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PROGRESS REPORT

Executive Summary Report - ESA project MCSIC

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PHYSICS INSTRUMENTATION ENVIRONMENT SPACE
DEPARTMENT

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PHYSICS INSTRUMENTATION ENVIRONMENT SPACE DEPARTMENT

Progress Report N° RA 10/32018 DPHY

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Executive Summary Report - ESA project MCSIC

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Abstract :

This report is the Executive Summary Report of the ESA project MCSIC (ESA Contract No. 4000133577/21/NL/CRS). This document presents the work and results coming out from the different tasks of this project. The objective of this project was to build up a material database that would gather information on the charging properties for the most common materials used on spacecraft. A thorough experimental characterisation task has therefore been performed for the evaluation of electron induced secondary emission and photoelectron emission, bulk and surface conductivities, permittivity and to study the effect of radiation and electric-field on conductivities. This work has been followed by the development of a space material database for electrical properties aimed for the use in dedicated software such as SPIS. This project was then divided in two phases:
- Phase 1: Experimental characterization of the electrical parameters
- Phase 2: Development of a material database for electrical parameters
We will present in this summary report the main results obtained in the different tasks of this project.

Key Words :

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1. INTRODUCTION

The project aimed to create a material database that gathered information on charging properties for common materials used on spacecraft. Phase 1 involved characterization of charging properties for various materials, including polymers, polyimide materials, paints, ceramics, and epoxy resins. Tasks included secondary electron emission yield, photo-electron emission yield, bulk and surface conductivity, radiation induced conductivity, and dielectric permittivity. Task 2 focused on procuring material samples for each task. The ultimate goal was to provide physical parameters for charging prediction at material and spacecraft systems level and assess the influence of physical processes. Phase 2 aimed to create a European database of electrostatic characteristics of space materials, archived measurements, and developed a software framework for simulation SPIS software.

2. PHASE 1 : CHARACTERISATION OF MATERIAL PROPERTIES

2.1. Secondary Electron Emission measurements (Task 3)

For secondary electron emission measurement, the materials defined for SEE yield (TEEY) assessment are the following:

- **Black Kapton**
- **CFRP Cyanate**
- **CMX AR**
- **CMX ITO**
- **PCBE**
- **SG121**

The experiments have been done in the ALCHIMIE facility located in ISO8 lab at the ONERA. For black Kapton, we measured the effect of a bake out at 100°C for 48 h on the evolution of the Total Electron Emission Yield (TEEY). For all materials, we measured the evolution of TEEY as a function of temperature.

The results are summarized in the following tables

CMX ITO

TEEY curve parameters	$TEEY_{max}$	E_{max} (eV)	E_{C2} (eV)
23	3.17	340	3600
70°C	3.17	340	3600
100°C	3.19	380	3600
150°C	3.17	450	3600

PCBE

TEEY curve parameters	$TEEY_{max}$	E_{max} (eV)	E_{C2} (eV)
-100 °C	1.73	220	?
23°C	1.59	220	?
150C	1.47	200	?

CMX AR

TEEY curve parameters	$TEEY_{max}$	E_{max} (eV)	E_{C2} (eV)
23	1.4	60	
70°C	1.4	60	
100°C	1.2	60	

CFRP Cyanate

TEEY curve parameters	$TEEY_{max}$	E_{max} (eV)	E_{C2} (eV)
-100°C	2.06	180	1600
23 °C	1.9	200	1600
150°C	1.87	200	1600

SG121

TEEY curve parameters	$TEEY_{max}$	E_{max} (eV)	E_{C2} (eV)
-100°C	1.56	220	?
23 °C	1.47	200	?
150°C	1.77	220	?

2.2. Photo-electron emission measurements (TASK 4)

For photo-electron emission measurement, the materials defined for photo-emission yield assessment are the following:

- **CMX AR**
- **CMX ITO**
- **PCBE**
- **SG121**
- **Black Kapton**

The experiments were done on CELESTE facility located in ISO8 lab at the ONERA.
The results are given in the table below.

Sample	**Aluminium (reference)**	Black Kapton	PCBE	SG121	CMX AR	CMX ITO
Slop (V/s)	**0.26**	0.19 V/s	0.20	0.22	0.11	0.29
Photoelectron yield X 10^{-5}	**1**	0.73	0.77	0.85	0.42	1.11

There is no huge difference between the measured yields on the five samples. This result may be explained by the fact that the photoelectron emission process is, as secondary electron, extremely sensitive to the first surfaces monolayers. As all the samples were stored a long time to uncontrolled atmosphere, their surfaces are covered by contamination layers of hydrocarbon and hydroxide contamination. This is attested by XPS analyses.

2.3. Bulk conductivity measurements (TASK 5)

For bulk conductivity, it was decided to test 6 different materials. 4 more materials have been added to the list for a better extraction of Radiation induced conductivity parameters.

The materials tested for bulk conductivity assessment are the following:

- Insulating material for connector: liquid Crystal Polymers **LCP** (average thickness of the sample: **190 µm)**
- Insulating material for connector: **Silastic 9280** (3 mm thick) used on Souriau like connector
- **CFRP cyanate** (5 mm thick)
- **PCBE** with PSX primer
- **SG121** with PSX primer
- **CMX 100 µm**
- **VESPEL SP1 180 µm**
- **Kapton® HN 25 µm**
- **PEEK Victrex grade APTIV 1000 25 µm**
- **Teflon® FEP 127 µm**

Bulk conductivity has been assessed in this study through the analysis of the electric potential relaxation after charging the sample with low energy electrons (20 keV). The material sample is modelled as a system composed of capacitance/resistance in parallel.

Table 1 and Table 2 show conductivity values for the various materials at different temperatures. Some materials had low conductivity, resulting in maximum provided values. PCBE and SG121 paint samples did not present surface potential due to high relaxation kinetics. The Adamec & Calderwood law was used to determine bulk conductivity for these materials:

$$\sigma(E,T) = \sigma(0)\left(\frac{2 + Cosh\left(\frac{\beta_{PF}\ E^{0.5}}{2kT}\right)}{3}\right)\left(\frac{2kT}{eE\delta}\sinh\left(\frac{eE\delta}{2kT}\right)\right)$$

with $\beta_{PF} = \left(\frac{e^3}{4\pi\varepsilon_0\varepsilon_r}\right)^{1/2}$

Table 1 : Conductivity values extracted for all materials except PCBE and SG121

	CMX	Kapton® HN 25 µm	PEEK APTIV 1000	Teflon® FEP	LCP	Vespel SP1	Silastic	CFRP Cyanate
70°C	$2.5\ 10^{-13}$	$< 6.\ 10^{-17}$	$< 6\ 10^{-18}$	$< 2.4.\ 10^{-17}$	$< 3.\ 10^{-16}$	$< 1.3.\ 10^{-16}$	$1.4.\ 10^{-15}$	$> 10^{-12}$
20°C	$2.1\ 10^{-13}$	$< 2.\ 10^{-17}$	$< 1.5\ 10^{-18}$	$< 2.\ 10^{-17}$	$< 3.\ 10^{-17}$	$< 8.\ 10^{-17}$	$8.\ 10^{-16}$	$> 10^{-12}$
-150°C	10^{-14}	$< 3.\ 10^{-18}$	$< 8\ 10^{-19}$	$< 1.\ 10^{-16}$	$< 6\ 10^{-18}$	$< 1.\ 10^{-16}$	$2.8.\ 10^{-17}$	$> 10^{-12}$

Table 2 : Conductivity values and model parameters extracted for PCBE and SG121

	PCBE		SG121	
	Conductivity values ($\Omega^{-1}.m^{-1}$)	Adamec-Calderwood parameters	Conductivity values ($\Omega^{-1}.m^{-1}$)	Adamec-Calderwood parameters
70°C	> 10^{-12}	-	> 10^{-12}	-
20°C	> 10^{-12}	-	> 10^{-12}	-
-150°C	8.7 10^{-14} @ 2.5 10^{6} $V.m^{-1}$	$\beta_{PF} = 10^{-23}$ $J.m^{1/2}.V^{-1/2}$ $\sigma(0) = 4.5\ 10^{-15}\ \Omega$ $\delta = 5\ 10^{-9}$ m	1.7 10^{-14} @ 8.5 10^{6} $V.m^{-1}$	$\beta_{PF} = 8.10^{-24}$ $J.m^{1/2}.V^{-1/2}$ $\sigma(0) = 8\ 10^{-17}\ \Omega$ $\delta = 3\ 10^{-9}$ m

2.4. Radiation-Induced Conductivity measurements (Task 6)

For radiation-induced conductivity, 6 different materials have been tested:

- **Insulating material for connector**: Liquid Crystal Polymers LCP
- **CFRP epoxy**
- **Kapton** (thin – 25 µm)
- **Teflon FEP**
- **PEEK**
- **VESPEL SP1**

Radiation-induced conductivities have been assessed in this study through the analysis of the electric potential relaxation after charging the sample with low energy electrons. In most prediction codes, RIC is considered to be dependent on radiation dose rate dD/dt and on two parameters k and Δ characteristic of each material:

$$\sigma_{ric} = k\left(\frac{dD}{dt}\right)^{\Delta} \quad (2)$$

for which σ_{RIC} is the radiation-induced conductivity, D is the dose, dD/dt is the dose rate, Δ a coefficient (without unit) with a value generally between 0.5 and 1 and k is the radiation-induced conductivity coefficient.

The objective, in the frame of this project, was to extract the k and Δ parameters for each defined material, as a function of temperature and electric field.

Table 3 to Table 7 present the values for the k and Δ parameters for the different materials and for the different applied temperatures and electric fields.

The CFRP epoxy sample did not present any significant charging potential. It was thus not possible to extract RIC on this material.

Table 3 : RIC related parameters, k and Δ, for Vespel as a function of temperature and electric field (no unit for Δ, unit for k : $S.m^{-1}.(Gy.s^{-1})^{-\Delta}$)

		Electric field (V/m)		
Temperature (°C)		5.10^6	6.10^6	1.10^7
-150	k	5,71E-13	7,26E-13	2,20E-12
	Δ	1,02	1,05	1,26
20	k	4,03E-13	6,69E-13	2,83E-12
	Δ	0,93	1,02	1,29
70°C	k	4,54E-13	8,58E-13	1,57E-12
	Δ	0,99	1,15	1,19

Table 4 : RIC related parameters, k and Δ, for LCP as a function of temperature and electric field (no unit for Δ, unit for k : $S.m^{-1}.(Gy.s^{-1})^{-\Delta}$)

		Electric field (V/m)		
Temperature (°C)		4.10^6	1.10^7	$1.5.10^7$
-150	k	9,94E-14	1,34E-13	1,16E-13
	Δ	0,84	0,88	0,83
20	k	1,47E-13	2,18E-13	2,37E-13
	Δ	0,81	0,90	0,94
70°C	k	1,78E-13	1,34E-13	2,60E-13
	Δ	0,78	0,88	0,89

Table 5 : RIC related parameters, k and Δ, for Teflon® FEP as a function of temperature and electric field (no unit for Δ, unit for k : $S.m^{-1}.(Gy.s^{-1})^{-\Delta}$)

		Electric field (V/m)		
Temperature (°C)		2.10^7	3.10^7	4.10^7
-150	k	3,03E-14	4,94E-14	8,16E-14
	Δ	0,62	0,68	0,79
20	k	4,67E-14	7,52E-14	9,26E-14
	Δ	0,65	0,76	0,79
70°C	k	1,82E-13	3,04E-13	2,88E-13
	Δ	0,64	0,74	0,70

Table 6 : RIC related parameters, k and Δ, for Victrex PEEK 1000 as a function of temperature and electric field (no unit for Δ, unit for k : $S.m^{-1}.(Gy.s^{-1})^{-\Delta}$)

		Electric field (V/m)		
Temperature (°C)		1.10^7	2.10^7	4.10^7
-150	k	2,42E-13	3,58E-13	2,29E-13
	Δ	0,94	0,96	0,91
20	k	2,34E-13	3,71E-13	6,21E-13
	Δ	0,89	0,94	1,07
70°C	k	2,83E-13	4,05E-13	5,79E-13
	Δ	0,94	0,94	1,03

Table 7 : RIC related parameters, k and Δ, for Kapton® HN 25 µm as a function of temperature and electric field (no unit for Δ, unit for k : $S.m^{-1}.(Gy.s^{-1})^{-\Delta}$)

		Electric field (V/m)		
Temperature (°C)		1.10^7	2.10^7	3.10^7
-150	k	2,00E-13	1,43E-13	5,46E-13
	Δ	0,97	0,88	0,96
20	k	1,91E-13	1,55E-13	7,26E-13
	Δ	0,93	0,88	1,05
70°C	k	2,74E-13	2,11E-13	8,33E-13
	Δ	1,04	0,98	1,04

2.5. Surface conductivity measurements (Task 7)

For surface conductivity, it was decided to test 8 different materials.

The materials defined for surface conductivity assessment are the following:

- **Coverglass CMX AR (P1)**
- **Coverglass CMX (P1)**
- **OSR UVS / CMX (P1)**
- **PCBE (P1)**
- **SG121 (P1)**
- **Teflon® FEP (P1)**
- **PEEK (P1)**
- **Kapton (thin – 25 µm) (P1)**

We also tested a film of **germanised Kapton (Kapton/Ge)** as a reference material for the different tested sample batches. The method applied for the measurement of surface conductivity is based on the conventional ASTM-D257 test standard method. In this method, the surface resistance is determined by the measurement of current flowing between two concentric electrodes placed at the surface of the tested sample.

Table 8 to Table 10 present the measurements results and the extracted values for surface resistance for all materials at the three temperature levels. For material SG121, the measurements were erratic and it was not possible to extract the surface resistance: the reason is certainly due to the fact that the metal deposited at the surface of the material (for the electrode fabrication) may diffuse in the bulk of the paint because of its porosity.

Table 8 : Results on surface resistance measurements at -150°C

	CMX AR	CMX	OSR UVS	PCBE	SG121	Teflon® FEP	PEEK	Kapton 25 microns	Kapton / Ge
Applied voltage (V)	325	325	25	375		225 V	225 V	225	125
Measured current (A)	5,00E-14	2,00E-14	> 0,02	2,00E-14		< 1 fA	< 1 fA	< 1 fA	5,00E-08
Resistance (Ω)	6,50E+15	1,63E+16	< 1250	1,88E+16					2,50E+09
Surface resistance (Ω□)	1,67E+17	4,17E+17	< 3,2E4	4,81E+17	Not measurable	>6e18	>6e18	>6e18	6,41E+10

Table 9 : Results on surface resistance measurements at 20°C

	CMX AR	CMX	OSR UVS	PCBE	SG121	FEP	PEEK	Kapton 25 microns	Kapton / Ge
Applied voltage (V)	325	325	25	225		225 V	225 V	225	125
Measured current (A)	8,00E-14	1,00E-13	> 0,02	3,00E-14		< 1 fA	< 1 fA	1,00E-14	2,60E-05
Resistance (Ω)	4,06E+15	3,25E+15	< 1250	7,50E+15				2,25E+16	4,81E+06
Surface resistance (Ω□)	1,04E+17	8,33E+16	< 3,2E4	1,92E+17	Not measurable	>6e18	>6e18	5,77E+17	1,23E+08

Table 10 : Results on surface resistance measurements at 70°C

	CMX AR	CMX	OSR UVS	PCBE	SG121	FEP	PEEK	Kapton 25 microns	Kapton / Ge
Applied voltage (V)	325	325	25	225		225 V	225 V	225	75
Measured current (A)	1,00E-13	3,50E-13	> 0,02	1,60E-13		< 1 fA	< 1 fA	1,00E-14	6,40E-05
Resistance (Ω)	3,25E+15	9,29E+14	< 1250	1,41E+15				2,25E+16	1,17E+06
Surface resistance (Ω□)	8,33E+16	2,38E+16	< 3,2E4	3,60E+16	Not measurable	>6e18	>6e18	5,77E+17	3,00E+07

2.6. Dielectric permittivity measurements (Task 8)

The dielectric permittivity has been measured on ten materials:

- Insulating material for connector: Liquid Crystal Polymers **LCP**
- Insulating material for connector: **Silastic 9280** used on Souriau like connector
- **CFRP epoxy**
- **PCBE** with PSX primer
- **SG121** with PSX primer
- **CMX**
- **VESPEL SP1**
- **Kapton® HN 25 µm**
- **PEEK 1000**
- **Teflon® FEP**

Dielectric permittivity has been assessed by the application of two electrodes on each side of the samples. The electrodes are then connected to a capacitance meter (Amprobe LCR55A).

The dielectric permittivity has been assessed on all materials at 70°C, room temperature and -150°C using a capacitance meter Amprobe LCR55A (Test frequency at 1000 Hz, accuracy: ±1%).

Table 11 presents the different dielectric constant values derived from the measurements at the three temperature levels.

Table 11: Extracted values of dielectric constant for the different tested samples at 70°C, room temperature and -150°C

	Thickness (µm)	Electrode surface area (cm^2)	Permittivity @ 70°C	Permittivity @ room t°	Permittivity @ -150°C	Datasheet
LCP	205	2,5	6,4	5,6	4,5	2,9 - 3,2
Silastic	3000	4,7	Thickness too large for accurate measurement			2,9
CFRP epoxy	300	4,7	Material too conductive for capacitance			3,5 - 4,5
CFRP Cyanate	5000	4,7	Material too conductive for capacitance			
PCBE	112	10	8,2	2,5	2,2	
SG121	112	10	5,7	2,4	2,0	
CMX	100	4,7	8,4	7,8	7,2	
Vespel SP1	173	4,7	3,9	3,9	3,6	3,6
Kapton	25	4,7	3,6	3,4	3,4	3,46
PEEK 1000	25	4,7	3,3	3,3	3,2	3,2 - 3,3
Teflon® FEP	100	4,7	2,2	2,2	2,2	2,2

3. PHASE 2 : MATERIALS LIBRARY AND PLUG-IN IMPLEMENTATION

3.1. Material library and plugin requirements (Task 9)

An extensive User Requirements phase has been performed to identify the needed elements for the material library. The requirements have been produced considering various inputs:

- The statement of work for this activity provided by ESA has been a first starting point of requirements.
- The SPINE community has been consulted, especially in the frame of the 28th SPINE meeting, the 08th of June 2021 (Web meeting) and with the users' feedback collected on the SPINE forum (see https://www.spis.org). The precise requirements provided by the SPINE community remain very limited but have outlined the relevance to improve the list of materials provided with SPIS and this in both number of materials and updates of properties to follow the technological evolutions.
- The collection of feedback and results of several previous activities related to material properties databases, conversions bridges and multi-physics approaches have also been considered. It includes the study for the interoperability between the CNES/Matrex database and the SPIS tool, the material local database tool CNES/Mama, the ESA/Cirsos project, the ESA/Interop project and the human-science data tool ArchEthno for CNRS and ENS.
- The ChaMISEn database and format has been studied in detail with the help of the ONERA team who also provided inputs and feedback on requirements.

All these inputs have been treated to obtain the final list of User Requirements presented in detail in the deliverable D4 "User Requirement Document for the SPIS Materials Catalogue Manager (MCM)".

A total of 48 User Requirements (UR) have been identified, sorted into 6 categories:

- 16 UR in Software execution, functions and user-interface.
- 13 UR in Data-models and conversion requirements.
- 5 UR in Software Quality requirements.
- 7 UR in Software design requirements and constraints.
- 5 UR in Software management and operation requirements.
- 2 UR in Software validation requirements.

3.2. Material library and catalog manager (Task 10)

This task consisted in two main actions:

- The development of the Charging Catalogue Manager to ease the visualisation, edition and selection of materials for Spacecraft Charging
- The extraction of relevant data from raw measurements from phase 1 to produce the material catalogue under ChaMISEn format.

A new application has been developed using the Keridwen framework to implement the needed functions for the catalogue manager. The developed application covers most of the User Requirements, with only 4 UR of low priority (“shall” priority) have not been implemented in the final application.

Following the development, a verification campaign started to validate the developed application against the User Requirements. An elaborated test plan has been previously established to cover all the functions of the software. The verification campaign was successful and all tests have been performed without any issue discovered.

3.3. Gap Analysis and roadmap (Task 11)

The ChaMISEn data-model, based on the SPASE model for space physics, aims to track experiment performance information and store material characteristics datasets for scientific exploitation. However, it faces challenges in defining access rights, particularly for non-European and private sector entities. The ChaMISEn specification does not impose a preferred Data Management System (DMS), but the heterogeneous nature of ChaMISEn resources prevents relational databases like SQL from being used. To create a centralized European database for material properties, a network of databases should be created, with a governance body acting as a forum and standardization authority. A decentralized scheme is essential for academic institutions and industries to manage their databases while contributing to a central registry. A user-friendly database requires a centralized registry with access to all affiliated databases, under governance body responsibility. ChaMISEn advocates for persistent data formats for archiving data and suggests using XML formats like VOTable for ASCII human-readable data.

The ChaMISEn framework offers metadata for material characteristics and experimental measurements but lacks search and interrogation capabilities. It could be improved by integrating with databases through standard libraries, such as ONERA's COMPEX, for efficient data extraction and model-specific characteristics. Proper handling of data and diffusion schemes is crucial for accurate simulations in open-source models and software like SPIS. Access control mechanisms and identification mechanisms like

DOIs can help control material properties and ensure long-term traceability. The identification mechanism for material properties should include a validation criteria, like the CNES/Matrex database. The ChaMISEn database emphasizes the importance of storing data and models in a material database, enabling better understanding by consuming software. The proposal is to upgrade the catalogue file format for SPIS to 2.0.0-XML file format to improve persistency and facilitate future evolutions. An identification tag for each material, similar to the Digital Object Identifier (DOI), is proposed to ensure material validity and reliability.