SPACECRAFT CHARGING AND PLASMA INTERACTION IMPLICATIONS FOR LARGE SPACE SYSTEMS

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WHAT IS THE PROBLEM? (Figure 1)

Many conventional satellites have experienced performance anomalies and possible damage in geosynchronous orbit (GEO). The majority of anomalies correlate with environmental disturbances (magnetic substorms) when the spacecraft encounters high energy electrons which differentially charge exposed surfaces.

Although a spacecraft in low earth orbit (LEO) encounters only low energy plasma, high voltage systems will accelerate plasma particles, resulting in surface charging and damage possibly more severe than in GEO. The high particle density in LEO could also contribute to high power losses for multikilovolt systems.

Spacecraft charging studies have been conducted since the early 1970's. Little is known, however, about specific discharge mechanisms, plasma interactions, and scale effects associated with very large spacecraft. The large area, low density character, and extensive use of non-conducting materials could have a major impact on the performance and survivability of many Large Space Systems (LSS).

WHAT IS THE PROBLEM?

- "DISTURBED" GEO ENVIRONMENT MAY PRODUCE HIGH DIFFERENTIAL CHARGING & ELECTRICAL DISCHARGES RESULTING IN:
  - MATERIAL/COMPONENT DEGRADATION
  - EQUIPMENT MALFUNCTION/DAMAGE
- HIGH VOLTAGE (MULTIKILOVOLT) SYSTEMS IN LEO MAY:
  - INDUCE HIGH DIFFERENTIAL CHARGING/ELECTRICAL DISCHARGES, SPUTTERING & RADIATION DAMAGE
  - EXPERIENCE LARGE POWER LOSS THRU PLASMA
- SPECIAL LSS CHARACTERISTICS COULD COMPOUND CHARGING/PLASMA INTERACTION PROBLEMS
- SPACECRAFT CHARGING STUDIES TO DATE EMPHASIZE CONVENTIONAL DESIGNS – LITTLE EFFORT ON LSS

Figure 1

MAGNETOSPHERE (Figure 2)

The magnetosphere is the region of the earth's space in which the geomagnetic field exerts a dominant influence on the motion of low-energy plasma and fast-charged particles. The solar wind, primarily ionized hydrogen gas, distorts the earth's dipole magnetic field and forms the magnetopause boundary which excludes all impinging plasma particles. A detached shock wave is formed on the sun side of the magnetosphere at about 9 earth radii (R_e), and an elongated magnetotail is formed on the opposite side which extends for hundreds of earth radii.

The magnetosphere is immersed in the weak interplanetary magnetic field whose direction depends on the rotational position of the sun from which it emanates. This field combines with the dipole field to create open field lines allowing plasma exchange between the ionosphere and interplanetary space.

The plasma sheet, a broad ($\sim 4\ R_e$) region of dilute, warm ($n \sim 1$ cm^{-3}, $T \sim 500$ ev) plasma lying in the equatorial plane, extends from the dawn to dusk side of the magnetotail. During quiet periods, a geosynchronous satellite at $6.6R_e$ will pass through the plasma sheet and other regions where particle energies are generally less than 10 ev with densities from 10 to 1000 cm^{-3}. During disturbed periods (magnetic substorms), the character of the plasma sheet changes rapidly in the region from 3 to 12 R_e where the quiescent plasma is replaced by an energetic plasma with electron energies up to 20 kev.

MAGNETOSPHERE (NOON-MIDNIGHT PLANE)

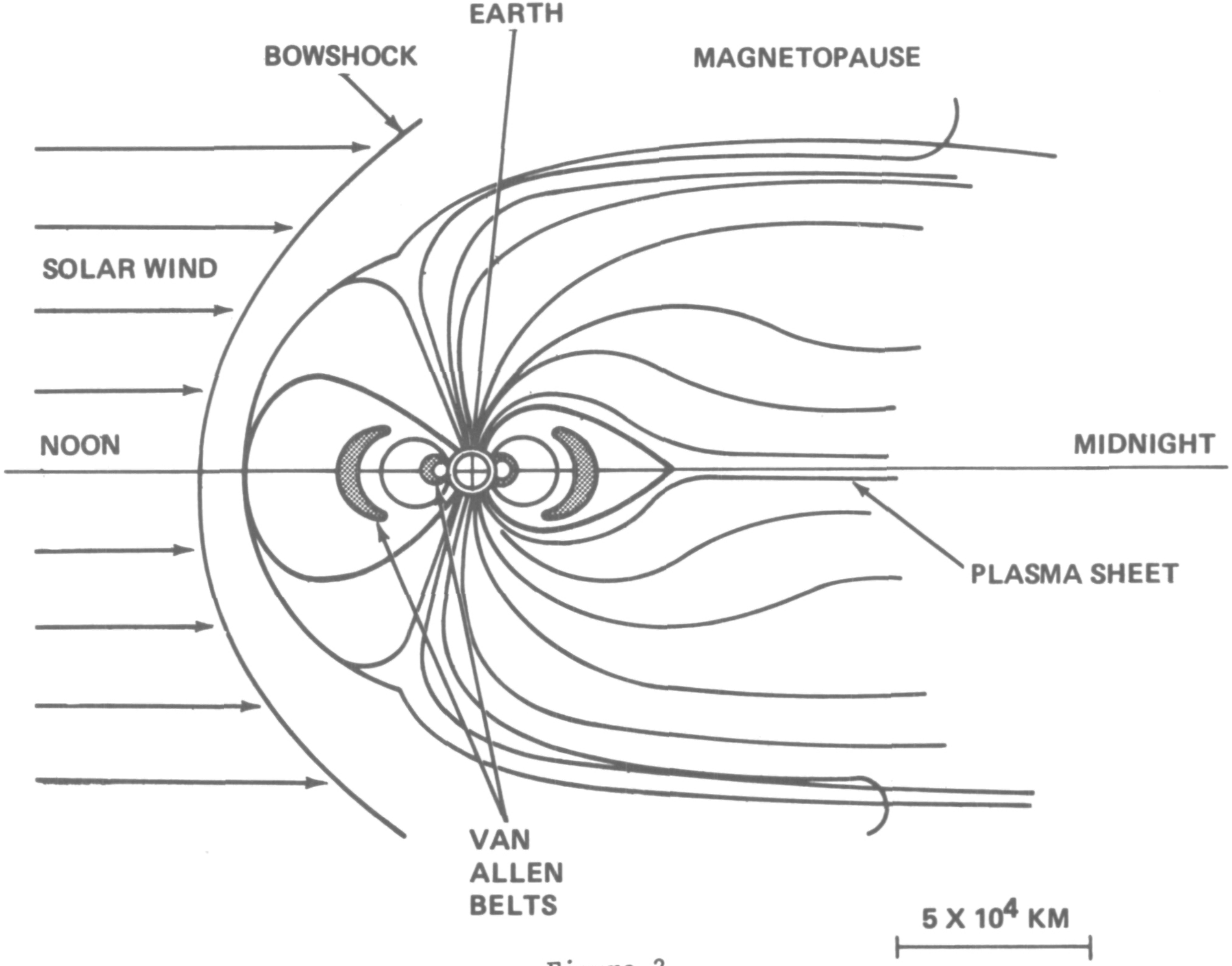


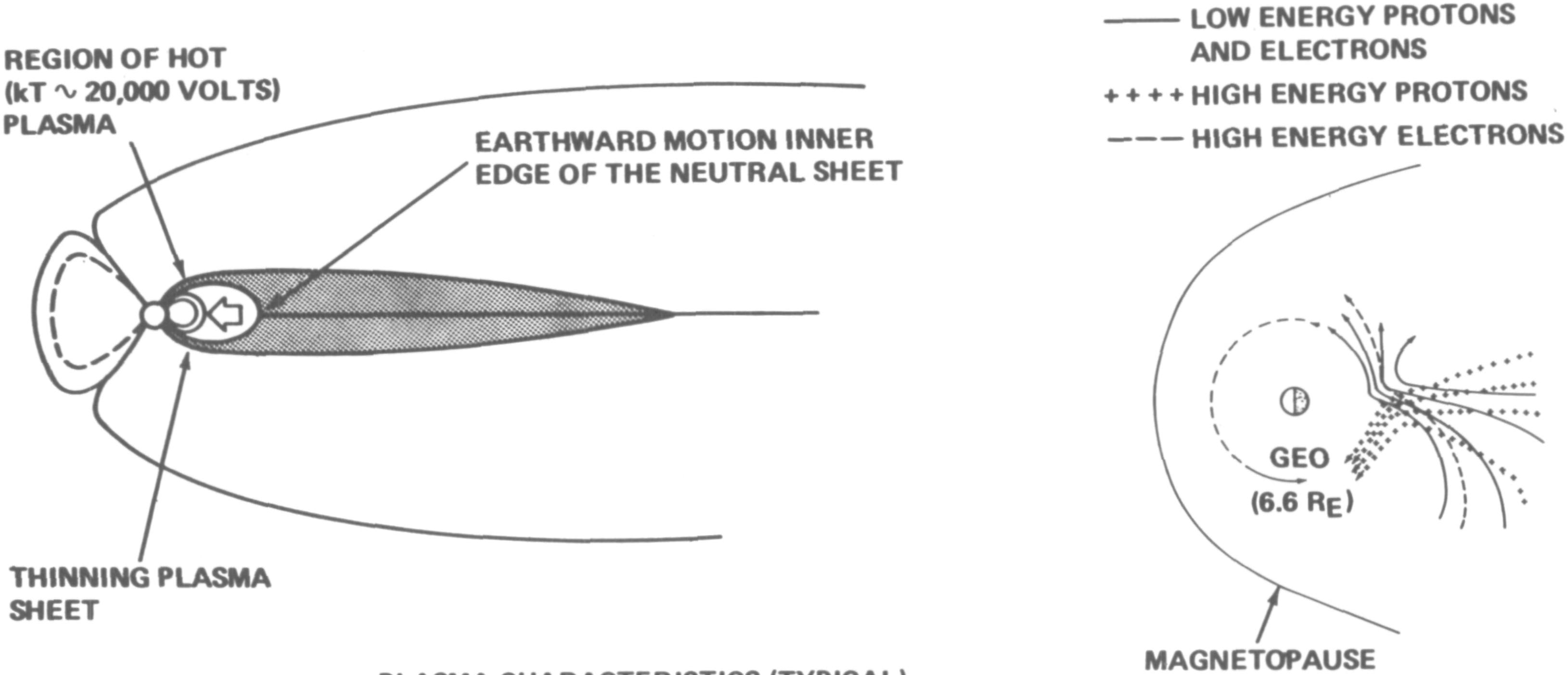
Figure 2

MAGNETIC SUBSTORMS (Figure 3)

Magnetic substorms occur as isolated events every few days or hours, or they may occur in rapid sequence. There is yet no conclusive theory to explain the generation and development of the substorm. It appears, however, that substorms occur when the interplanetary magnetic field, convected by the solar wind, develops a southward-directed component. The magnetosphere is compressed, magnetic field lines merge, and stored energy is somehow released resulting in a high energy plasma flow toward the earth. The energy of the plasma particles increases as they encounter stronger fields and changing field line curvatures and gradients. Magnetic gradient and curvature effects cause electrons and ions to drift into different hemispheres. The preferential drift of high energy electrons in the local midnight to dawn region is believed responsible for most high differential spacecraft charging and performance anomalies observed on geosynchronous satellites.

GEO and LEO plasma characteristics are compared in the table. LEO is characterized by very dense, low-energy electrons where, except for high voltage systems, spacecraft charging is not a problem. During magnetic substorms, the low energy/density electrons at GEO are replaced by a tenuous plasma containing high-energy electrons.

MAGNETIC STORMS



PLASMA CHARACTERISTICS (TYPICAL)

	LEO	GEO	
		QUIESCENT	SUBSTORM
AVG ELECTRON ENERGY (EV)	∿ 1	1–500	5000–20,000
PLASMA DENSITY (PARTICLES/CM^3)	10^5–10^6	∿ 100	< 10

Figure 3

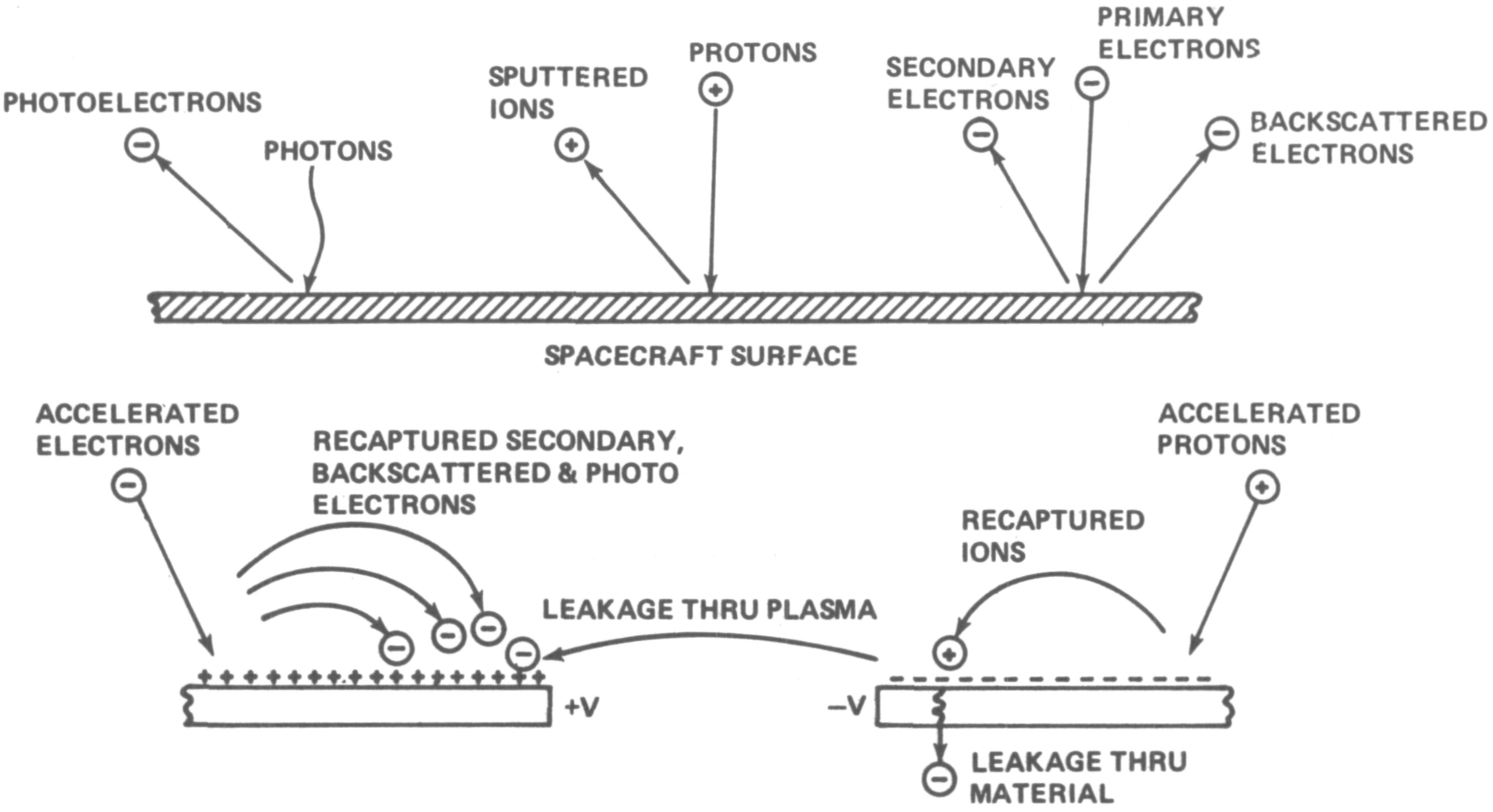
MAJOR SPACECRAFT CHARGING PROCESSES (Figure 4)

A variety of processes and properties determine the magnitude and polarity to which a surface will charge in a plasma. Primary electrons and sputtered ions contribute to negative charging, while photoelectrons, secondary and backscattered electrons which escape result in a positively-charged surface. If the surface is charged, it will attract particles of opposite polarity and recapture some portion of those particles which might otherwise escape. In addition, electrons may leak between differentially charged surfaces through the plasma or through the bulk material.

The charging processes continue until the algebraic sum of all currents equals zero. An electrically powered structure will float at some equilibrium voltage with respect to the plasma such that $J(+)A(+) = J(-)A(-)$, i.e., total negative and positive current-area products are equal.

Charge levels depend on spacecraft configuration, composition, orientation, and local plasma characteristics.

MAJOR SPACECRAFT CHARGING PROCESSES



CHARGE MAGNITUDE DEPENDENCE

- SOLAR INTENSITY
- LOCAL PARTICLE DENSITY/ENERGY
- SURFACE POTENTIAL
- MATERIAL PROPERTIES
  - SECONDARY/PHOTOEMISSION
  - RESISTIVITY
  - BREAKDOWN POTENTIAL

Figure 4

ELECTROSTATIC CHARGING/DISCHARGING (PASSIVE ELEMENTS) (Figure 5)

Several charge/discharge mechanisms may be responsible for spacecraft performance anomalies and material damage.

A charged dielectric will polarize and large electric field stresses can exist in a thin sheet of material. If the breakdown potential is exceeded, discharge will occur through the bulk. Besides possible damage to the bulk, some material might be removed from the surface; this contaminant could redeposit on nearby surfaces. If one surface is metallized, the contaminant could include vaporized metal.

Very high current metal to metal discharges are another possibility where ungrounded metallized surfaces are in close proximity to grounded structure. If the metallized layers of thermal blankets are electrically isolated, the layers will charge differently; and, high current discharges could occur between layers or from any layer to the conducting structure.

Other mechanisms which have been postulated include bilayer and Malter discharge. Bilayer discharge may occur immediately within the outer surface layer of a dielectric and arises from electrons that penetrate the bulk and the positive surface charge resulting from secondary emission. Insulating film deposited on a metal surface can form a lossy semiconductor junction which can break down at potentials of only a few tens of volts. These (Malter) discharges can vaporize the metal as well as damage the insulating surface. Bilayer and Malter discharges may be partly responsible for spacecraft anomalies which have been recorded in the absence of major substorms.

Studies have shown that when electrical discharge occurs in a dielectric, negatively charged material (electrons, surface atoms) is repelled to several centimeters above the surface. This acts as a dipole antenna producing large, directional r.f. signals

ELECTROSTATIC CHARGING/DISCHARGES (PASSIVE ELEMENTS)

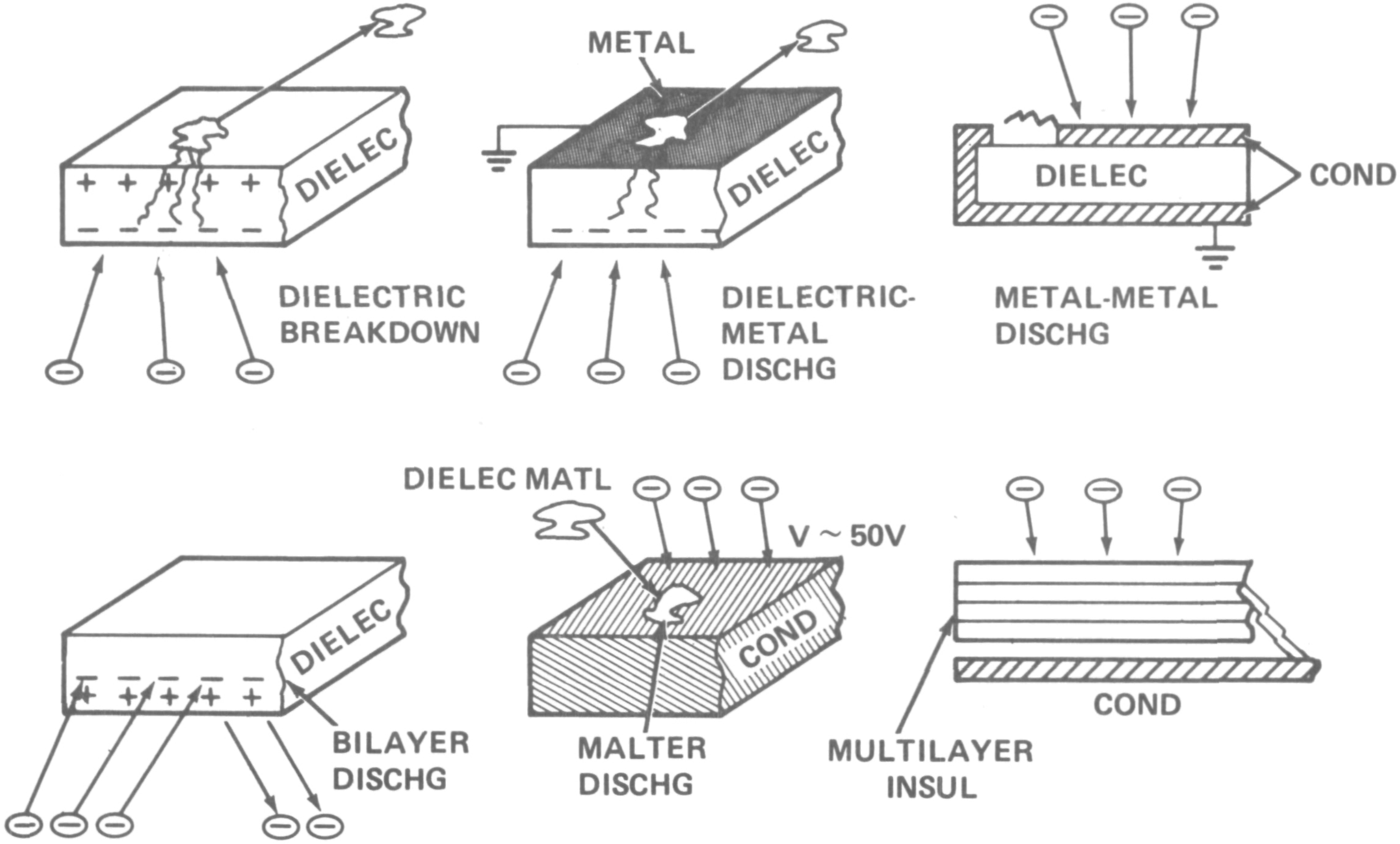


Figure 5

DIFFERENTIAL CHARGING/PLASMA INTERACTIONS (ELECTRICALLY POWERED SYSTEMS) (Figure 6)

Magnetic and electric field effects in electrically-powered systems may produce higher charge differentials than would exist in similar passive systems.

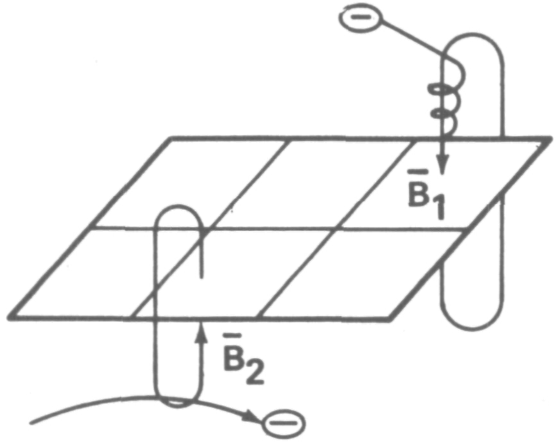
Many current loops are incorporated in large area solar cell arrays and active antennas. The resulting magnetic fields could focus or deflect electrons at various points throughout upper and lower surfaces. Distributed high voltage sections could accelerate electrons from a discharge at one point, producing increasing numbers of secondaries, and lead to a discharge avalanche.

Conductors exposed to the space plasma in electrically powered systems will attract electrons or ions depending on the conductor voltage with respect to the plasma. This particle flow constitutes a current loss through the plasma. The magnitude of this current is a function of electrical configuration, voltage level, exposed conductor area, and plasma characteristics.

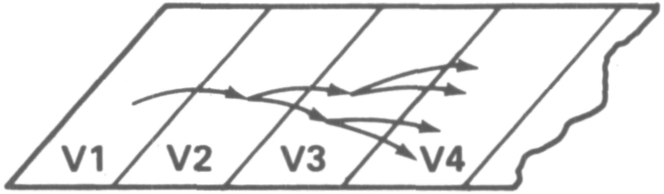
Electric fields will attract charged particles to the surface of insulated conductors, thereby increasing the voltage gradient across the insulator. If insulator breakdown occurs, electrons may stream through the pinhole created by the rupture resulting in further material erosion and increased current loss.

For systems containing waveguide antennas, multipactor discharge is an additional concern; this phenomenon can occur if electrons enter the waveguide. Electrons within the waveguide will experience acceleration at the transmission frequency which will generate secondary electrons and create an electron plasma within the waveguide.

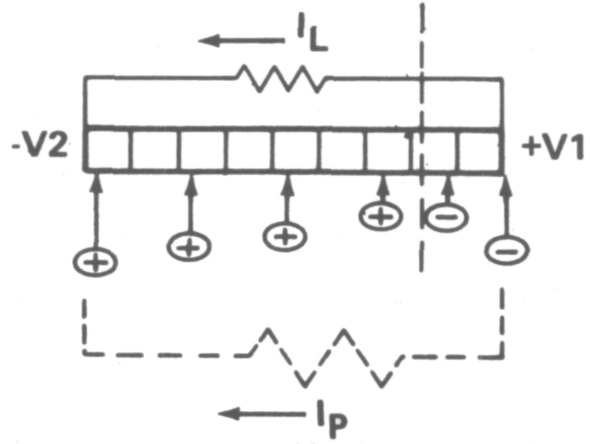
DIFFERENTIAL CHARGING/PLASMA INTERACTIONS (ELEC POWERED SYSTEMS)



MAG FIELD FOCUSING/DEFLECTION



ELEC FIELD ACCEL – AVALANCHE



POWER LOSS THRU PLASMA

INSULATOR RUPTURE

Figure 6

ELECTRICAL CHARGE/DISCHARGE EFFECTS (Figure 7)

Repeated electrical discharges can degrade optical properties of dielectric and metal surfaces used for thermal control, reflectors, solar cell covers, lenses/sensors, etc. These surfaces will degrade further from deposition of discharge contaminants.

Material breakdown could produce corrosive agents which accelerate erosion of integral metal conductors and electrical connections in the discharge vicinity.

Insulation pinholes can result from material breakdown and lead to shorting of electrical elements. All discharges will produce electromagnetic pulses resulting in possibly severe interference or electrical system voltage transients.

ELECTROSTATIC CHARGE/DISCHARGE EFFECTS

- DIELECTRIC CRAZING, DARKENING, EMBRITTLEMENT
- METAL CRAZING/VAPORIZATION
- COMPOSITE STRUCTURE BREAKDOWN/DAMAGE
- CONTAMINANT DEPOSITION
- CORROSIVE MATERIAL PRODUCTION
- EROSION/CORROSION OF THIN METAL CONDUCTORS
- INSULATION BURNTHRU/SHORTING
- EMI/VOLTAGE TRANSIENTS

Figure 7

PLASMA INTERACTIONS (Figure 8)

Plasma coupling currents and power losses could be significant for high voltage systems in LEO. Magnetic and electric fields associated with high power/voltage systems will influence local charge levels and discharge effects. These fields might be shaped where possible to reduce charging.

Coupling currents, system-generated fields, geomagnetic fields and accelerated ions will induce forces and torques which could impact structural, attitude/control/stationkeeping design requirements. Ions accelerated by high voltage systems will also increase surface sputtering and radiation damage.

If ion thrusters are used for transportation/control, thruster particles could be attracted to charged spacecraft surfaces, contributing to local spacecraft charging and contamination and reducing thruster effectiveness.

Electron multipacting can result in transmission power loss, shorting or damage to waveguide antennas.

PLASMA INTERACTIONS

- POWER LOSS THRU PLASMA
- MAGNETIC/ELECTRIC FIELD FOCUSING/ACCELERATION-AVALANCHE
- INDUCED FORCES/TORQUES
- INCREASED ION SPUTTERING/RADIATION DAMAGE
- ION THRUSTER CHARGING CONTRIBUTION, REDUCED THRUSTER EFF

Figure 8

LSS CHARACTERISTICS OF MAJOR CONCERN (Figure 9)

Many advanced missions (e.g., communications and surveillance) require very large area dielectric surfaces or coatings for antennas, optics, control skins, etc. These spacecraft may also include large solar cell arrays to satisfy high system/payload power requirements. Electrical discharges between differentially charged dielectrics, metals, and composites may seriously affect system performance and life. Additionally, very large, lightweight structures may be affected by disturbance forces and torques resulting from dynamic plasma interactions.

The synergistic effects of prolonged exposure to the space environment and repeated electrical discharges on material properties are of major importance and are among the greatest unknowns.

Multikilowatt power systems incorporate high current loops, and possibly high voltages, which could compound differential charging and plasma effects.

Full size or even large area ground testing under simulated combined environments may be prohibitive, thereby requiring accurate scaling techniques and large scale flight experiments. There is currently no activity which specifically addresses LSS requirements.

LSS CHARACTERISTICS OF MAJOR CONCERN

- MANY COMPOSED OF VERY LARGE AREA DIELECTRICS WITH INTEGRAL THIN CONDUCTORS – SUSCEPTIBLE TO DAMAGE
- EXTENSIVE USE OF COMPOSITE MATERIALS
- LARGE, LOW DENSITY STRUCTURES – INDUCED FORCES/TORQUES
- LONG LIFE REQUIREMENTS – MATERIAL AGING EFFECTS
- MAY INCLUDE HIGH POWER/VOLTAGE NETWORKS
  - CURRENT COUPLING/STABILITY
  - MAGNETIC/ELECTRIC FIELD FOCUSING/ACCEL
  - ECLIPSE & LOAD TRANSIENT EFFECTS
- LARGE SCALE EFFECTS UNKNOWN
  - CHARGE PROFILES/DISCHARGE MECHANISMS
  - EFFECTIVENESS OF CHARGE CONTROLS
  - PLASMA SHEATH FORMATION/CHARACTERISTICS
  - $\bar{B} \times \bar{v}$ & WAKE EFFECTS

Figure 9

DEPLOYABLE ANTENNA (Figure 10)

An example of a large spaceborne antenna is shown. This deployable design could scale to a 300m diameter with over 70,000m^2 projected surface area.

The antenna consists of several gores, the upper and lower planes of which are entirely composed of dielectrics (kapton) and thin metallic (aluminum, copper) elements. The ground plane is a metal mesh. Separation between ground and antenna planes is 3-25 cm. Kapton - copper delay lines interconnect antennas and ground planes. The gores are attached to a rim which is supported from the hub with upper and lower stays. The rim and stays are of graphite-epoxy composite; the remainder of the structure is aluminum alloy.

In an active array configuration, low power r.f. amplifiers, switches, and digital chips are distributed throughout the lower antenna plane. The feed system (not shown) is located on a mast deployed from the center cannister. Up to 50 kilowatts of electrical power could be supplied by a large solar cell array mounted on the same mast. Multiple current loops, connected to the common ground plane, feed the active elements in the lower antenna plane.

Electrostatic charging and discharges along, through, and between the dielectric-metallic gore layers and delay lines could cause material damage and antenna malfunction.

Another version of this deployable structure incorporates aluminized kapton gores which form a large sunlight reflector. The solar cell array and subsystem package is located at the hub in this case. Degraded surface reflectivity and structural properties of the substrate resulting from electrical discharges are of primary concern with systems of this type.

Possible physical and optical degradation of solar cell arrays and thermal control surfaces is

DEPLOYABLE ANTENNA

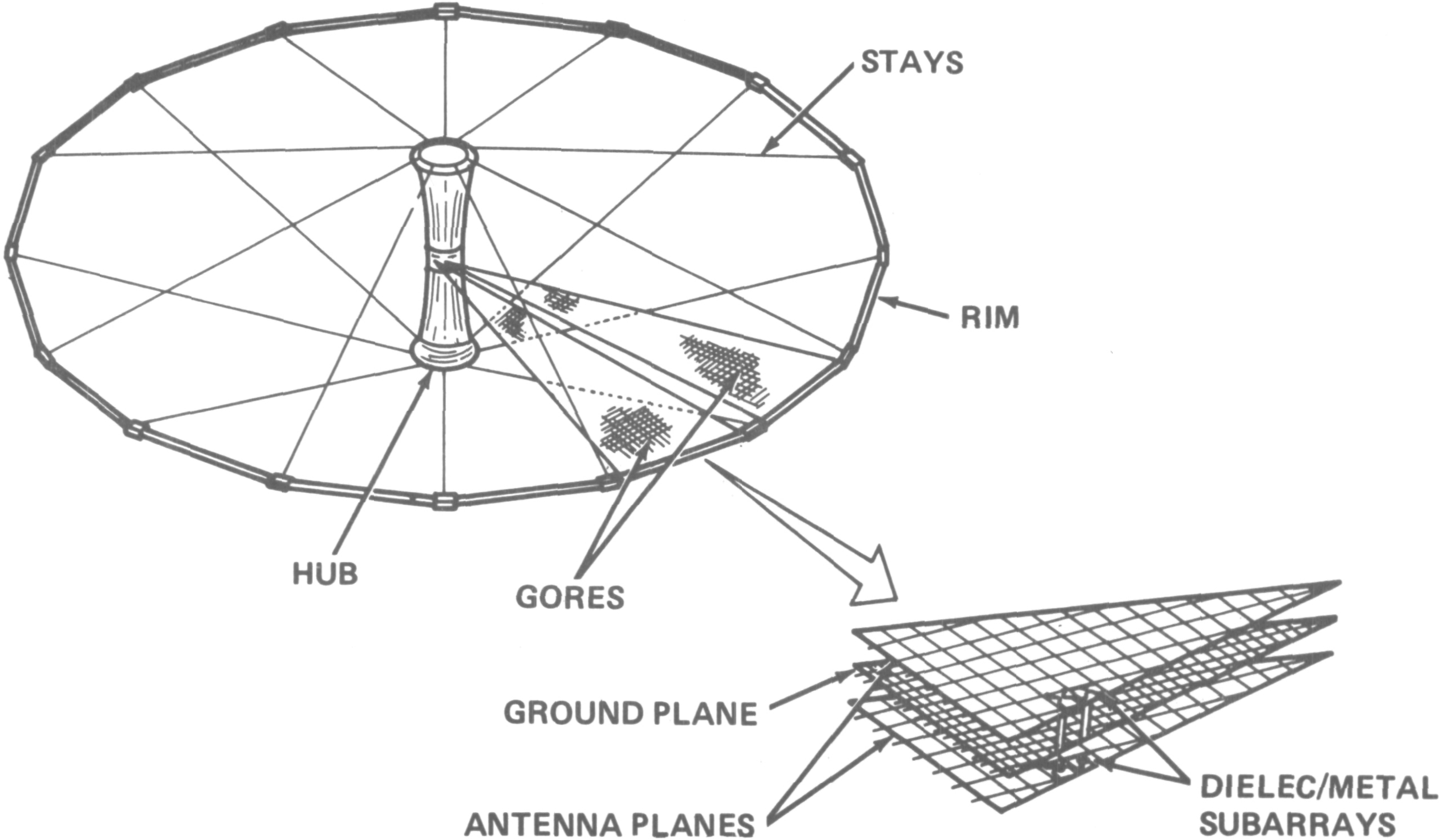


Figure 10

COMMUNICATIONS PLATFORM (Figure 11)

A concept for an advanced communications platform is shown. This design is constructed on orbit and consists of three multifunction systems, coupled in a platform, measuring 140M x 61M x 68M not including the solar cell arrays. The total projected surface area of the three lens antennas is 6100 M^2.

The lens aperture structure consists of hexagonal panels which are joined at the corners with a connection plate. The panels are of plastic honeycomb construction with photoetched, crossed-dipole conductors on the outer surfaces (antenna planes). Conductive sheets, bonded to the opposite honeycomb faces, form the ground plane. Antenna and ground planes are interconnected with metallized dielectric delay lines.

Support beams are graphite-epoxy with other structural elements of aluminum alloy. The feed/subsystem modules are of aluminum with some thermal control surfaces.

Power requirements for the communications and other subsystems could range from 80 to 100 kilowatts, requiring very large area solar cell arrays. Advanced solar cell arrays might incorporate thin, continuous, dielectric substrates and covers as shown in the detail. Dielectric breakdown and arcing in the vicinity of thin solar cell grids and interconnects could cause damage and output power degradation. The concerns regarding electrostatic charge/discharge effects are similar to those for the deployable antenna; long-term integrity and performance of dielectric and conductive elements and

COMMUNICATIONS PLATFORM

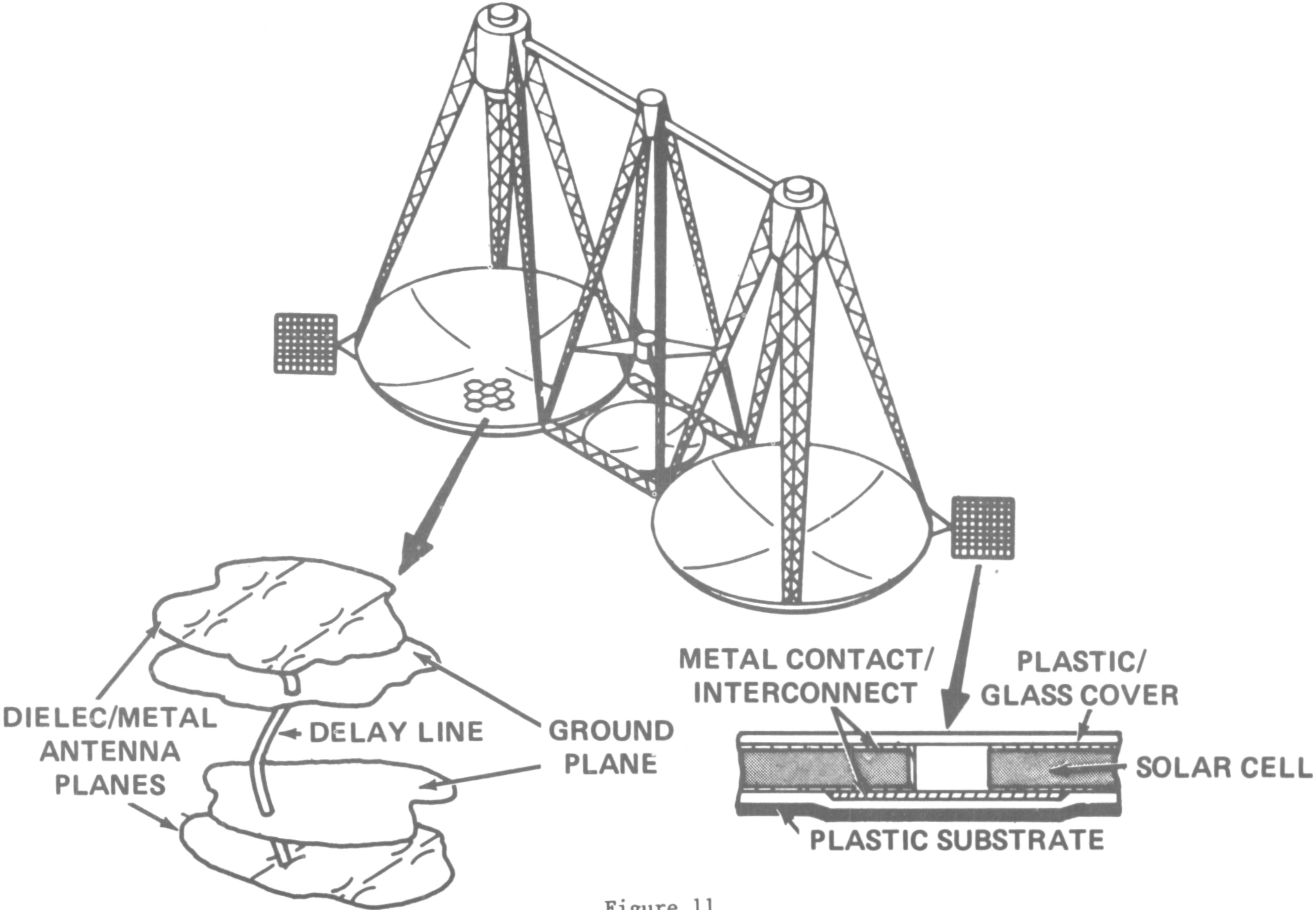


Figure 11

SPACECRAFT CHARGING INVESTIGATION PROGRAM (Figure 12)

A cooperative NASA/Air Force five-year program was initiated in 1976 to investigate spacecraft charging. The program plan includes environment definition, materials evaluation/development, test facility improvement, development of analytical tools, and generation of spacecraft design requirements/test specifications.

GEO environment models are derived through orbital data from ATS and other previous satellites and from ISEE (International Sun-Earth Explorer) satellites, the third of which will be launched by mid-1978. The SCATHA (Spacecraft Charging At High Altitudes) satellite will be launched in early 1979 and is dedicated to space plasma/charging evaluations.

A NASCAP computer program has been generated to predict charge levels on any conventional spacecraft but requires much improved plasma/materials response data. Charge response tests have been performed on some common space materials, but much has been exploratory in nature. Specific charge/discharge mechanisms have yet to be identified, and no work has been done on long-term effects. Materials development has concentrated on conductive coatings, paints, and alternate thermal blanket materials.

Several new activities must be initiated to evaluate the special problems posed by many Large Space Systems. These include development of plasma/charge/discharge models and NASCAP modifications and/or new programs for large, high power systems and accelerated materials ground or flight tests.

SPACECRAFT CHARGING/PLASMA INTERACTIONS— POSSIBLE CONTROL TECHNIQUES

- MAT'L SELECTION
- CONDUCTIVE COATINGS
- CONDUCTOR GRIDS/FRAMES
- "CONTROLLED" PIN HOLES
- DIELECTRIC SHAPING

- ELECTRON EMITTERS
- ELEC/MAG/RF FIELDS
- SHIELDS/GROUNDING
- LOW VOLTAGE SECTIONS
- CONDUCTOR INSULATION

Figure 12

SPACECRAFT CHARGING/PLASMA INTERACTIONS - POSSIBLE CONTROL TECHNIQUES (Figure 13)

Although all of the discharge effects and plasma interactions described previously are possible, their severity depends on the specific application. In addition the data presently available will not permit evaluations with confidence for most applications.

When estimates are made of the location and magnitude of charging/plasma effects on a particular design, one or more controls might be used to prevent discharge/interaction problems.

Relatively simple (passive) controls include selection of suitable materials, designed charge leakage paths, and elimination of high electrical stress locations.

Use of active controls (electron emitters, shaped electromagnetic fields) has been shown to reduce surface charging, but large scale designs and performance estimates have not yet been developed.

Good electrical design practices must be followed to minimize breakdown/arcing problems in high voltage systems; special design requirements will probably have to be developed to cope with compounding effects of space charging. Also, maximum system voltages may have to be limited to control plasma acceleration/power loss problems.

The LDEF (Long Duration Exposure Facility) will include some charge response tests in LEO; others may be planned for recovery from GEO or elliptical orbits. The SPHINX (Space Plasma, High Voltage, Interaction Experiment) was fully ground tested but failed to orbit. These experiments, if modified and launched on early Shuttle flights, could provide valuable new data for LSS modelling. At least one large area GEO experiment will be required to measure LSS plasma sheath characteristics and verify scaling techniques. Once sufficient ground/flight materials effects data is generated and analytical predictions are verified, LSS design specifications can be developed.

SPACECRAFT CHARGING INVESTIGATION PROGRAM

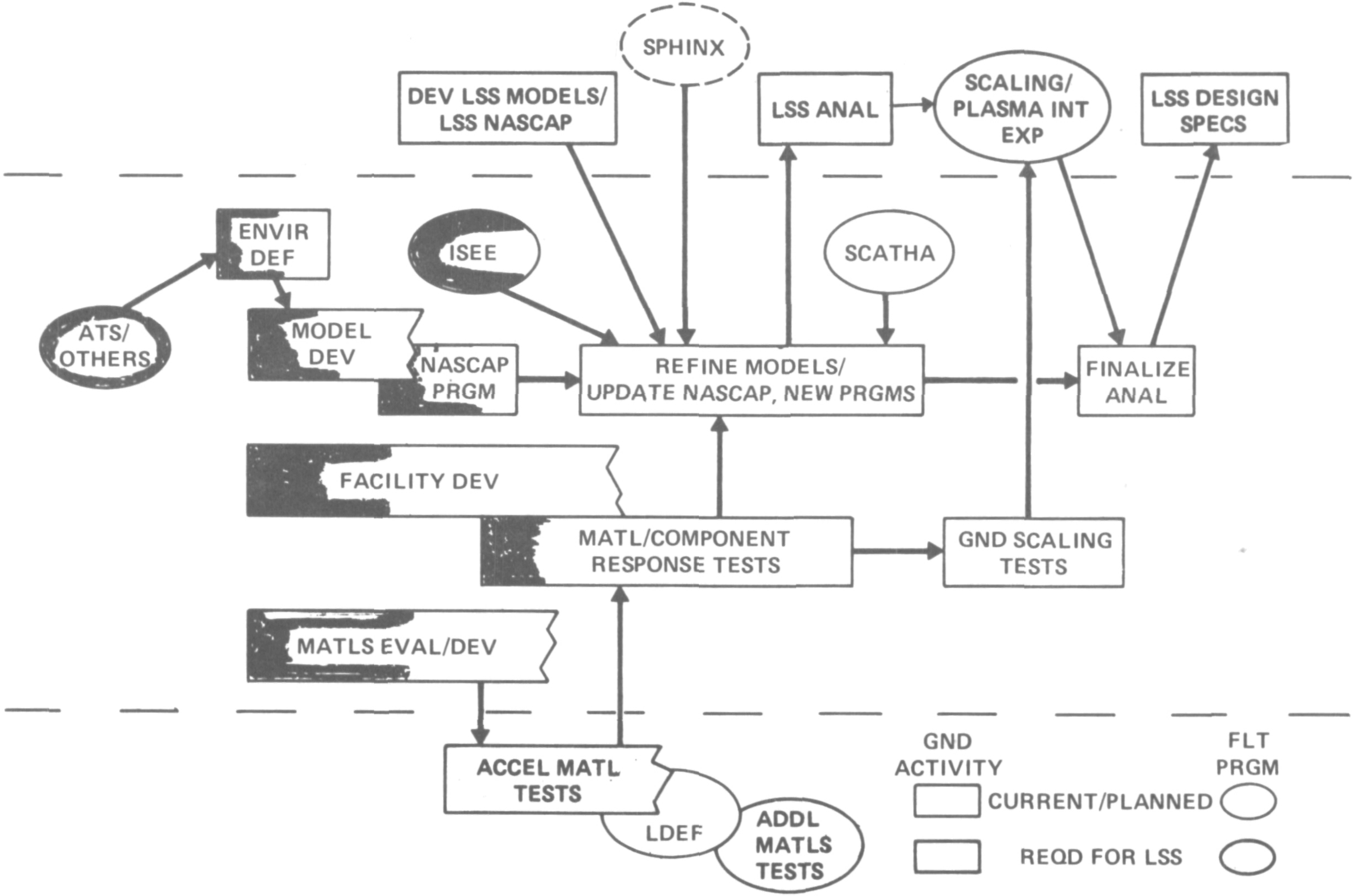


Figure 13

SCALING/PLASMA INTERACTION FLIGHT EXPERIMENT CONCEPTS (Figure 14)

A large area, scaling/plasma interaction flight experiment is an obvious requirement in an LSS-oriented spacecraft charging investigation program. Although it is premature to define specific requirements, two distinct concepts should be considered.

The first is a low power (less than one kilowatt) satellite which deploys (rollout/foldout) a large area blanket composed of material/component test samples and sensors. Exposed test area and orientation would be variable to provide parametric scaling, illumination, and geomagnetic data. Experiments might include plasma sheath formation/stability/uniformity, charge response, passive/low - power active controls, and high voltage interactions.

A power module could be used to support a high power (10-20 kilowatt) experiment which incorporates a variable power network and a simple, instrumented, deployable structure. In addition to the tests listed above, an experiment of this type could evaluate magnetic field, current coupling, eclipse, and load transient effects on plasma sheath characteristics, charge response, and structural dynamics. The higher-powered electromagnetic charge controls could also be evaluated.

The maximum dimension of these test articles might be anywhere from 100 m to 1 km. Mission times would be set to include a reasonable number and variety of substorm events, or the experiments could be flown for several years to derive additional aging effects data.

SCALING/PLASMA INTERACTION FLIGHT EXPERIMENT CONCEPTS

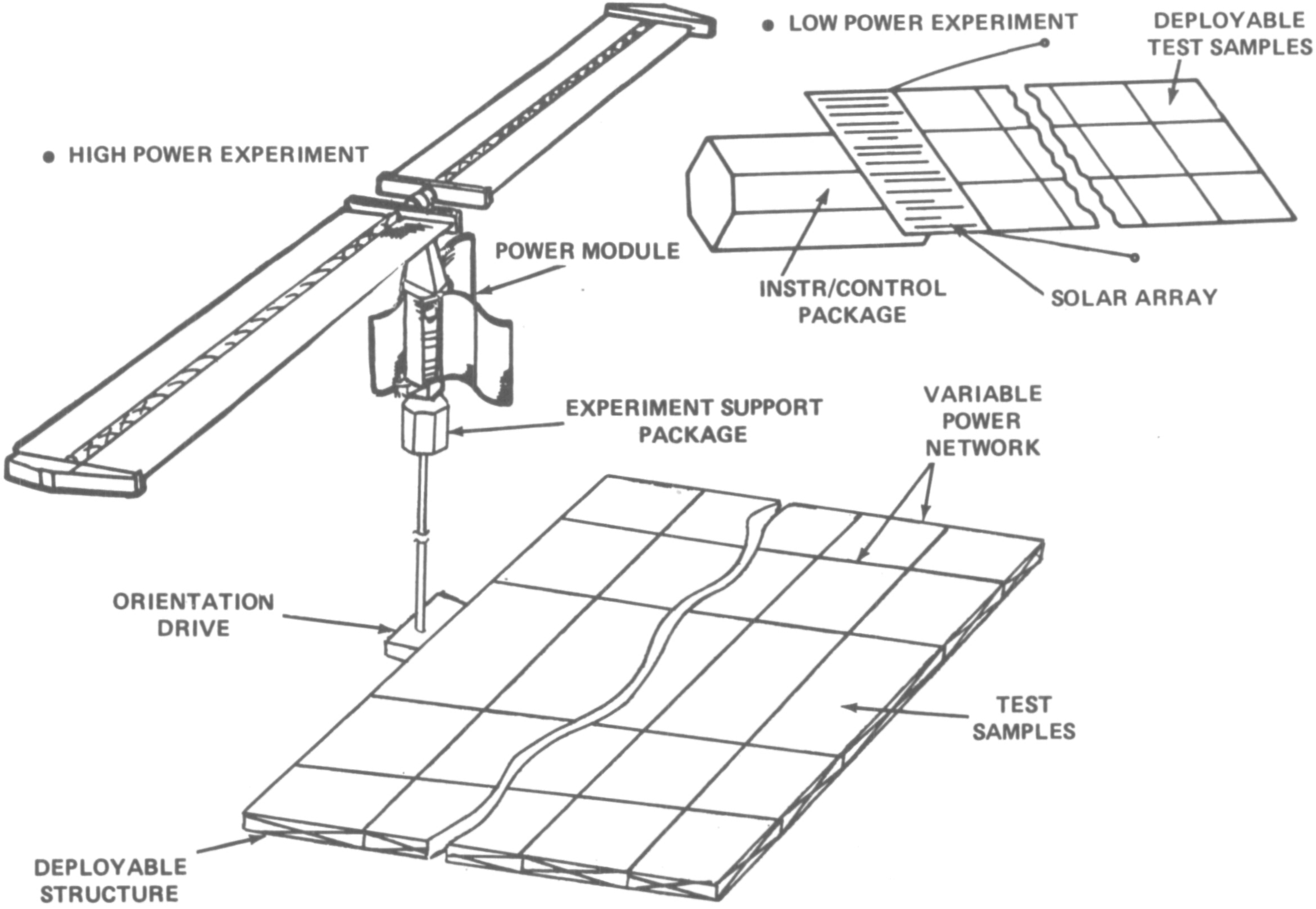


Figure 14

CONCLUSIONS (Figure 15)

Potentially serious consequences may arise from electrostatic charging and plasma interactions with Large Space Systems. Little is known about the specific mechanisms which must be controlled, and almost no data exists on large-scale or long-term environmental effects.

Although current programs promise answers to many fundamental questions and near-term solutions for conventional satellites, they do not address specific LSS problems.

Since few estimates have been made of the magnitude of LSS charging problems, the list of potentially damaging effects is impressive. Specific LSS charging studies could, however, show that many problems can be eliminated with relatively simple controls with minor impact on spacecraft designs.

Now is the time to address these LSS charging/plasma interaction problems; their impact must be assessed before LSS programs proceed much beyond the conceptual design phase.

CONCLUSIONS

- ELECTROSTATIC CHARGING/PLASMA INTERACTIONS MAY HAVE SERIOUS IMPACT ON PERFORMANCE/COST OF LSS IN GEO
- CURRENT STUDIES DO NOT ADDRESS SPECIFIC LSS PROBLEMS
- LONG TERM ENVIRONMENT/ELECTRICAL DISCHARGE EFFECTS ON MATERIALS MOST CRITICAL DATA REQUIREMENT
- MANY PROBLEMS MIGHT BE ELIMINATED WITH RELATIVELY SIMPLE CHARGE CONTROLS

Figure 15

RECOMMENDATION (Figure 16)

A detailed LSS charging investigation program plan should be developed now; major LSS-oriented activities should be integrated into the current NASA/Air Force program.

The first steps in the program will include preliminary modelling/analysis of typical large systems which appear most susceptible to charging problems. Development of accelerated ground and/or flight tests to determine materials aging effects for long duration LSS missions is a most important early activity. Maximum use should be made of LDEF and SPHINX experiments to derive early material response/plasma interaction data.

Emphasis should be placed on development of flight experiments to investigate large scale plasma characteristics/interactions and verify analytical models.

RECOMMENDATIONS

- PLAN & IMPLEMENT A LSS CHARGING INVESTIGATION PROGRAM
  - INTEGRATE LSS IN CURRENT NASA/AF STUDIES
  - DEVELOP CHARGING/INTERACTION MODELS FOR LSS OPTIONS; MODIFY NASCAP PROGRAM & ESTIMATE IMPACT
  - ANALYZE ACCELERATED MATERIALS TEST METHODS; DESIGN GROUND/FLIGHT TESTS
  - DEVELOP LDEF CHARGING EXPERIMENTS; CONSIDER ELLIPTICAL OR GEO LDEF FLIGHTS
  - UPDATE SPHINX EXPERIMENTS; FLY IN LEO/ELLIPTICAL ORBIT
  - DEVELOP SCALING/PLASMA INTERACTION FLIGHT EXPERIMENTS

Figure 16