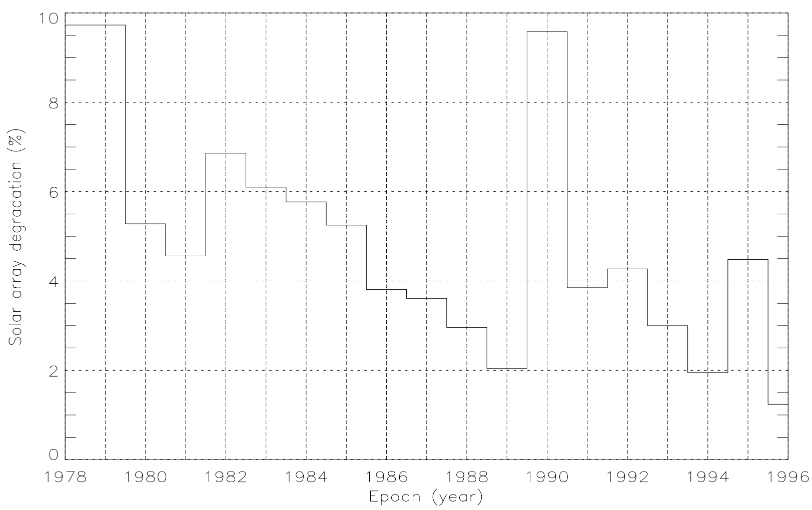

Figure 5-4. History of solar array degradation.

Solar array #1 has been producing slightly more than solar array #2 since launch, as shown in the figures 5-5 and 5-6 (this data was measured on September 29, 1996).

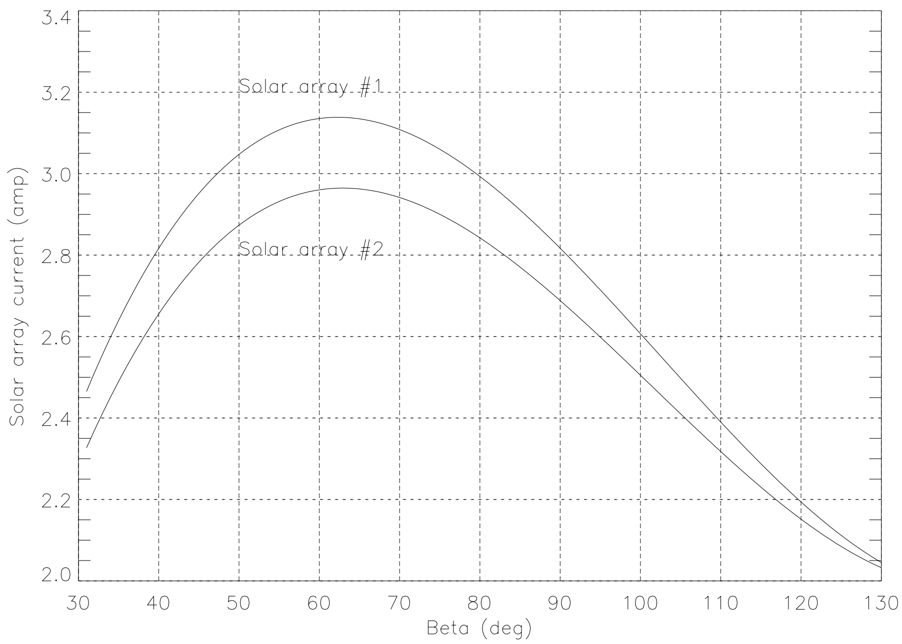

Figure 5-5. Solar array 1 and 2 output on September 29, 1996.

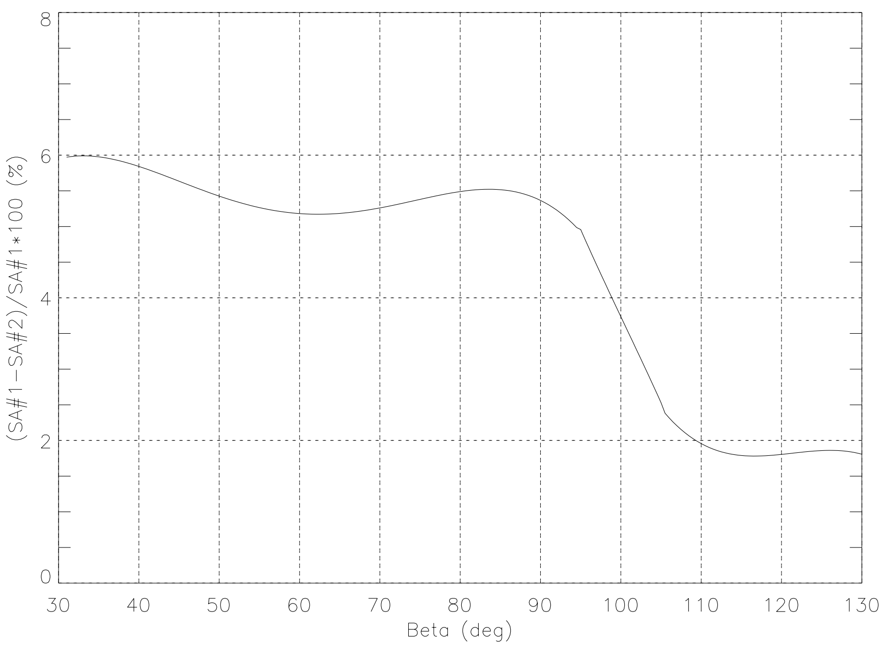

Figure 5-6. Comparison between solar array 1 and 2 vs. Beta.

5.1.1.1. Beta restrictions.

The operational beta range continually decreased from the beginning to the end of the spacecraft life due to power and thermal restrictions. The power positive beta range is defined as the beta range where the solar array current is greater than the spacecraft load. Along the IUE life, the spacecraft load was decreasing due to several changes in the control mode and the failure or degradation of several devices. The power positive beta ranges for each February and the average spacecraft load in the correspondent year are shown in the table below.

Year	Beta Range	S/C load (watt)
1978-1984	24° - 120°	186
1985	25° - 115°	186
1986	25° - 121°	165
1987	25° - 120°	165
1988	24° - 120°	160
1989	28° - 112°	160
1990	30° - 112°	160
1991	31° - 113°	148
1992	31° - 112°	148
1993	30° - 109°	148
1994	35° - 103°	148
1995	41° - 102°	148
1996	41° - 102°	148

5.1.1.2. Solar array EOL characterization.

The Solar Array Characterization was performed on the 29th of September in 1996, it was a part of the plan for the IUE End Of Life operations. The test consisted of collecting solar array current measurement while maneuvering the spacecraft from 31° to 130° beta angle. Throughout the life of IUE the solar array data has been collected only at the beta angles permitted during planned science operations, which has provided data points within a limited region (roughly 40° - 100°) centered on the power positive range of sun angles. In this EOL test the spacecraft supplied a more complete set of data which added the last values on the total radiation dosage experienced by the IUE. These data (shown in figure 5-7) provided a unique set for possible comparison to the current models of the radiation environment. The discontinuities at approximately beta 58° and 90° are caused by thermal variations experienced by the solar arrays resulting from the manner in which the spacecraft was maneuvered in collecting this data.

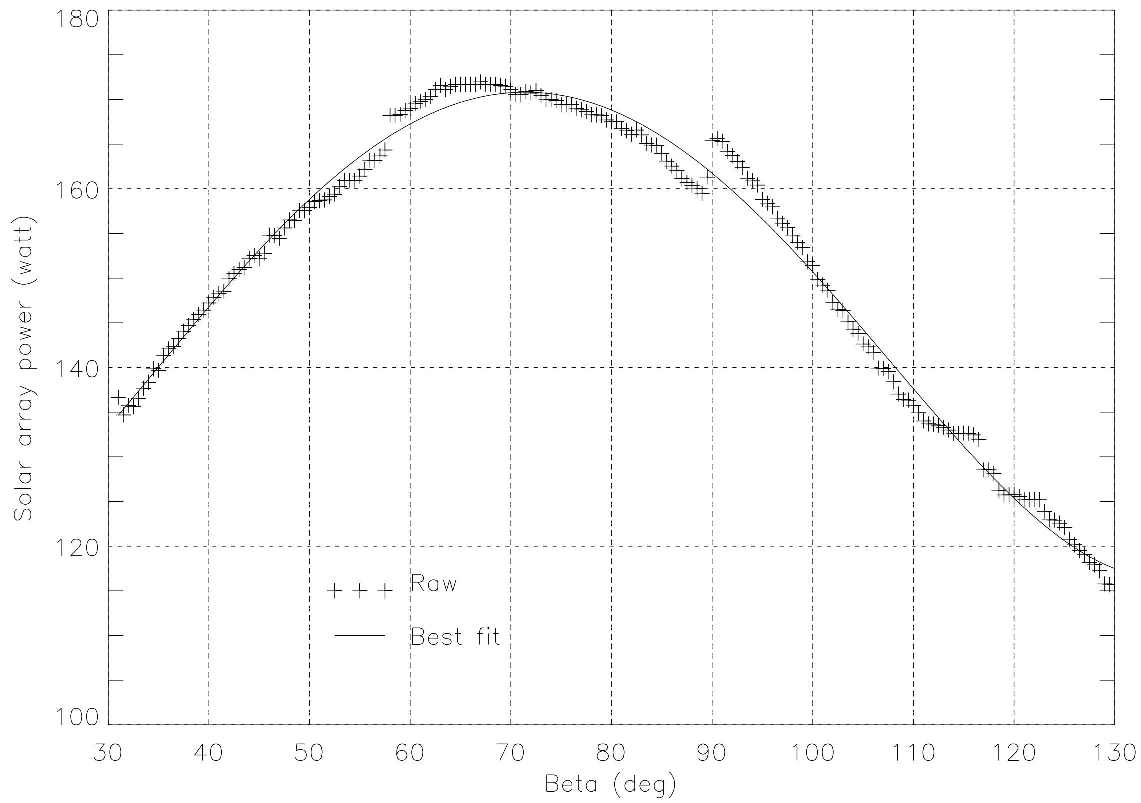

Figure 5-7. Solar array EOL characterization.

5.1.2. Batteries.

The IUE power subsystem uses two nickel-cadmium batteries interfaced through the mission adapter module in a parallel discharge/independent charge configuration. The batteries have 6 ampere-hour capacity and are used to power the essential loads during shadow periods, which occur during the equinox solar eclipse periods. The selection of nickel-cadmium batteries was based on the 3-year design life requirement (5-year design goal) and the demonstrated cycle capability under repetitive deep discharges. Each battery contains 17 series-connected cells and weighs 13.6 pounds. Each cell has both the positive and negative terminal insulated from the cell case to ensure maximum reliability. Each battery also contains one cell which incorporates a third electrode for overcharge control.

Temperature.

The IUE battery size was predicated on an average battery life temperature of 10° Celsius with variations during the 3 year life of ±10° Celsius. As shown in the figure 5-8, a temperature difference appeared between the two batteries and remained that way during the entire spacecraft life. Battery 1 was about 6° warmer than battery 2, which is less exposed to solar radiation than the first one.

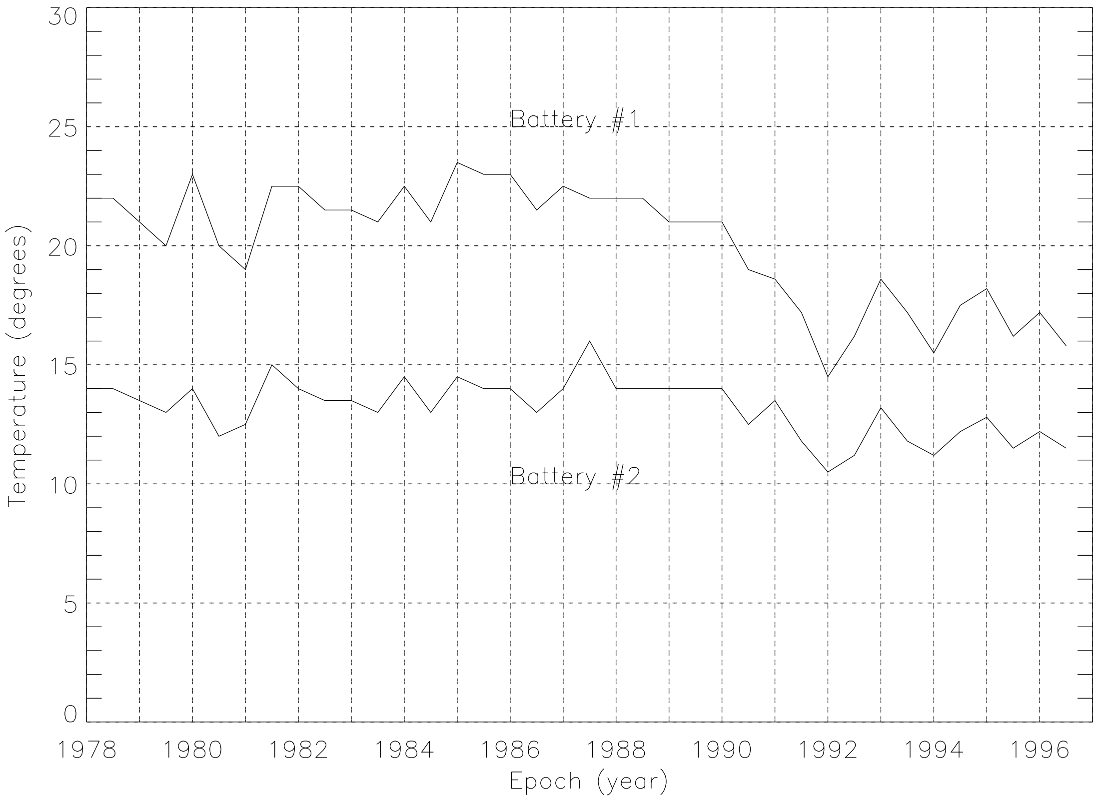

Figure 5-8. History of average temperature of the batteries.

Heat dissipation occurs from battery discharging and battery overcharging. For an average spacecraft load of 185 watts and a boost regulator efficiency of 90%, the dissipation will be approximately 18 watts per battery during discharge and about 3 watts per battery during overcharge.

Charge control.

Each battery is charged from the 28 volts bus through a series type charger. Charging is accomplished using a maximum current / maximum voltage limit concept. With a charge rate of 0.6 amperes, the battery recharge time following a 72 minutes eclipse would be approximately 11 hours. When not in shadow season, the batteries are charged at a much lower rate. This feature is accomplished by charging the battery from the 28 volts bus through one of two resistors, which can be selected by a command relay. These are the trickle-high or trickle-low modes.

At the beginning of the IUE life, battery charging at 0.6 amperes was maintained until the third electrode signalled the battery charger to begin reducing the rate of charge. Thereafter, charge rate was a function of third electrode voltage. In that way, the primary advantage gained was the reduction of battery thermal dissipation during the long periods when the spacecraft was power positive. During the shadow season 19 (January, 1987), the third electrode behaviour became erroneous and it was necessary to perform recharge independent of the third electrode. On February 22, 1990 the third electrode on battery 1 was turned off, and on March 19, 1990 the third electrode on battery 2 was also turned off.

Undervoltage and overcurrent protection.

Undervoltage protection is provided by two voltage detectors on each battery. One detector is connected to eight cells, the other is connected to nine cells. With the undervoltage detectors turned on, detection of an undervoltage condition (17 volts) on either battery would result in the automatic removal of all nonessential loads (everything but VHF receivers and command decoders).

The undervoltage detectors on both batteries were turned off on August 31,1983. As the batteries aged, there was an increasing probability that the capacity of one or more cells in the batteries would become depleted with the batteries in use under heavy load conditions.

There are also undervoltage (26.5 volts) and overcurrent (12 amperes) detectors on the main bus. At the end of the mission, only the overcurrent detector was on.

5.1.2.1. Battery 1 degradation.

The health of battery#1 came into question since the end of shadow season 26 in August, 1990. On May 25th, 1990, battery#1 had been already configured with the main charger on permanently, with the usual trickle-low mode reserved for over-voltage, over-temperature or under-charge conditions.

On August 26, the charge current dropped to 0.0 amperes and remained there, with the battery voltage at 24.72 volts, the charge current had been gradually decreasing for several months. The trickle-low charger was commanded on in an attempt to force some charge current into Battery 1. Within ten minutes the battery voltage had exceeded its redline limit of 25.84 volts and the main charger was commanded back on, discontinuing any charge current. The battery voltage returned to 24.72 volts, the maximum allowed by the main chargers. The rapid rise in battery voltage in response to the forced charge current indicated that the battery was fully charged and the main charger was operating correctly. The concern was that a lack of charge current can cause crystallization of the battery plates, impairing their performance. There was also the problem of forced charging producing hydrogen gas, possibly with enough pressure to rupture the battery case. To avoid any of these undesirable situations, a weekly charging routine was used to get some charge current into battery#1 without overcharging it. This operation was called top-off.

Top-off.

“Top-off” was called a procedure to ensure that full-charge on the batteries was maintained in the absence of the third electrode control. Top-off’s were performed weekly on battery 1.

The charge sequence consists of turning off the main charger, so the battery receives a low trickle charge. This charge, however, raises the battery voltage and must be removed before the voltage becomes too high (25.84 volts). Each charging sequence lasted on the order of minutes before this high battery voltage dictates that the charger be turned back on.

5.1.2.2. Battery EOL characterization.

A characterization of the batteries was desirable for comparison to pre-launch data on the batteries. This test was intended to determine the degradation of battery 1, determine the EOL capacity on battery 2, determine the charge efficiency of the batteries under various IUE charge control modes, determine the state of the third electrode and implement the lessons learned on the battery management of on-board UARS, EUVE, ERBS and TOPEX batteries.

The operations necessary to collect the desired battery data consisted basically of discharging the batteries each on an individual basis as well as together. The minimum voltages and depths of discharge reached are shown in the table below.

Day	Configuration	Duration (minutes)	Min. voltage (volt) Bat#1	Bat#2	D.O.D (%) Bat#1	Bat#2
26	Only Battery#2 ON	168 m	----------	18.0 v	---------	73.9 %
27	Only Battery#1 ON	180 m	18.0 v	----------	69.0 %	---------
28	Both Batteries ON	74 m	21.2 v	21.2 v	16.8 %	15.1 %
29	Both Batteries ON	114 m	20.6 v	20.6 v	26.7 %	26.1 %

5.1.3. Shadow.

Twice a year the IUE experienced a shadow season when the Earth moves between the spacecraft and the Sun. This “Shadow Season” lasted between 24 and 30 days, with the duration of the daily shadow varying from a few minutes up to a maximum of 82 minutes. The daily shadow consisted of two parts, penumbra and umbra. During penumbra or light shadow, the spacecraft was partially shielded from the Sun. During umbra or deep shadow, the spacecraft was completely shielded from the Sun by the Earth. Special consideration was given to spacecraft configuration and operations concerning temperatures and power loads during shadow periods. While in the umbra portion of shadow, the spacecraft was entirely dependent on its two 6 ampere-hour batteries for its power requirements.

The minimum load configuration during shadow seasons changed along the spacecraft life. Excessive use of the batteries accelerated the aging of the batteries considerably during the first eclipse seasons. Although, the battery design parameter indicated a maximum limit of 80% for the depth of discharge, it was evident, during the second shadow season, that the amount of power required from the batteries was excessive if the batteries were to survive more than five years. Therefore, it was decided to limit the depth of discharge to about 50 %. In order not to exceed this value, the load configuration during the eclipse periods was modified as is explained below.

- S-Band system off.
- PASs off.

- Science instrument heaters off.

- Until shadow season 4 the gyros 2, 4 and 6 were turned off for the duration of the eclipse season. After the third eclipse all attempts to restart gyro 6 failed, so, the decision was made not to turn the gyros off for eclipse seasons.
  After shadow season 4, Gyro 6 and its heater off; all Gyro heaters low.
  After shadow season 10, Gyro 2 and 6 off and their associated heaters off.
  After shadow season 13, Gyro 1, 2 and 6 off.
  After shadow season 26, Gyro heaters 4 and 5 on high, all other Gyro heaters off.
  At shadow season 38, Gyro 4 on, Gyro heaters 4 and 5 on high, heater 6 on low, all other gyro heaters off.

- After the shadow season 29 the FPM was turned off due to a failure. The SMSS, which was useful only during the launch phase of IUE, received power from the same relay as the FPM, thus it was also powered off.

- VHF on. After shadow season 5, the VHF was cycled on for 1 minute then off for 4 minutes when ever the depth of discharge was predicted to be greater than 50 %.

- SWP camera in standby mode.

- After shadow season 5, the long wavelength camera indicated as prime (LWP or LWR) was turned off, when the depth of discharge predicted exceeded 50 % except in shadow seasons 31, 33, 35 and 37.

- The OBC computer NO-OP instruction changed to HALT instruction from shadow season 5 to 29.
  After shadow season 18, two different modes of attitude control were used: FES Only mode, which consist of the FES tracking a guide star for pitch and yaw control and gyros for roll control, and a new mode called Shadtrack. This mode is a combination of two attitude control workers: worker 10 (hold on wheels) and worker 0 (hold/slew), the first one maintains the attitude control while worker 0 monitors the spacecraft drift in the pitch and yaw axes using the gyros. After shadow, control of the spacecraft attitude is returned to worker 0 which slews the spacecraft back to the original position by zeroing out the accumulated angular errors. When the predicted depth of discharge was to exceed 50 %, Shadtrack was used.
  After shadow season 28, a patch referred to as Automatic Worker 10 (AUTOW10) was uplinked to prevent a complete loss of attitude control in the event that track was unexpectedly broken during the daily shadow period. If a loss of star presence causes track to be broken, with the AUTOW10 code in line and activated control is immediately and automatically transferred to the Shadtrack mode.
  After shadow season 29, the control with FES Only mode was improved by reducing the roll gain. This mode was used during the whole shadow.

The battery recharge policy was also redefined along the mission life. At the conclusion of eclipse season 18, battery#1's third electrode voltage reading began to steadily decline. Because of the erroneous readings the third electrode was no longer used to determine the charge state of the batteries. For the shadow season 19, the batteries were recharged to 115-120 % of the measured discharge. For the next shadow season (20), a manual recharge procedure was implemented. To ensure that the batteries were fully charged for the daily shadows, the amount of charge returned to the batteries was 130 % of the measured discharge. This method was followed in the next shadow seasons until shadow season 26. On May 25, 1990, the main charger on battery#1 was turned on and remained on permanently. Battery#2 was declared to be fully charged by achieving a predefined increase in the battery's temperature which was correlated to an approximate amount of recharge.

After shadow season 12, reconditioning of both batteries was observed. Battery reconditioning occurs when a battery is drained close its minimum capacity and then slowly recharged back to full capacity. The battery cells are rejuvenated during this process, thus, resulting in greater battery capacitance.

The next figures display several shadow parameters over the life of the IUE, such as the battery power sharing, the booster efficiency at minimum voltage, the maximum length of umbra, the temporal occurrence (the shadow season dates are also displayed in Appendix A), the spacecraft bus power during shadow minimum load configuration, the maximum depth of discharge and the battery voltage compared to the depth of discharge.

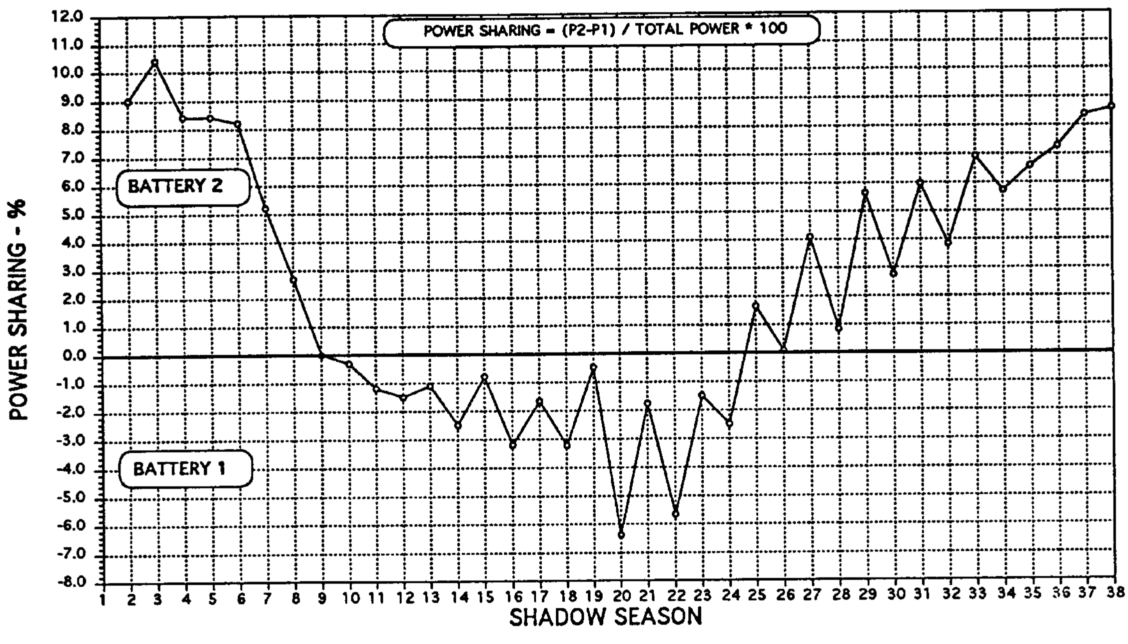

Figure 5-9. Average Battery Power Sharing vs. Shadow Season.

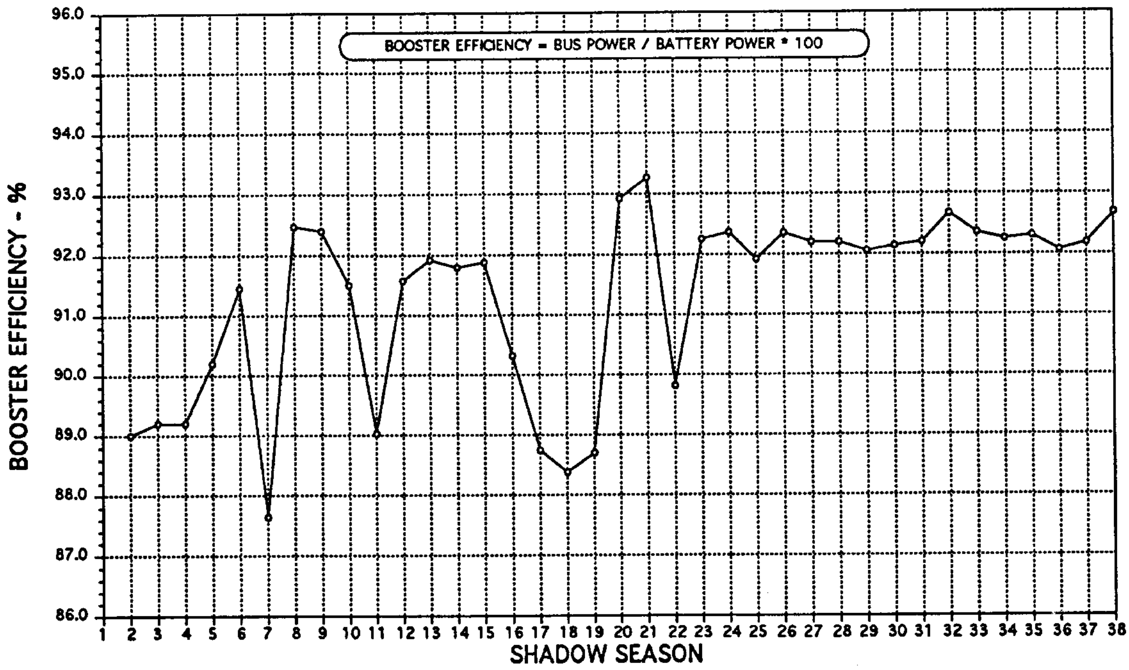

Figure 5-10. Average Booster Efficiency vs. Shadow Season.

Due to the variations in battery discharge current and spacecraft load current during the time of minimum voltage, an accurate calculation of booster was difficult. Beginning with shadow season 23 a new method that involves averaging these values during the duration of minimum voltage has been used.

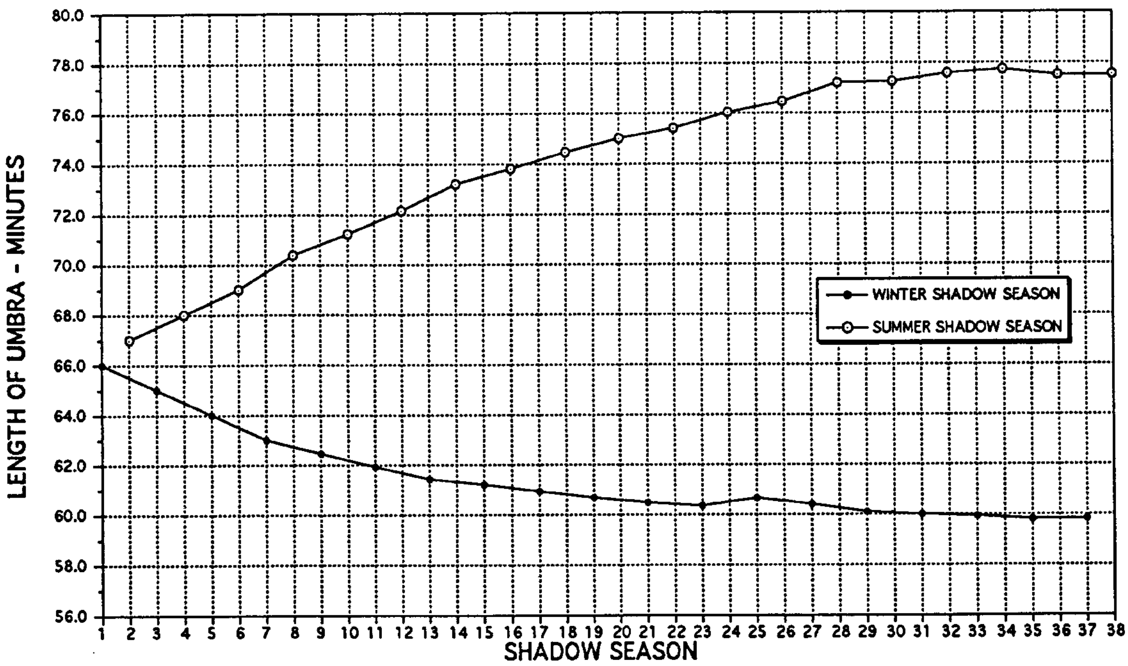

Figure 5-11. Maximum Umbra Length vs. Shadow Season.

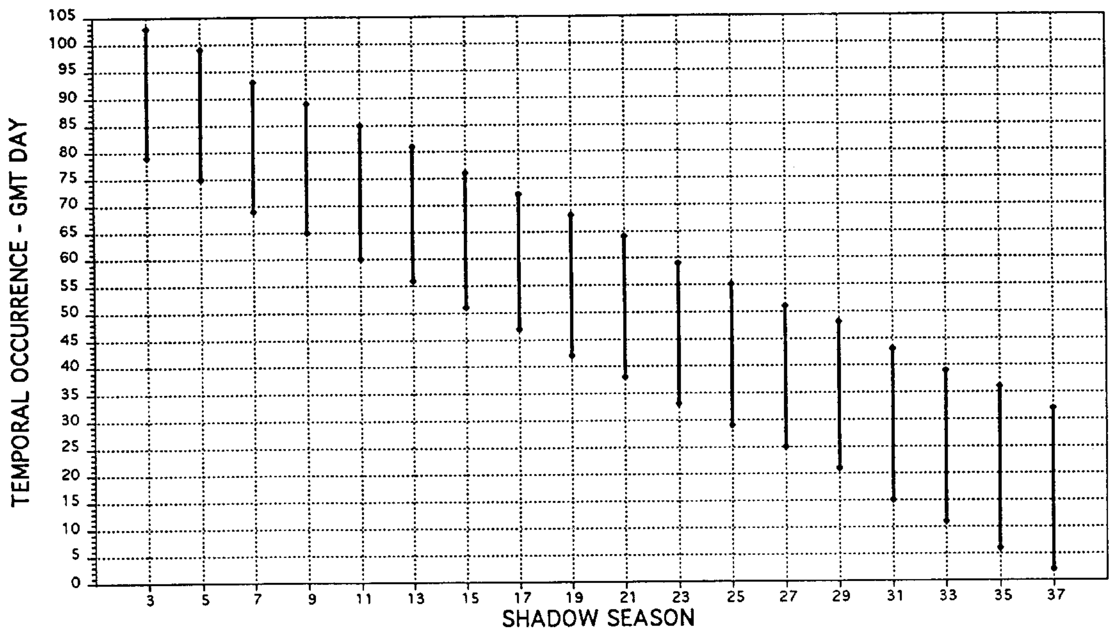

Figure 5-12. Winter Shadow Season Temporal Occurrence.

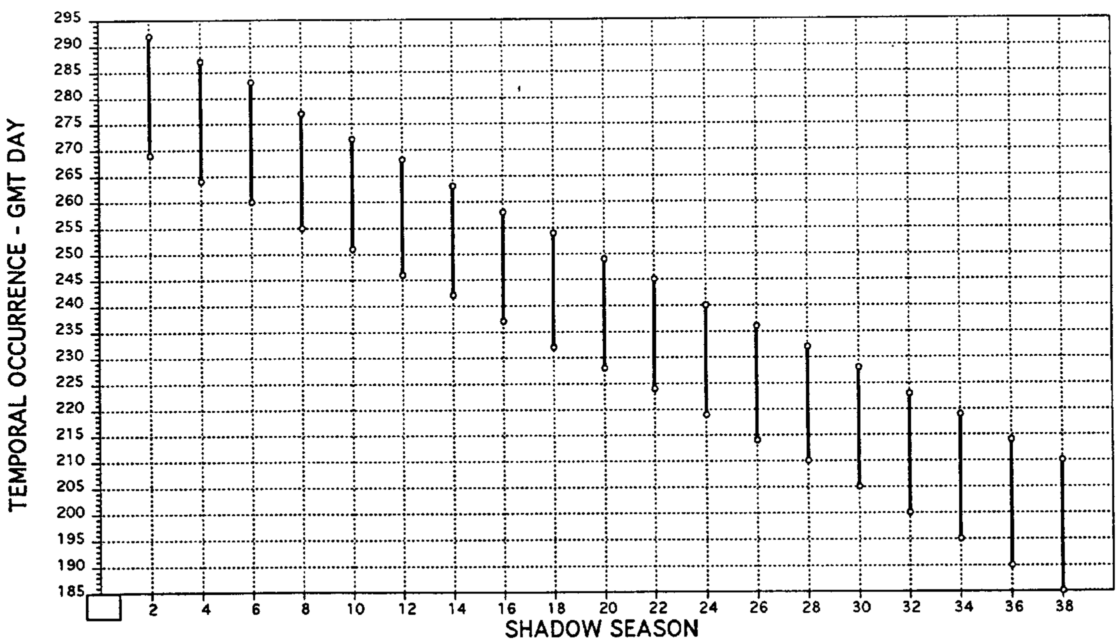

Figure 5-13. Summer Shadow Season Temporal Occurrence.

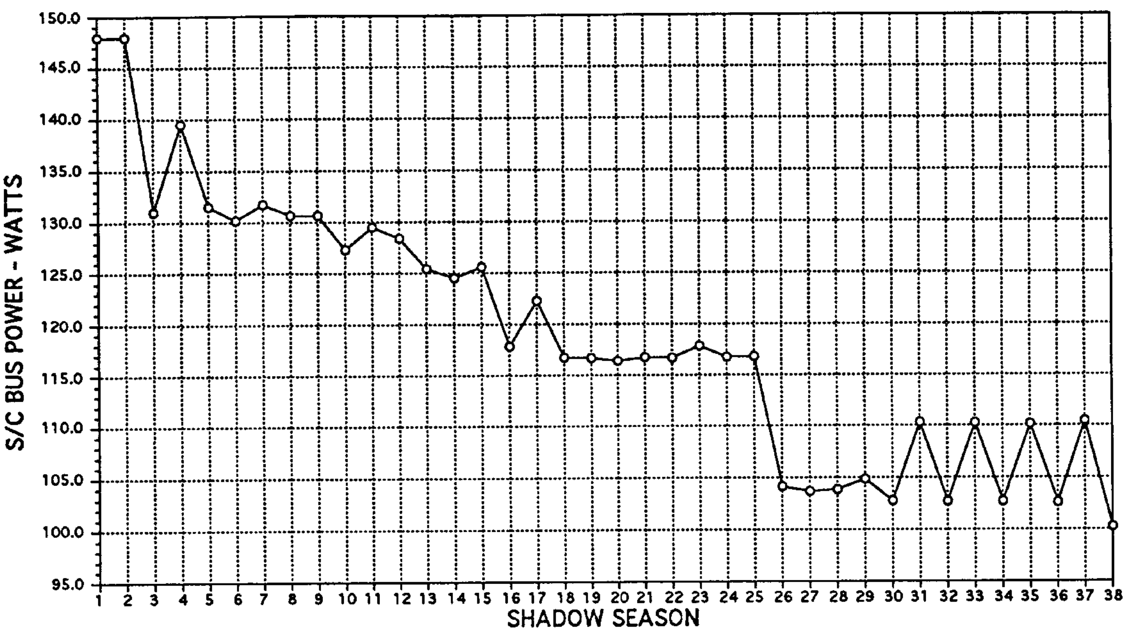

Figure 5-14. S/C Bus Power During Minimum Load vs. Shadow Season.

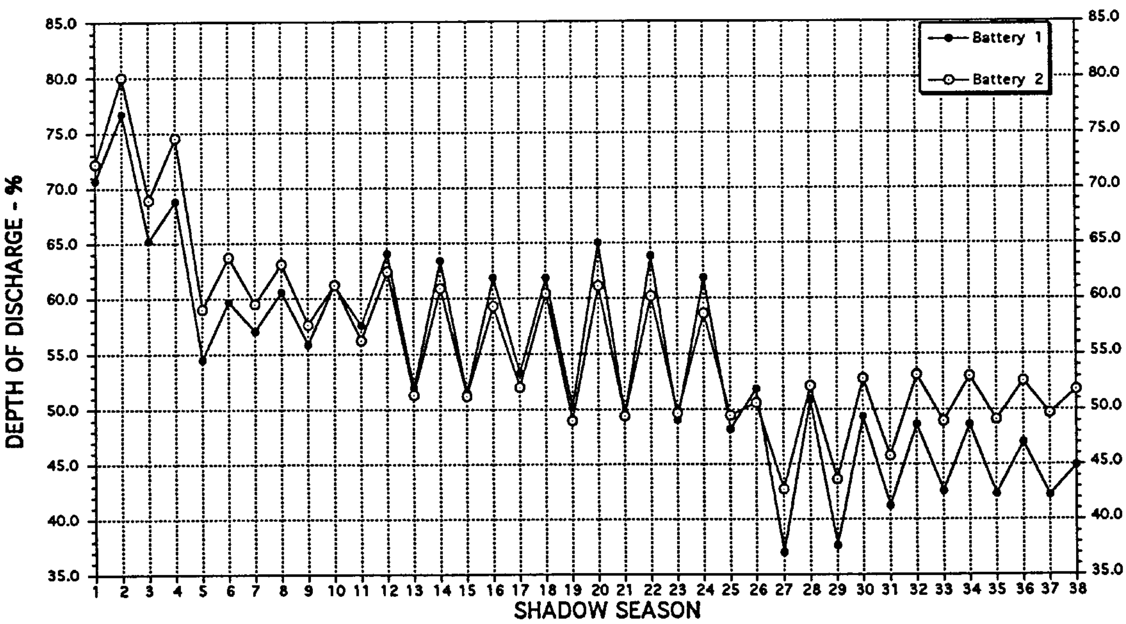

Figure 5-15. Maximum DOD vs. Shadow Season.

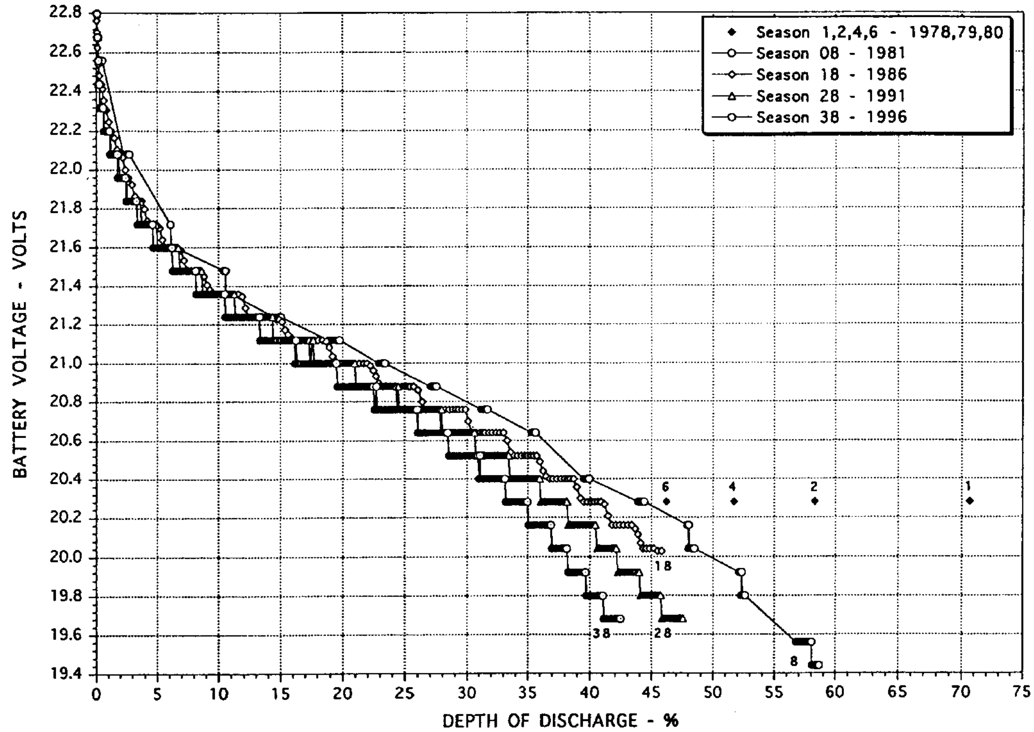

Figure 5-16. Battery 1 Voltage vs. DOD during Season 1-38.

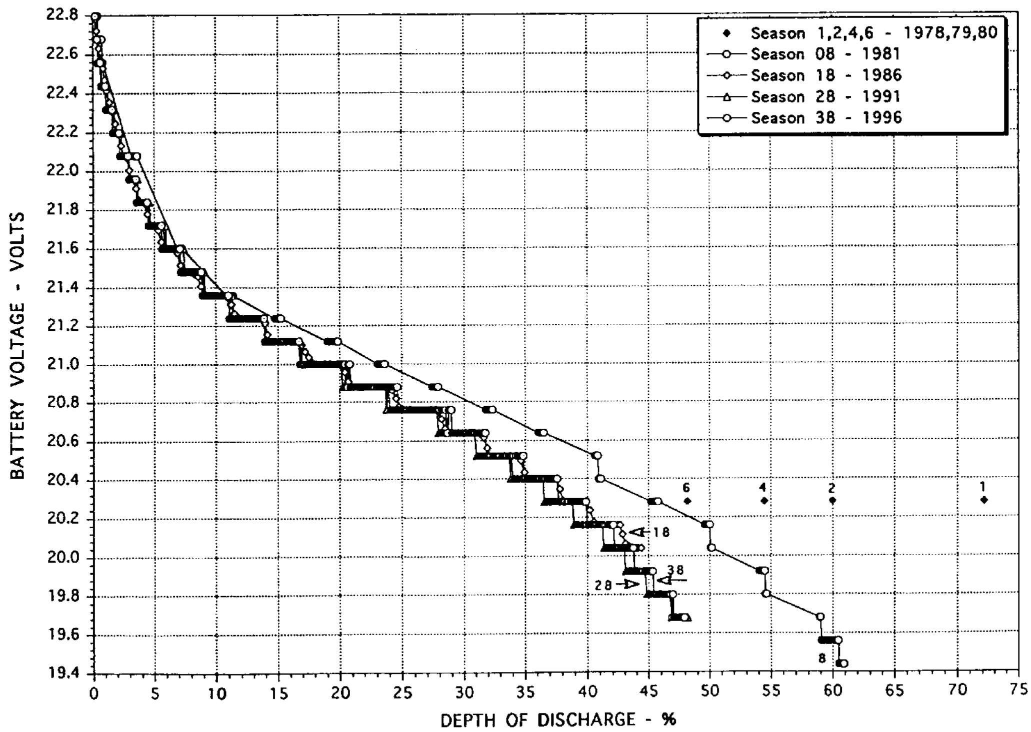

Figure 5-17. Battery 2 Voltage vs. DOD during Season 1-38.

Although the data sets for shadow seasons 1, 2, 4 and 6 were limited, the singles points are included in the figures to provide a complete image of the batteries performance.