SPACECRAFT CHARGING MATERIAL PROPERTIES DATABASE

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ABSTRACT

NASA is developing a Spacecraft Charging Materials Database (SCMD), an on-line resource for archive and distribution of material electrical properties data required for performing surface charging, internal charging, and radiation transport analyses. Examples of relevant material parameters are volume and surface resistivity, dielectric constant, secondary electron and backscatter yields, photoelectric current density, radiation induced conductivity coefficients, material mass density, atomic number, and atomic weight. In addition, full text reports describing the laboratory test methods used to obtain the material parameters will be included when available. The sources of material properties data to be included in SCMD include parameters from the original NASCAP surface charging model materials and new test data contributed from industry, academia, and government laboratories. The goal is to provide a resource for the US and international spacecraft charging community to share the electrical properties of materials required for conducting charging analyses. This paper presents an overview of the basic equations used to model surface and internal charging, the material parameters included in those equations, a description of the SCMD, and information on how to access SCMD and submit new material information for inclusion in the database.

INTRODUCTION

Materials exposed to the space environment accumulate a net charge due to differential collection of ion and electron currents from the space radiation and plasma environment. The magnitude of the electric potential and electric fields generated by an excess charge density on (or in) a material is an important consideration for the design and operations of space systems. Accumulation of significant charge can lead to electric fields that exceed the electrostatic breakdown strength of materials, resulting in an electrostatic discharge (ESD). ESDs can be responsible for a number of detrimental effects including material degradation, electromagnetic interference, lock-up of computer systems, solar array damage, and even catastrophic failure of electronic components in extreme cases. Evaluating possible charging threats to a spacecraft depends on knowledge of both the range of environmental conditions (charged particle flux as a function of energy) to be encountered by the spacecraft during its operational lifetime and the electrical properties and grounding configuration of the materials exposed to the charged particle environment. The material properties are particularly important since two spacecraft may exhibit dramatically different charging behaviour in the same environment if different materials are used in their construction. Therefore, evaluating spacecraft charging risks requires a knowledge of the fundamental physical and electrical properties of the materials exposed to the space environment. Exposure to the environment includes both surface materials impacted by low energy charged particles (surface charging) as well as thicker materials and hardware inside the spacecraft impacted by penetrating energetic electrons (internal charging).

The outline of this paper is as follows. First, we present a summary of the basic equations used to model surface and internal charging and discuss the material parameters included in those equations. We then describe the new Spacecraft Charging Materials Database (SCMD) in development by NASA to collect and share information on the electrical properties of materials required for conducting charging analyses. Finally, we provide information on how to access the SCMD and the process used to submit new material information for inclusion in the database.

SECTION 2 SPACECRAFT CHARGING MODELS

Spacecraft charging processes are commonly described as either surface charging or internal (sometimes called "deep dielectric") charging based on the penetration depth and energies of the charged particles available in the space radiation environment. The surface charging classification applies to low energy ion and electron currents to and from material surfaces due to charged particles with energies approximately 50 keV or less. Internal charging occurs when energetic electrons with energies exceeding 50 keV up to 1 to 10 MeV or more penetrate into the interior of insulating materials or completely through a spacecraft wall to charge insulators and conducting components on the interior of a spacecraft body.

2.1 Surface Charging

Surface charging models are numerical finite element codes that solve for potentials and electric fields on the

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surfaces and region of space surrounding a spacecraft as a function of time dependent ion and electron currents to and from the spacecraft surface. In its simplest form, surface charging of a surface area exposed to a charging environment is described by

$$\frac{dQ}{dt} = C\frac{dV}{dt} = \sum_j I_j \qquad (1)$$

where Q is the net charge on the surface, C is the capacitance of the surface with respect to space, and the sum over I_j currents represent the j=1,2,3,… current collection processes that add or remove charge from the surface. The currents most commonly encountered in spacecraft surface charging include

$$\sum_j I_j = \qquad (2)$$

$+I_i(V)$	incident ions
$-I_e(V)$	incident electrons
$+I_{bs,e}(V)$	backscattered electrons
$+I_{e,se}(V)$	secondary electrons due to electrons
$+I_{i,se}(V)$	secondary electrons due to ions
$+I_{ph,e}(V)$	photoelectrons
$+/-I_C(V)$	conduction currents
$+/-I_{beam}(V)$	active current sources including charged particle beams, thrusters

Currents with a positive sign include incoming ions and outgoing electrons while currents with a negative sign are due to incident electrons. The conduction and beam currents may be positive or negative depending on the sign of the net current flowing into or out of the surface. The magnitude of the backscattered, secondary, and photoelectron currents are all fundamental properties of the materials and how they interact with the charged particle and energetic photon environments in space.

Material electrical properties are important in the conduction current term. The conduction current density J_C due to currents I_C in an element with area A is

$$J_C = \frac{I_C}{A} = [\sigma_{dark} + \sigma_{RIC}]E \qquad (3)$$

where σ_{dark} is the intrinsic (or bulk) electrical conductivity of the material in the absence of charged particles or photons and E is the electric field driving the current. The additional radiation induced conductivity (RIC) term, σ_{RIC}, is due to charge carriers generated in the material by energetic charged particles and photons in the space radiation environment.

Equations (1) - (3) are useful to demonstrate how current collection results in charge accumulation on a single surface generating a potential V that varies in time and the presence of material properties in the current collection terms. However, the physics of surface charging is complicated due to interactions between electric fields generated by charge densities on the many surfaces that occur on a realistic spacecraft body.

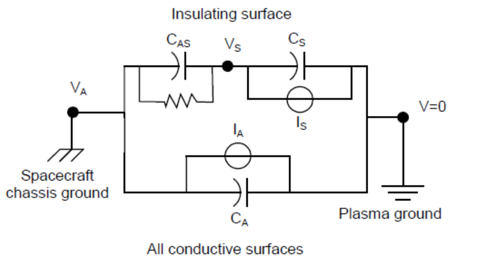

Fig. 1. Circuit Model of a Simple Spacecraft with One Insulating Surface Element and Exposed Conducting Elements [1].

A more general formulism describing the basic equations for surface charging can be seen by considering the circuit model shown in Figure 1 for a simple spacecraft composed of one insulating surface element with area S and exposed conducting elements of area A. The potentials ϕ_A and ϕ_S on the surface elements as a function of time are computed using the time integration of the coupled charging equations for the j currents to the A and S surface elements given by [1]

$$\begin{aligned} C_A\dot{\phi}_A + C_{AS}(\dot{\phi}_A - \dot{\phi}_S) &= \sum_j I_{A,j} \\ -C_{AS}(\dot{\phi}_A - \dot{\phi}_S) + C_A\dot{\phi}_S &= \sum_j I_{S,j} \end{aligned} \qquad (4)$$

The capacitances C_A and C_S of the conductive and insulating surface elements, respectively, to infinity and the capacitance C_{AS} of the insulating surface to the conducting ground are

$$C_A \sim C_S = 4\pi\varepsilon_0 r \sim rx10^{-10}\ Farad \qquad (5)$$

$$C_{AS} = \kappa\varepsilon_0\frac{S}{d} \sim \frac{S}{2}x10^{-7}\ Farad \qquad (6)$$

More complex spacecraft geometries with many surface elements require adding additional coupled equations to (4)-(6), linearizing the currents and inverting the matrix

$$\boldsymbol{C}\dot{\boldsymbol{\phi}} = \boldsymbol{I}(\boldsymbol{\phi}) \qquad (7)$$

Equations (4) – (7) are the basis of surface charging models and techniques used in the NASA and Air Force Surface Charging Model (NASCAP-2k) codes [1,2,3]. Table 1a lists the material properties required for input to NASCAP-2k along with examples for each parameter. Note that the numerical values provided in Table 1 are intended to be examples only and are not intended to represent any particular material.

The international community has developed a number of surface charging codes. The open source SPIS software is perhaps the most widely used in Europe offering many of the features of NASCAP-2k [4,5] and the SPAcecRaft Charging Software (SPARCS) is an advanced surface charging code developed in France [6]. The Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT) developed in Japan includes functions for 3-D satellite modelling, parameter inputs for material properties and orbital environment, data transfer, and visualization of numerical results [7,8]. COULOMB-2 is a surface charging code developed for spacecraft modelling applications in Russia [9]. All of the surface charging codes require access to accurate material property information similar to that used in NASCAP-2k in order to obtain quantitative results from the surface charging simulations.

2.2 Internal Charging

Internal charging models for insulators exposed to penetrating energetic electron environments are numerical finite difference solutions to the bulk charging equation set [10,11]

$$\boldsymbol{\nabla} \cdot \boldsymbol{E} = -\nabla^2 \varphi = {}^{\rho}/_{\kappa \varepsilon_0} \qquad (1)$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (J_R + J_C) \qquad (2)$$

where **E** is the electric field, Φ the electric potential, ρ the charge density, J_R the radiation (electron) current density, J_C the conduction current density in the insulator, and κ and ε_0 are the dielectric constant for material exposed to the charging environment and permittivity of free space, respectively.

Typically, contribution from energetic electrons is the only radiation current considered in the internal charging analysis. Ions at a similar energy as the electrons will not penetrate as deeply into materials. The flux of ions that have enough energy to penetrate deeply into a material or a spacecraft wall is generally small compared to the penetrating electron flux in strong internal charging environments such as radiation belts trapped in planetary magnetic fields. Therefore, ions are not a significant contribution to internal charging.

Conduction currents are given by

$$J_C = \frac{I_C}{A} = \left[\sigma + k_{RIC} \dot{D}^x\right] E \qquad (3)$$

where the bulk conductivity of the insulator σ is divided into the σ_{dark} conductivity (in the absence of exposure to photons or charged particles) and a radiation induced conductivity that depends on the dose rate $\dot{D}$ with the material generated by interaction of the radiation field with a dielectric. If the internal charging material is a

Table 1.
Spacecraft Charging Model Input Parameters

(a) NASCAP-type Surface Charging Models

Parameter	Example[1]
Trade/brand/chemical formula	Teflon®, $(C_2F_4)_n$
Atomic number[2]	19[2]
Thickness	1 mm
Dielectric constant	κ= 2.15
Volume (bulk) resistivity	$\rho_v = 1\text{x}10^{16}$ ohm-meter
Radiation induced conductivity	$\sigma_{RIC} = 1\text{x}10^{-18}$ 1/ohm-meter
Surface resistivity	$\rho_s = 10^{16}$ ohms/square
Photoelectron emission yield	$j_{pho} = 2\text{x}10^{-5}$ amp/meter^2
Secondary electron yield, electron-induced	
Yield curve fit parameters	$\delta_{max} = 3$, $E_{max} = 250$ keV
Electron range parameters	b1=142.63, q1=0.2335, b2=245.15, q2=1.7269
Secondary electron yield, ion-induced	
Yield curve fit parameters	$\delta_{1\text{-keV proton}} = 1.36$, $E_{max} = 100$ keV

(b) RIC-type Internal Charging Models

Parameter	Examples
Trade/brand/chemical formula	Mylar®, $(C_{10}H_8O_4)_n$
Atomic number[2]	11.99 atomic mass units[2]
Atomic weight[2]	6.24[2]
Thickness	2 mm
Density	1.4 g/cm^3
Dielectric constant	κ= 2.15
Volume (bulk) resistivity	$\rho_v = 1\text{x}10^{18}$ ohm-meter
RIC dose rate factor	$k_{RIC} = 2.0\text{x}10^{-14} \frac{siemens}{meter}\left(\frac{sec}{rad}\right)^x$
RIC dose rate exponent	x = 0.7
Activation energy	1.0 eV

[1]Example values are notional and do not represent any specific material
[2]Mean values defined by [12] are used for compounds and mixtures

conductor there is no additional radiation induced conductivity since charging models typically consider conductors to have infinite conductivity. The parameter k_{RIC} is the coefficient of radiation induced conductivity and the exponent 0.5<α<1 depends on the energy distribution of electron trapping states in the insulating material.

Evaluation of internal charging requires solving both a radiation transport problem to compute the charge deposition and radiation dose rates within the material and the electrostatic problem to obtain the electrostatic fields and potentials due to the accumulating charge density. The radiation transport component of the problem will require information on the density of the material and its chemical composition.

Material parameters required for an internal charging analysis are summarized in Table 1b. These examples are the material property inputs used in the 1-dimensional

(1-D) NUMIT (for "numerical integration") internal charging models [13-16] and their numerous variants [17-21]. NUMIT is widely used in the US aerospace community with the current NUMIT 2.0 version [22] the most widely used software for 1-D internal charging analyses. A 3-dimensional (3-D) version has also been developed that requires similar material property inputs [23,24].

Varieties of 1-D and 3-D internal charging models have been developed that all require similar electrical properties of materials for inputs to the codes. One example is the European DICTAT model [25-27] which is frequently used for quick internal charging analyses since it is conveniently available online at the Space Environment Information System (SPENVIS) website (URL: https://www.spenvis.oma.be/). Another example is the ESA Deep Dielectric Charging (ESADDC) code, a 1-D model utilizing the Integrated Tiger Series Monte Carlo radiation transport code [28,29]. The Moscow State University 1-D internal charging code based on the GEANT-3 [30] radiation transport code is described by [31]. Similarly, the Assessment Tool of Internal charging for Satellites (ATICS) code developed by the China Academy of Space Technology uses the GEANT-4 radiation transport code to provide a 3-D capability for modeling spacecraft structures although the current version of the code treats spacecraft panels as 1-D problems for simplicity [32]. A 1-D model has been developed by Xi'an Jiaotong University which includes temperature dependent electric field effects on the electrical conductivity [33]. The Multi-Utility Spacecraft Charging Analysis Tool (MUSCAT) developed by a Japanese Exploration Agency (JAXA) and Kyushu Institute of Technology collaboration also includes an internal charging code [34,35]. These models all use similar material properties inputs as those required for the NUMIT family of internal charging codes.

SECTION 3 SPACECRAFT CHARGING MATERIALS DATABASE (SCMD)

Whether a space environment engineer is conducting a surface or internal charging analysis, they will eventually need to identify the electrical properties of the materials used as inputs to any one the charging codes described in the previous section. Sources of good information on the electrical properties of materials have long been an issue in the space environments and effects community.

Laboratory testing is required to establish the electrical properties of a material. Many users end up testing established materials that for which test data may already exist if they do not have access to the data source and new materials will always require testing. While test data for many materials already exists, an established clearing house to let potential users know where the data can be obtained does not exist. Access to the existing data has been problematic at best and the spacecraft charging community has long recognized the need for a publicly-available electrical properties of materials database.

NASA is currently developing the Spacecraft Charging Materials Database (SCMD) to address this need to archive and share information on electrical properties of materials for the charging community. We are using the Materials and Processes Technical Information System (MAPTIS) software structure developed at NASA's Marshall Space Flight Center. NASA developed MAPTIS to archive and distribute physical properties of materials of interest to the space engineering community. While the existing databases within MAPTIS contained little information to support the spacecraft charging community before SCMD, it was relatively easy for the MAPTIS software developers to implement the new SCMD option with attributes tailored to address the spacecraft charging community needs. NASA benefited from the cost effective solution of developing SCMD inside the MAPTIS software infrastructure because it provides a ready mechanism to deploy a material property database. An additional benefit from using the MAPTIS infrastructure is that it comes with a staff of maintenance and programming support personnel available to address technical issues with the new database should they arise.

The initial (home) page that is accessed when a user logs in to SCMD is shown in Figure 2. The home page presents an introduction to the database, hyperlinks to the database template used to submit additional materials to the database, and links to NASA relevant standards, handbooks, and guidelines that are useful to the spacecraft charging community. Two links are currently provided to the NASA 4002 and 4002A spacecraft charging handbooks [36,37] but we anticipate adding additional documents in the near future. NASA documents are easily included since SCMD is a NASA developed site, but standards and guidelines from ESA, JAXA, and other space organizations can be added as well with approval from the relevant organizations. We are also planning to provide a "user manual" to help the users navigate the database and efficiently utilize the plotting and data export options.

The database was initially populated with a set of 49 materials to facilitate database development and testing activities and provide users with electrical properties of materials from a couple of sources to they can start testing the functionality of the database. One source of

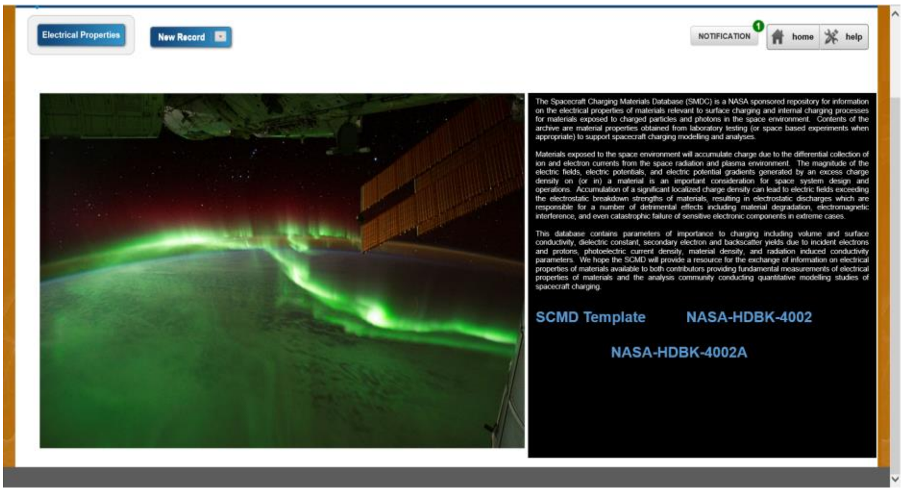

Fig. 2. Spacecraft Charging Materials Database (SCMD). This is the home page a user will see when accessing the current version of the SCMD. Links provide access to the materials properties information, the template use to submit new materials to the SCDM database, and links to standards and handbooks relevant to the spacecraft charging community.

data is the default materials properties from the NASCAP surface charging code [1,2,3] and a second source of data test results from electrical properties of materials measurements by Utah State University under contract to NASA [38].

We are currently looking at options for increasing the database holdings with additional NASA and other sources of test data. A particularly important data source for future updates will be contributions from the US and international spacecraft charging community. Towards this end, an e-mail request sent in early January 2018 to distribution lists of space environments engineering and applied space science personnel announced SCMD and provided a point of contact for interest parties to sign up for notices on future SCMD developments, how to access the database, and how to submit materials information. In addition, SCMD presentations at recent spacecraft charging and space weather conferences have served to further distribute information about the database and solicit input and recommendations for improvements from the potential user community [39,40,41].

In the upper left corner of the home page, the "Electrical Properties" button is the link that takes a user to the list of materials contained in the database. Figure 3 shows an example of the first SCMD page of materials that appears when selecting this link. An example of the material properties for aluminum is shown in Figure 4. This example shows the current material properties available in the database. Additional material properties options will be added to the database if desired by the user community. When available, full text test reports will be included in the database and users can access them through links within the pages for individual materials. Examples of relevant test information that is best captured in test reports include whether the material properties were measured under vacuum or ambient pressure, what temperatures were used for the tests, test methods used for obtaining the resistivity parameters as well as backscattered and secondary electron yields, and other information on the hardware used in the measurements. Test groups regularly write test reports documenting the methods used in their measurements of material electrical properties and archiving this information along with the material parameters is an important functionality provided by SCMD.

SCMD includes a number of functional features that are available from the MAPTIS software architecture that will provide an efficient and practical experience for the

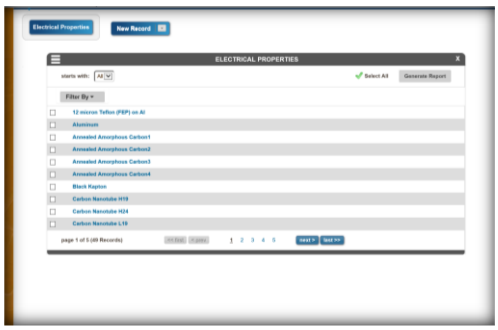

Fig. 3. SCMD List of Materials. This example shows the first page of materials that show up when first accessing the electrical properties link. Five additional pages are currently available that contain the 49 materials initially used to populate the database.

database user. Examples include options for users to search the database for specific materials or material properties, export material information to external files, generate a report for any number of properties for one or more materials at a time, or plot a particular parameter extracted from a number of materials. The information can be exported into a number of standard file formats including Excel® spreadsheets, Portable Document Format (PDF), comma separated variable (CSV), and ZIP files.

SECTION 4 SCMD ACCESS AND MATERIAL PROPERTIES SUBMISSION

We intend for the database to be publically available to the entire international spacecraft charging community. The goal is to provide a resource for the exchange of information on electrical properties of materials available to contributors providing fundamental measurements of electrical properties of materials and the user community who use the data when conducting quantitative modelling studies of spacecraft charging.

The NASA Spacecraft Charging Material Database is available to the charging community at the URL:

https://maptis.ndc.nasa.gov/scmd

Access is free and open to the international space environments and effects engineering and science community. Registration is required so the SCMD administrators can track the number of users. The current registration process requires filling out a form and emailing to the SCMD technical points of contact (POC):

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As described in the previous section, contributions of new materials and material properties from the user community are welcome and requested in order to continue to grow the database and provide a useful product to the user community. An Excel® spreadsheet template is used to submit materials data to SCMD. This template can be downloaded from SCMD for users with access to SCMD or by e-mailing a request for the template to the POC. Because the database is available to the public, no proprietary or export controlled data will be accepted

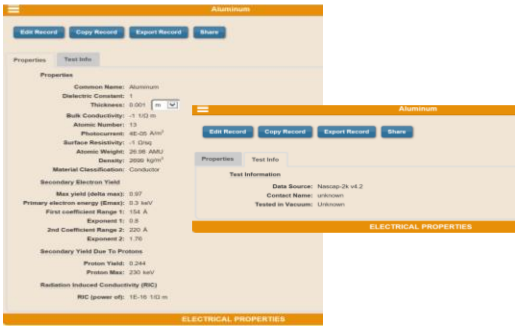

Fig. 4. SCMD List of Materials. This example shows the first page of materials that show up when first accessing the electrical properties link. Five additional pages are currently available containing 49 materials initially used to populate the database.

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