SCATHA Conductive Spacecraft Materials Development

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The development of new or modified spacecraft materials that would limit, control, and/or prevent spacecraft charging was included as part of the cooperative, interdependent Air Force/NASA Spacecraft Charging/Spacecraft Charging at High Altitudes (SCATHA) program. Materials of interest included conductive polymers, paints, transparent films and coatings, as well as fabric coatings and interweaves. The evaluation of materials charging/discharging properties in the laboratory as well as under simulated and actual space substorm charging conditions were included in the overall integrated SCATHA program. Conductive inorganic thermal control paints with a range of thermo-optical properties were developed and have been successfully applied to operational spacecraft. Conductive transparent indium oxide and indium tin oxide spacecraft charging control coatings have been developed to control the charging of flexible Kapton and FEP Teflon polymeric thermal control materials, OSR and solar cell covers, and other nonconductive dielectric surfaces. A conductive glass for application as OSR and solar cell cover glasses has been prepared. Fabric spacecraft charging control materials have been developed and evaluated. Conductive adhesives for use in conjunction with conductive antistatic spacecraft charging materials have been developed.

Introduction

A COORDINATED Air Force/NASA program to develop new or modified conductive spacecraft materials that could control or eliminate spacecraft charging was initiated as part of the cooperative, interdependent Air Force/NASA Spacecraft Charging/Spacecraft Charging at High Altitudes (SCATHA) program.[1,2] The program road map is indicated in Fig. 1. The materials of interest included conductive polymers, paints, transparent films, coatings and low outgassing adhesives, as well as fabric coatings and interweaves.

In order to meet the near-term satellite conductive materials requirements the primary approach was to investigate the development of materials modifications and techniques that could be applied to current state-of-the-art thermal control and other materials. These modified materials could then be integrated directly into the current and near-term generation of satellites without the long period (5 yr or more) necessary to space qualify new materials and to gain acceptance for their application by spacecraft designers and engineers.

Materials characterization beyond the initial screening evaluations of the materials development efforts was included in the overall SCATHA program as two individual tasks. The evaluation of the materials engineering charging/discharging characteristics and properties were to be evaluated in synchronous orbit environmental simulation facilities. The evaluation and characterization of the classical material properties, that is, photoemission, secondary emission, thermo-optical, physical and electrical properties, and so on, important to the achievement of charge control was assigned to another laboratory. However, the classical materials characterization portion of the program was delayed and it has had little impact on the materials development effort. A major objective of the characterization efforts was to provide the technical background, approaches, and direction for longer range materials development efforts.

The SCATHA P78-2 Satellite Thermal Control Materials/Contamination (ML12) and Satellite Surface Potential Monitor (SSPM), SC1 experiments were designed to measure the performance of typical conductive and nonconductive spacecraft materials under actual spacecraft charging substorm conditions. The results and status of these and related material development investigations will be reviewed.

The background and rationale for the conductive spacecraft materials development program have been reported.[2,3]

Materials Development Efforts

Conductive Thermal Control Paints

Potential approaches for development of space stable white paint-type thermal control coatings were investigated elsewhere under a contractual program.[4] Approaches included the investigation of conductive and nonconductive polymeric organic (quaternary ammonium polymers, polyvinylcarbazole) and inorganic (alkaline silicate) binders applied separately or in conjunction with conductive pigments, fibers, or filaments. The development of conductive, space stable (5-10 yr), white thermal control coatings by these routes was judged to be a long-term, high-risk task requiring a minimum of at least 5 yr of research and development, and further development was not pursued.

A series of conductive inorganic based thermal control paint-type coatings have been developed[5] at NASA Goddard Space Flight Center for application to the International Sun Earth Explorer (ISEE A, B, and C) spacecraft (Table 1). The coating specification called for bulk resistivity less than 1×10^5 Ω-m^2, absorptance less than 0.59, and normal emittance of 0.90 after exposure to a 4×10^{16} protons/cm^2 of solar wind particles and 5300 ESH (equivalent sun hours) with less than 0.07 degradation in absorptance. These coatings are formulated of doped, conductive zinc oxide pigments in mixed alkali silicate binders. The development of the conductive doped oxide pigments was based in part on an earlier Air Force sponsored program. Formulations of these materials were qualified in the laboratory and have been flown successfully on the ISEE A, B, and C spacecraft, SCATHA P78-2, GEOS, and Dynamic Explorer. They have also been applied to a Swedish satellite and are scheduled for application to the Italian San Marcos spacecraft. White, green, and yellow formulations have been flown and operational performance has followed laboratory predictions. Materials and specifications are available through NASA Goddard.

A silicate binder-zinc orthotitanate (ZOT) pigmented thermal control coating has been developed under NASA sponsorship.[6] Solar absorptance to emittance ratios as low as 0.12 can be achieved and the change in solar absorptance after

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Table 1 Conductive inorganic thermal control paints

Paint	Area resistance, ρd (Ω-m^2)	Absorptance, α	Emittance, ϵ
NS 43G	1.7×10^3	0.38	0.90
NS 53B	1×10^3	0.52	0.87
NS 43E	2×10^3	0.57	0.89
NS 43C	1×10^3	0.20	0.92
NS 55F	6×10^4	0.57	0.91

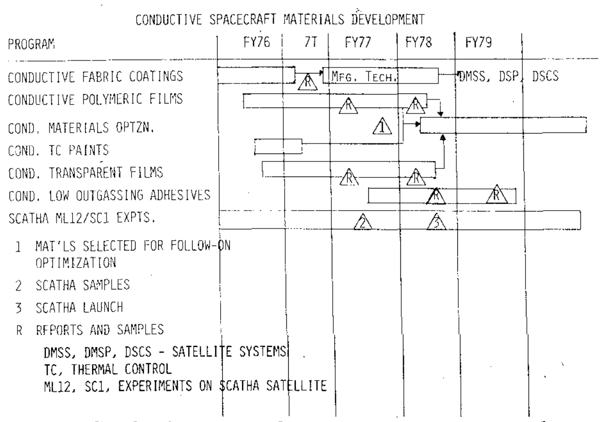

Fig. 1 Conductive spacecraft materials development road map.

1000 ESH of laboratory simulated ultraviolet (UV) exposure is less than 0.01. The material, when applied over a grounded metallic substrate, does not charge under simulated spacecraft charging conditions. Performance over nonconductive substrates has not been determined. Limited synchronous orbit performance indicates a higher, steady rate of increase in solar absorptance than measured in the laboratory with no evidence of levelling off or saturation. Further development to obtain optimum properties has been proposed.

Conductive Polymeric Films

The development of techniques and modifications that would reduce or prevent the accumulation of charge on FEP Teflon and Kapton polymeric films was also pursued under contract elsewhere.[7] These two materials in the form of metallized second surface mirror-type coatings or as the outer layers of multilayer insulation blankets find extensive use on satellites. They can comprise over 90% of the outer covering of a spacecraft, excluding solar array panels. Approaches included materials modifications, application of conductive metallic or oxide screens or grids, and the application of the transparent conductive coatings.

Modification of the basic polymer films to increase the inherent electrical conductivity through the introduction of metal complexes or other chemical entities or the development of new conductive polymers were considered to be long term and high risk and were not attempted. Production of radiation damage tracks through the films and subsequent chemical treatment to provide localized charge leakage paths to the back surface was also considered but not pursued due to significant on-orbit degradation in optical properties which would result.

Application of conductive grids were evaluated in considerable detail.[8,9] Conductive grids formed by photoetching copper or silk screening silver paint were found to be effective in controlling the charge buildup and discharging on Kapton in electron plasmas up to 25 keV and 30 nA/cm^2. Thermo-optical properties of the Kapton were not seriously degraded since only 6% of the Kapton was covered by the grid. Very poor performance was realized with metallic grids on FEP Teflon. The material was difficult to handle. The chemical treatments required to effect the adhesion of the grids degraded the space radiation stability of the substrate FEP and the shadowing due to the grids significantly reduced the thermo-optical properties of the metallized film. Because of the difficulties in grid application and degradation of thermo-optical properties of the resulting films, this approach was dropped. Emphasis shifted to the more promising thin, transparent conductive coating approach that was being investigated concurrently under a separate contractual program.

Kapton polymeric film has long been accepted as a space stable insulating material. Laboratory measurements to explore the effects of various external parameters of a simulated space environment on the conductivity properties of Kapton and several other materials indicated significant increases in the bulk conductivity of Kapton after photoillumination.[10] Measured bulk currents under illumination were more than four orders of magnitude higher than the dark bulk current. Results from the Satellite Surface Potential Monitor (SSPM) flown on the P78-2 SCATHA satellite indicate long-term changes in the properties of Kapton when exposed to the space environment.[11] Kapton, when exposed to long-term solar UV in the synchronous space environment, changed its electrical conductivity to the extent that surface charging was no longer important after one year in space. Further work will be required to explain and exploit this technology.

A contractual program to develop noncharging dielectric polymeric spacecraft materials by "molecularly engineering" bulk conductivity into them has recently been initiated.[12] The goal of the program is to find candidate polymers with bulk conductivity exceeding 10^{-12} mho/cm and to propose a list of potential polymers with this conductivity which simultaneously satisfy other spacecraft polymer requirements. Potential approaches include charge transfer complexing, ion mobility enhancement, conductive polymerization, and so on. The bulk conductivity is necessary to prevent in-depth trapped charges which can cause spacecraft charging problems. This program is in progress.

Conductive Adhesives

A conductive low outgassing/contamination graphite loaded adhesive has been developed and evaluated for bonding conductively coated OSRs.[13] The adhesive composition consisted of RTV silicone filled with 13% by weight of 0.25 mm chopped graphite fibers. The RTV formulation produced a resistivity of about 7.5×10^4 Ω-cm. Used in combination with IO- or ITO-coated OSRs, it has been shown to provide a space stable system that provides a reliable conductive path between the coating and grounded support.

In another program, filler studies indicate that graphite fiber fillers provide increased conductivity in DC 93-500 and RTV 567 silicones at lower loadings than silver powders or silver-coated glass spheres.[14]

A conductive adhesive technique for the grounding of transparent conductive thin film ITO-coated polymeric thermal control coating materials has been developed at ONERA/CERT under an AFOSR grant.[15-17] Good electrostatic performance and durability of the components combining ITO-coated metallized Kapton and FEP Teflon

Table 2 Indium tin oxide (ITO) and indium oxide (IO) with dc biasing

Deposition	Thickness, Å	Substrate	Resistance (as deposited), Ω	Resistance (2 weeks later), Ω
ITO	300	Microsheet	10-20 K	10-20 K
		Kapton	10 K	700 K
		FEP	4 K	200 K
ITO	100	Microsheet	30-40 K	5-10 MEG
		Kapton	10 K	2-5 MEG
		FEP	2-5 MEG	20-50 MEG
IO	300	Microsheet	1 K	2 K
		Kapton	1 K	2 K
		FEP	4-7 K	16-40 K
IO	100	Microsheet	10 K	100 K
		Kapton	10-14 K	50-100 K
		FEP	10-30 K	70-100 K

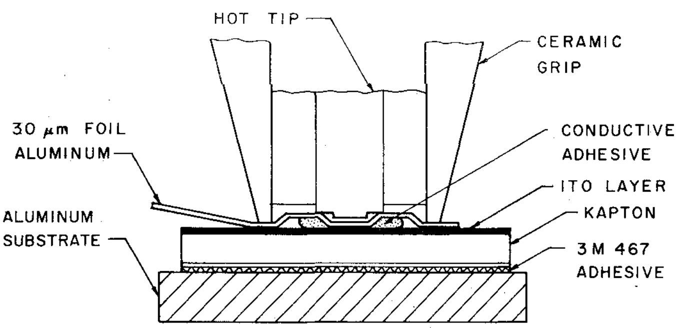

Fig. 2 Conductive adhesive/ITO heated tool bond formation.

films with aluminum foil ground straps by means of a silver (CHO-bond 1029B) loaded silicone (RTV 566A plus RTV 566B catalyst) have been achieved. A heated tool (Fig. 2) was designed and developed to cure the electrical joints. A prequalification test program has confirmed this technique for satellites.[17]

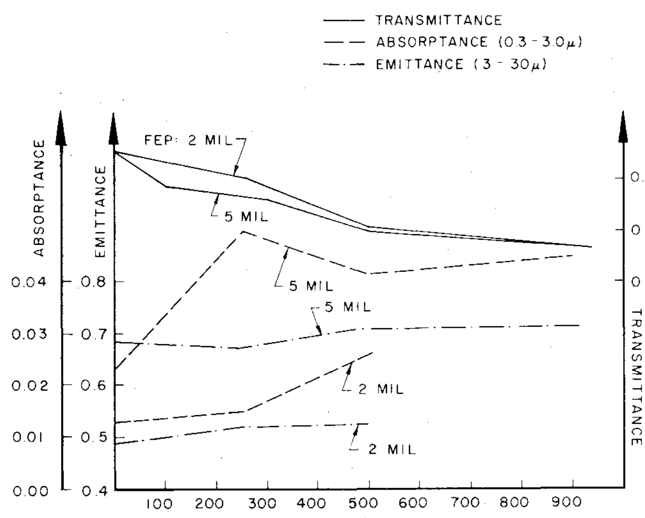

Fig. 3 Variation of ITO thermo-optical properties with thickness.

Conductive Transparent Films

Conductive transparent thin films of indium oxide (IO) and of 90% indium oxide: 10% tin oxide mixture (ITO) have been developed[7] that will control the electrostatic charge buildup on metallized Kapton and FEP Teflon thermal control coating materials (Table 2). These same films have also been applied to OSR and solar cell coverglass tiles as well as other dielectric substrates. Deposition has been demonstrated reactively by Magnetron and dc sputtering and by resistive heating from In/Sn and In targets in a controlled oxygen and argon atmosphere and nonreactively from metal oxide targets. Magnetron reactive sputtering from the metal or metal alloy in a controlled oxygen-argon atmosphere with dc bias appears to be the preferred technique for producing uniform, reproducible conductive coatings on metallized Kapton and FEP Teflon.

The conductive IO and ITO films have little effect on the thermo-optical properties of the basic metallized Kapton and FEP Teflon thermal control substrate materials. The effect of coating thickness on optical properties is shown in Fig. 3. In general, the IO and ITO films on Kapton and glass substrates are quite durable and stable to handling and abrasion. Similar films applied to FEP Teflon are relatively soft and must be handled with care. Laboratory shelf life of over 2 yr has been demonstrated with little or no change in properties.

IO and ITO conductively coated FEP Teflon and Kapton films have been tested under electron irradiation in charging control facilities and the materials do not charge or display any evidence of discharge.

Combined simulated space electron and solar UV irradiation for 500 and 1000 h of IO and ITO coated and uncoated Kapton and FEP Teflon caused the same relative change in solar absorptance indicating the stability of the thin films. Samples of IO coated aluminized Kapton and a fused silica mirror were included in the SCATHA ML12 Thermal Control/Contamination Experiment.[18] Comparison of the solar absorptance vs time curves of the conductively coated samples with their uncoated counterparts suggests that both coated samples degraded more rapidly during the first four months on orbit than did the uncoated samples.[19] No attempt was made to ground the coating on these samples in the experiment. Therefore, the surface may charge and affect the kinetic energy of the arriving charged particles just as occurs with uncoated samples. Similar considerations have been presented relative to ITO coated FEP Teflon.[20] The degradation of the optical properties of ITO layers on polymeric films under simulated space environmental radiation is reported to be very dependent on deposition method and manufacturer.[21] Additional work will be required to resolve the results observed.

As indicated under the adhesives section, a stable grounding system for application with the thin IO and ITO coated polymeric films has been developed.

Experience indicates that Magnetron sputtering can be scaled up with little loss in coating characteristics. Efforts are currently underway to scale up from 12×12 in. coated samples to continuous 36 in. widths using a planar Magnetron and roll-to-roll techniques.[22]

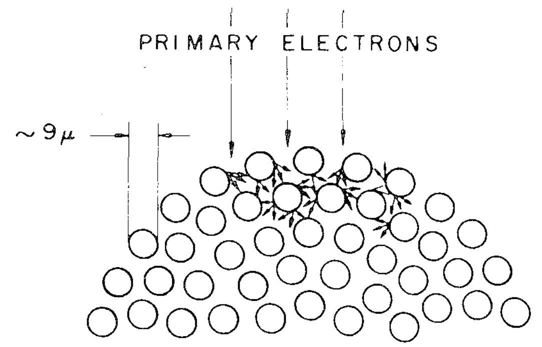

Fig. 4 Quartz fabric thermal control coating yarn cross section.

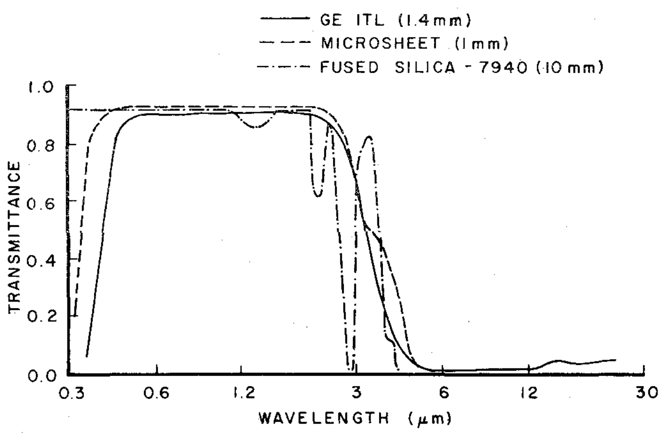

Fig. 5 Transmittance of fused silica, borosilicate, and conductive lithium borosilicate glass.

Fabric Spacecraft Charging Control Materials

High purity silica fabrics and interweaves of silica with metallic and conductive carbon fibers have been proposed and developed for application as stable, low outgassing thermal control coatings to control the effects of spacecraft charging.[23] These materials exhibited very quiet behavior, nonarcing, under laboratory simulated substorm conditions to at least 30 keV. Secondary emission conductivity has been proposed to explain this desirable behavior. Secondary electrons produced by the primary electron beam are thought to be a cloud of free charges in the voids between the silica (Fig. 4) which can migrate/drift and conduct the charge through the fabric to the conductive back surface or edge attachment. Secondary emission is enhanced due to the extremely high surface area encountered by the incident electron and the enhanced efficiencies of secondary electron production as the higher energy incident electrons are decelerated due to the many collisions to energies more favorable for efficient secondary production. Electron bombardment-induced surface conductivity probably also contributes to the discharging process.

Results from the SCATHA SSPM experiment indicated an unexpected high, 3600 V, negative voltage on a sample of quartz fabric during a natural charging event. The quartz fabric sample is a composite of quartz fabric bonded to aluminum foil by a thin layer of FEP Teflon which is, in turn, adhesively bonded to the satellite or substrate. Studies[16,24] as part of the program under an AFOSR grant have indicated that the charging performance of the fabric is a function of secondary emission, induced charging and discharging, sample capacitance, and beam current and voltage. Surface potentials as high as those measured on orbit have been measured at low flux rates, less than 0.1 nA/cm^2. However, only microarc discharges carrying very small amounts, microamperes, of current are observed when the fabric does discharge. Although this charge level would interfere with scientific satellite instrumentation to make measurements of low level incident radiation the material does not arc and can be effectively applied as a nonarcing space stable thermal control material. Results from the ML12 experiment indicate that the FEP Teflon bonded fabric has a lower absolute increase in solar absorptance than plain FEP Teflon/Ag for long missions.

Contamination of the fabric increases the surface potential under low-energy electron irradiation because the secondary emission is lowered. Therefore, in space the good electrostatic behavior of the fabric will be progressively degraded if care is not exercised in controlling or preventing contamination.

Wren et al.[25] specifically recommend that the role of secondary emission in controlling the potential of electron irradiated surfaces be investigated and that the development of space stable materials with a secondary yield greater than unity for incident multi-keV electrons would be particularly important. Variations of the fabric approach may play a key role in the development of such improved materials.

Development of Conductive Glass

A conductive lithium borosilicate glass was developed.[13] The material has good optical transmission (Fig. 5) and resistance to high-energy (beta) radiation and is considered a potential substitute for application as OSRs and solar cell covers to prevent static charge buildup. Silvered OSRs prepared from this material had a solar absorptance of 0.12 and an emittance of 0.86. With a resistivity of 2×10^{10} Ω-cm the material eliminates the need for transparent conductive coatings, interconnects or fillets in order to effect a durable conductive path from front surface to ground. Electron irradiation tests of an OSR array of conductive mirrors made of this material showed no significant charge buildup. Further development and scaleup are required before practical applications of this material are possible.

Summary and Conclusions

New and improved conductive spacecraft materials and associated grounding materials have been developed and evaluated under the SCATHA and related materials development programs. These materials, properly applied in conjunction with proper circuit design satellite charge modeling studies, etc., will do much to help control or essentially eliminate the problems associated with spacecraft charging/discharging. Additional approaches for the development of other new materials and of materials requiring further development and optimization have been identified. Work is continuing on a limited basis due to limited resources and higher priorities in other areas.

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