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Instructor

Dr. Robert A. Nelson is president of Satellite Engineering Research Corporation, a consulting firm in

Bethesda, Maryland, with clients in both commercial industry and government. Dr. Nelson holds the degree of Ph.D. in physics from the University of Maryland and is a licensed Professional Engineer. He is coauthor of the textbook *Satellite Communication Systems Engineering, 2nd ed.* (Prentice Hall, 1993) and is Technical Editor of *Via Satellite magazine.* He is a member of IEEE, AIAA, APS, AAPT, AAS, IAU, and ION.

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Course Outline

1. Mission Analysis. Kepler's laws. Circular and elliptical satellite orbits. Altitude regimes. Period of revolution. Geostationary Orbit. Orbital elements. Ground trace.

2. Earth-Satellite Geometry. Azimuth and elevation. Slant range. Coverage area.

3. Signals and Spectra. Properties of a sinusoidal wave. Synthesis and analysis of an arbitrary waveform. Fourier Principle. Harmonics. Fourier series and Fourier transform. Frequency spectrum.

4. Methods of Modulation. Overview of modulation. Carrier. Sidebands. Analog and digital modulation. Need for RF frequencies.

5. Analog Modulation. Amplitude Modulation (AM). Frequency Modulation (FM).

6. Digital Modulation. Analog to digital conversion. BPSK, QPSK, 8PSK FSK, QAM. Coherent detection and carrier recovery. NRZ and RZ pulse shapes. Power spectral density. ISI. Nyquist pulse shaping. Raised cosine filtering.

7. Bit Error Rate. Performance objectives. Eb/No. Relationship between BER and Eb/No. Constellation diagrams. Why do BPSK and QPSK require the same power?

8. Coding. Shannon's theorem. Code rate. Coding gain. Methods of FEC coding. Hamming, BCH, and Reed-Solomon block codes. Convolutional codes. Viterbi and sequential decoding. Hard and soft decisions. Concatenated coding. Turbo coding. Trellis coding.

9. Bandwidth. Equivalent (noise) bandwidth. Occupied bandwidth. Allocated bandwidth. Relationship between bandwidth and data rate. Dependence of bandwidth on methods of modulation and coding. Tradeoff between bandwidth and power. Emerging trends for bandwidth efficient modulation.

10. The Electromagnetic Spectrum. Frequency bands used for satellite communication. ITU regulations. Fixed Satellite Service. Direct Broadcast Service. Digital Audio Radio Service. Mobile Satellite Service.

11. Earth Stations. Facility layout. RF components. Network Operations Center. Data displays.

12. Antennas. Antenna patterns. Gain. Half power beamwidth. Efficiency. Sidelobes.

13. System Temperature. Antenna temperature. LNA. Noise figure. Total system noise temperature.

14. Satellite Transponders. Satellite communications payload architecture. Frequency plan. Transponder gain. TWTA and SSPA. Amplifier characteristics. Nonlinearity. Intermodulation products. SFD. Backoff.

15. The RF Link. Decibel (dB) notation. Equivalent isotropic radiated power (EIRP). Figure of Merit (G/T). Free space loss. WhyPower flux density. Carrier to noise ratio. The RF link equation.

16. Link Budgets. Communications link calculations. Uplink, downlink, and composite performance. Link budgets for single carrier and multiple carrier operation. Detailed worked examples.

17. Performance Measurements. Satellite modem. Use of a spectrum analyzer to measure bandwidth, C/N, and Eb/No. Comparison of actual measurements with theory using a mobile antenna and a geostationary satellite.

18. Multiple Access Techniques. Frequency division multiple access (FDMA). Time division multiple access (TDMA). Code division multiple access (CDMA) or spread spectrum. Capacity estimates.

19. Polarization. Linear and circular polarization. Misalignment angle.

20. Rain Loss. Rain attenuation. Crane rain model. Effect on G/T.

Via Satellite, February, 1999

Spacecraft Battery Technology

by Robert A. Nelson

The electrical power subsystem of a spacecraft consists of three basic components: the solar array, the battery, and the power control electronics. The solar array converts light energy from the sun into electrical energy and is the primary source of power. The solar array must also recharge the battery in sunlight. The battery provides electrical power during periods when the sun is eclipsed by the earth and is the secondary source of power. The power control electronics maintain the bus voltage at the desired level.

This article will review the present state of battery technology. The types of batteries available, their physical characteristics, and their advantages and disadvantages will be discussed. In particular, reasons for the trend to use nickel-hydrogen batteries in high power, long lifetime satellite missions will be explained.

ELECTRICAL POWER SUBSYSTEM

In the mid-1980s a typical spacecraft in geostationary orbit had a power of about 1 kW, such as the Hughes HS-376 spin-stabilized spacecraft or the RCA/GE Series 3000 three-axis stabilized spacecraft. By 1990, a power of several kilowatts was common. Beyond 1 kW, three-axis configurations are preferable because they are more mass efficient than spinners.

Today, a typical high performance three-axis stabilized spacecraft has a power between 10 and 15 kW and a nominal lifetime of 15 to 17 years. The Space Systems/Loral Tempo direct broadcast satellite was the first commercial spacecraft in orbit to offer more than 10 kW of power. The Lockheed Martin A2100 Astrolink spacecraft will have 13 kW for broadband services. The Aerospatiale Spacebus 4000 and the Hughes 702 spacecraft will provide 15 kW. Industry analysts predict a power level of 20 kW in the near future. Within a decade, 30 kW satellites may become operational.

The battery must provide this power during each eclipse over the entire satellite lifetime. The battery mass --indeed the entire spacecraft mass -- scales with the total power. Thus the battery must have high reliability with maximum possible energy density.

In geostationary orbit, it has been the practice to design the spacecraft electrical power subsystem as two half-systems, each using one wing of the solar array and one battery. Recently, however, electrical designs using only one battery have been used, due to the proven reliability of nickel-hydrogen batteries and the mass savings that can be realized. For small Low Earth Orbit satellites, a single battery is also advantageous.

The selection of bus voltage is often based on the desire to use proven equipment that has flown on previous satellite programs. In the 1960s, bus voltages of 20 to 30 V were common. By the 1970s and early 1980s, bus voltages had reached 40 to 50 V.

Higher voltages are desirable in order to reduce the required current for a given power, and thus reduce resistive losses and the mass of electric power distribution components. The upper limit of the bus voltage is determined by the power-switching semiconductors. Large spacecraft now in production, such as the Hughes 702 spacecraft, use a bus voltage of around 100 V to handle the increased power.

Achieving high power is not the major problem. Rather, it is managing the heat that is produced as waste. This problem is addressed by designing more efficient components and heat dissipation systems.

ECLIPSES

In geostationary orbit, at an altitude of 35,786 km, the angular radius of the earth is 8.7°. Therefore, the sun is eclipsed by the earth during a portion of the orbit whenever the sun is within 8.7° of the equatorial plane.

There are two eclipse seasons centered about the equinoxes (March 21 and September 21). Each eclipse season lasts 45 days, which is the time the sun takes to move from 8.7° below the equatorial plane to 8.7° above the equatorial plane relative to the earth. Thus in geostationary orbit, there are 90 eclipses per year, requiring 90 charge/discharge cycles of the battery.

The maximum length of an eclipse is 72 minutes (1.2 hours), which occurs at the equinoxes when the sun crosses the equator. The battery must provide power during this time. There are nearly 23 hours available in each revolution to recharge the battery, and typically the battery is recharged in about half that time. Between eclipse seasons, the battery is trickle-charged.

In Low Earth Orbit, at a typical altitude of 1000 km, the orbital period is approximately 100 minutes. The maximum eclipse duration is approximately 35 minutes, which is about one-third of the orbital period, and occurs when the orbital plane is parallel to the earth-sun direction. Only 65 minutes are available to recharge the battery before the next eclipse occurs. For this orbit, there are as many as 14 eclipses per day. Depending on the orbital altitude and inclination, there can be 5000 or more eclipses per year.

BATTERY CHARACTERISTICS

Batteries are either of the primary or secondary type and are classified according to their electrochemistry.

A primary battery is designed for use in lieu of a photovoltaic system. It is discharged to completion and cannot be recharged. It is used for short life missions or for applications that require very little power. A secondary battery is rechargeable and provides power during eclipse periods when the primary source of power, the solar array, is unavailable.

The leading primary battery for spacecraft is the silver-zinc battery. There are also a variety of lithium-based primary batteries, including lithium sulphur dioxide, lithium carbon monofluride, and lithium thionyl chloride. Although lithium has a higher energy density, silver zinc is easier to handle and can be discharged at a much higher rate.

The principal types of secondary (rechargeable) batteries that are designed for spacecraft use include the nickel-cadmium (NiCd) battery, the nickel-hydrogen (NiH_2) battery, and the super (advanced) nickel-cadmium battery. Silver-zinc (AgZn), lithium ion (Li), and nickel-metal-hydride (NMH) batteries are used for limited applications. The sodium-sulphur (NaS) battery is a technology still in the process of development. Each type of battery has certain applications depending on its performance parameters, such as its energy density, cycle life, and reliability.

The fundamental electrochemical unit is the voltaic cell. A battery consists of several cells connected in series. The bus discharge voltage is equal to the cell voltage multiplied by the number of cells, diminished by the losses.

In each cell, the negative electrode is the source of electrons to the external circuit (oxidation) and thus represents the anode. The positive electrode accepts the electrons from the external circuit (reduction) and thus represents the cathode. The electrolyte is a conducting medium that transfers ions produced at the anode and cathode inside the cell. The separator is a porous material that holds the electrolyte in place and isolates the anode and cathode materials so that electron transfer must occur through the external circuit.

A battery is rated in terms of its capacity. The capacity is the total stored charge. Since charge is the product of the electric current and the time, capacity is measured in ampere hours. The total battery energy, measured in watt hours, is the product of the capacity and the bus voltage. The energy density (specific energy), in watt hours per kilogram, is an important figure of merit for spacecraft applications.

The index of utilization of the battery is the depth of discharge (DoD), defined as the amount of charge drained from the battery expressed as a percentage of its rated capacity.

The charging current, or C-rate, is expressed in the form C/h, where h is the time in hours to completely charge the battery from its ground state.

The life-limiting property of a spacecraft battery is the number of charge/discharge cycles at a given depth of discharge. The cycle life increases as the depth of discharge decreases. Consequently, a nickel-hydrogen battery rated for 12 years in GEO with 1080 cycles at a depth of discharge of 80 percent might have a life of only 5 years in LEO with 25,000 cycles at a 50 percent DoD.

For example, an *INTELSAT VII* satellite, built by Space Systems/Loral, has two nickel-hydrogen batteries, consisting of 27 cells each. The cells are grouped in two 15 cell modules and two 12 cell modules. The total power requirement during eclipse is approximately 3,100 W at an average discharge voltage of 33.3 V. Each battery has a capacity of 85.5 A h, which provides a total energy of 2847 W h. At 70 percent DoD, the available energy per battery is 1993 W h.

During sunlight operation, the available power from the two solar array wings is 3927 W at autumnal equinox, end of life, and the bus voltage is regulated at 42.0 V. The battery high charge rate is C/13 (6.7 A), and the time to recharge both batteries is about 14 hours.

The total spacecraft dry mass is 1450 kg. The mass budget includes 125 kg for the solar array, 187 kg for the electrical power subsystem, and 62 kg for electrical integration. The batteries alone contribute about 10 percent to the overall spacecraft mass.

NICKEL-CADMIUM

The conventional nickel-cadmium battery was widely used during the first 30 years in the aerospace industry. It consists of four principal components: the nickel positive electrode, the cadmium negative electrode, the aqueous 35 percent potassium hydroxide (KOH) electrolyte, and a nylon cloth separator. Capacities are available in the range of 10 to 40 A h. Nickel-cadmium batteries have high cycle life but have a low energy density of approximately 25 W h/kg.

The cell voltage is approximately constant until it is nearly fully discharged. The temperature is a critical parameter that affects the battery life and must be maintained within a narrow range. In practice, a radiator is used to keep the battery temperature below 24°C, while heaters are used to keep the temperature above 4°C.

Repeated cycling to a deep depth of discharge will cause cracking in the cell plate structures. Over a lifetime of 10 years in geostationary orbit, there will be 900 charge/discharge cycles. Therefore, the depth of discharge is limited to between 50 and 60 percent.

The primary modes of degradation are cadmium migration, hydrolysis and oxidation of the nylon separator material, and electrolyte redistribution. The first two modes are time and temperature dependent, while the third mode is primarily DoD dependent.

In the past, the nylon separator has occasionally posed some difficulties for quality control. In the late 1960s contamination of the Pellon 2505ml nylon material was a problem. A second problem developed in the late 1970s when environmental pollution restrictions caused Pellon to stop producing its 2505ml nylon cloth separator material. Thus substitute materials, such as Pellon 2536, were used that had different physical properties and essentially the nickel-cadmium battery cell had to be redesigned. Stricter environmental laws also increased the cost of working with cadmium, a toxic material, for the negative plate.

NICKEL-HYDROGEN

The nickel-hydrogen battery is now the industry standard. Nickel plates form the positive electrode. Since hydrogen is a gas, the negative electrode contains a platinum catalyst. An aqueous KOH solution is used as the electrolyte. Originally, the separator material was a nonwoven mat of asbestos fibers. Zircar (zirconium oxide) is now commonly used as a separator instead of asbestos.

The nickel-hydrogen battery combines the most stable electrodes of the nickel-cadmium and the oxygen-hydrogen cells. Nickel-hydrogen batteries have fewer inherent failure mechanisms than nickel-cadmium when operated at the same depth of discharge, resulting in higher reliability and longer lifetime in orbit.

The key improvement was the removal of cadmium as the negative electrode. This improvement eliminates cadmium migration as one of the two life-limiting degradation modes within the cell and also circumvents the environmental problems associated with the use of cadmium. The other life-limiting factor, the separator, has also been improved by its replacement first by asbestos and later by Zircar. Also, the stability of the electrode and the separator strongly reduces electrolyte redistribution. Thus the nickel-hydrogen battery has a considerably longer lifetime than that of nickel-cadmium.

The optimum temperature range for maximum nickel-hydrogen battery capacity is between 10°C and 15°C. On either side of the optimum temperature range, the capacity decreases at the rate of 1 A h per °C of variation.

Three alternative configurations are found in combining cells to form a nickel-hydrogen spacecraft battery: the Individual Pressure Vessel (IPV), which contains one cell per vessel; the Common Pressure Vessel (CPV), which contains two cells per vessel; and the Single Pressure Vessel (SPV), which contains twenty-two cells per vessel.

The Individual Pressure Vessel (IPV) is a widely-used configuration in which each elementary cell is packaged in its own pressure vessel. Each cell generates 1.25 volts. The cells are connected in series to provide the required bus discharge voltage. The mechanical structure required by the high pressure design contributes about 40 percent of the total battery mass.

Nickel-hydrogen cells are manufactured in a wide variety of sizes and capacities. Representative capacities are 5 to 30 A h for a 64 mm cell, 30 to 100 A h for a 90 mm cell, and 100 to 250 A h for a 114 mm cell. The specific energy is approximately 30 W h/kg at 80 percent DoD including packaging.

The Dependent Pressure Vessel (DPV) is a modular IPV type design. The DPV differs from the IPV cell primarily in geometry. The DPV cells are designed to be sandwiched between two endplates.

To reduce mass inefficiency, the Common Pressure Vessel (CPV) design uses two cells in a container. Two cells are connected in series internally within the container and each CPV cell delivers 2.5 volts.

The IPV and CPV cells are typically packaged into multiple cell batteries to provide 28 to 32 V for the spacecraft bus. One additional cell is usually included in an IPV design to allow for a cell failure. The cells are vertically mounted on a lightweight honeycomb baseplate, which provides mechanical structure and a thermal path to remove heat to the radiator.

In the Single Pressure Vessel (SPV) design, all of the cells are packaged in a single container. This design offers the advantages of reductions in mass, volume, and cost. However, the reliability is less because a failure of one cell will result in the failure of the entire battery. Bypass circuits that are generally used in the IPV design cannot be used in this case. The system is designed to operate at internal hydrogen pressures up to 1000 psia.

The trend in communications satellites has been to use nickel-hydrogen in place of nickel-cadmium batteries. There are now well over 5000 nickel-hydrogen cells in over 200 batteries in orbit. This trend in GEO has carried over to LEO. With few exceptions, nearly all GEO and LEO spacecraft are now using or will be using nickel-hydrogen batteries. There is no other chemistry presently available with its unique combination of advantages of energy density, cycle life, and reliability.

SUPER NICKEL-CADMIUM

The super (advanced) nickel-cadmium (S-nickel-cadmium) battery is a proprietary Hughes replacement technology that is now used for some small spacecraft. It consists of nickel plates, cadmium plates, a Zircar separator, and potassium hydroxide electrolyte. The battery is available in capacities ranging from 5 to 50 A h. The specific energy is 31 W h/kg.

The super nickel-cadmium technology has been developed by Hughes as a compromise between the conventional nickel-cadmium and the nickel-hydrogen cells. The goal was to produce a cell with many of the advantages of the nickel-hydrogen cell to prolong lifetime, but retain the packaging advantages offered by the prismatic shape of the conventional nickel-cadmium. They use the same Zircar separator as nickel-hydrogen and have other improvements that are proprietary to Hughes. The few that have been produced and flown are expected to have longer life than the conventional nickel-cadmium batteries. Super nickel-cadmium cells are low pressure, prismatic cells which package as easily as the conventional nickel-cadmium cells. Their use has been mainly on small, LEO missions where they are perceived to have a packaging advantage over nickel-hydrogen. Their disadvantages are that they are both heavier and more expensive than either the conventional nickel-cadmium or the nickel-hydrogen cells.

SILVER-ZINC

The silver-zinc battery is attractive because of its high energy density, which is roughly 110 to 130 W h/kg. Overcharge must be controlled because oxygen that is evolved does not recombine easily. The major disadvantage is low cycle life. It thus has limited application as a secondary battery, but as noted above, it is used widely as a primary battery.

LITHIUM ION

Lithium ion is another high energy density technology. The interest in lithium ion is due to its high specific energy of 85 to 130 W h/kg on a cell basis. It has higher energy density than the nickel-cadmium or nickel-hydrogen technology with fewer hazardous concerns than many other lithium technologies, such as lithium-thyenol-chloride. It can also accept deep discharges, which means more of the available energy can be used.

This technology provides hope that it may eventually be developed to accept a large number of cycles. For these reasons, rechargeable lithium ion development is being watched by all of the prime spacecraft manufacturers for its possible use on selected missions.

Lithium ion does not yet have a competitive cycle life. Typical 20 A h cells have exhibited a 20 percent loss in capacity after less than 200 cycles. At this stage of development, the technology can only be considered for those missions that require very few cycles, such as in sun synchronous orbits or on deep space scientific missions. They are not yet useful for either LEO or GEO orbits.

NICKEL-METAL-HYDRIDE

Nickel-metal-hydride electrochemistry was developed to replace the nickel-cadmium cell with a technology that did not have the problems caused by the cadmium plate. It is seldom used, since its cycle life never approached that of the nickel-cadmium. After significant development by several companies, it was determined that NMH would not have the mass, size, and cycle life that was initially expected.

SODIUM-SULPHUR

The sodium-sulphur battery is still a development technology. It promises to have potentially 50 percent better specific energy than nickel-hydrogen, but is not expected to have as much promise as lithium ion.

Sodium sulphur is a unique technology that must operate at 350°C. Some of the heat required for this high temperature is generated by the battery. But the battery presents a significant impact on the spacecraft thermal design. To minimize this impact, it must be thermally connected to the rest of the spacecraft through a very high, well controlled, thermal resistance.

PROJECTION

There is an enormous market for nickel-hydrogen batteries. These batteries have been demonstrated to be more reliable and mass efficient, with longer cycle life, than their chief competitor, nickel-cadmium. State of the art technologies include lithium ion and sodium sulphur, but these batteries do not have the required cycle life and are difficult to operate.

Spacecraft are being designed with ever higher power and longer lifetimes. Spacecraft powers are now typically around 10 kW and will soon reach 15 to 20 kW. Power levels at 30 kW are foreseen within the next decade.

As these powers increase, so do the satellite lifetimes in orbit. In the 1980s a ten year life was typical. Today, satellites are designed for 15 or more years in geostationary orbit. This lifetime can be extended for another two or three years using inclined orbit techniques, which is becoming standard practice for satellites nearing end of life.

These trends will dictate the use of highly reliable battery technologies, permitting high bus voltages and long life. Nickel-hydrogen will be the likely technology of choice to meet these criteria.

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