Simulated Aging of Spacecraft External Materials on Orbit

S.A. Khatipov[**]
Moscow Engineering Physics Institute (State University)
31, Kashirskoye Shosse, Moscow, 115409, Russia

Abstract

Moscow State Engineering Physics Institute (MIFI), in cooperation with Air Force Research Laboratory's Satellite Assessment Center (SatAC), the European Office of Aerospace Research and Development (EOARD), and the International Science and Technology Center (ISTC), has developed a database describing the changes in optical properties of materials used on the external surfaces of spacecraft due to space environmental factors. The database includes data acquired from tests completed under contract with the ISTC and EOARD, as well as from previous Russian materials studies conducted within the last 30 years.

The space environmental factors studied are for those found in Low Earth Orbits (LEO) and Geosynchronous orbits (GEO), including electron irradiation at 50, 100, and 200 keV, proton irradiation at 50, 150, 300, and 500 keV, and ultraviolet irradiation equivalent to 1 sun-year. The material characteristics investigated were solar absorption (α_S), spectral reflectance (ρ_λ), solar reflectance (ρ_S), emissivity (ε), spectral transmission coefficient (T_λ), solar transmittance (T_S), optical density (D), relative optical density (D/x), Bi-directional Reflectance Distribution Function (BRDF), and change of appearance and color in the visible wavelengths. The materials tested in the project were thermal control coatings (enamel, 8 trade marks), multilayer insulation (films, 3 trade marks), fabrics (6 trade marks) and solar cells (6 trade marks).

The ability to predict changes in optical properties of spacecraft materials is important to increase the fidelity of space observation tools, better understand observation of space objects, and increase the longevity of spacecraft. The end goal of our project is to build semi-empirical mathematical models to predict the long-term effects of space aging as a function of time and orbit.

Key words: *external materials of space vehicles; space environment factors; UV-radiation; electrons; protons; optical characteristics; the DB is in the format of DBMS Access2000*

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[*] This work was supported financially by Air Force Research Laboratory's Satellite Assessment Center (SatAC), the European Office of Aerospace Research and Development (EOARD, London) and performed under the contract #2342p to the International Science and Technology Center (ISTC, Moscow). Leading Institution – Moscow Engineering Physics Institute (MIFI), Supporting Institution 1 – D. V. Skobeltsyn Research Institute of Nuclear Physics of Moscow State University (NIIYaF MGU), Supporting Institution 2 – Space Research Institute of the Russian Academy of Sciences (IKI RAN).

[**] 115409, Moscow, Kashirskoe Shosse, 31, Russia Tel: (095) 324-94-92, Fax: (095) 324-77-77, E-mail: khatipov@cc.nifhi.ac.ru, http://www.mephi.ru

1. Introduction

The purpose of the work was a development of the data base (DB) on the changes in the optical propeties of materials used on the external surfaces of spacecraft, based on the results of both in-flight and laboratory simulation tests. Currently, there exists a large number of studies on the stability of the optical properties of materials used on the external surfaces (blankets, thermal control coatings, solar arrays etc.) of spacecraft. These studies have been based on experimental results obtained both in laboratory and actual in-flight conditions. All of them, particularly [1 — 9], confirm the fact that the factors of the space environment (FSE) exercise a strong influence both on the spectral and the integral optical parameters of the materials. Optical degradation of external surfaces may result in a change of the thermal regime of a spacecraft, in a malfunction of its orientation and communication systems and ultimately in the stoppage of its active functioning. In this connection, the problem of predicting changes in the optical properties of materials has always attracted the closest attention in world scientific literature. Predicting the aforementioned changes has become of particular importance recently, in connection with the trend to increase the lives of spacecraft up to 10 — 20 years, as well as with the development of spacecraft electronic surveillance and identification systems. The process of creating a method for the long-term prediction of changes in the optical properties involves several stages. The principal ones are the following: developing physical and mathematical models to describe the degradation of the optical properties [e. g. 3, 7, 10] and testing the validity of such models with regard to specific types of materials. In order to solve the problems posed by each of the above stages, it was necessary to create DBs that would include the results of in-flight and laboratory tests. It is only on the basis of extensive experimental material presented in such DBs that reliable empirical models describing the effects of the aging of space materials can be built and their validity can be tested in regard to specific materials and operation conditions. Currently, the use of such DBs both in Russia and worldwide is quite limited, whereas literary sources contain considerable amounts of experimental data that have not been given systematic form in electronic DB format.

2. Technical Approach

During the first stage, the DB was developed on the basis of published sources, such as monographs, articles in scientific journals, proceedings of conferences and symposiums. The structure and user interface of the DB were developed with the help of standard software: MS Access 2000. They allowed searching for and selecting data by material type and name, by physical parameter, space environment factor, type of test, etc. The DB contains the data in both graphical and table form. Each record in tables or forms of the DB corresponds to no more than one functional dependence. The reduction of the number of curves on one graph in one record or of the number of data represented in one record in table form promotes the expansion of search and information processing capabilities.

Tests under the action of electromagnetic solar radiation were conducted with exposures equivalent to up to 1 year of 1-sun on the geostationary earth orbit (GEO). The dependence of the optical parameters on the irradiation time for each material was determined for four values of the exposure. After the required value of the irradiation time had been reached, the samples were taken out of the test chamber and placed into an environmental container filled with inert gas.

Irradiation of materials with accelerated electrons was conducted for electrons with the energies 50, 100, 200 keV, with the fluence reaching $\Phi_e \approx 10^{17}$ cm^{-2} and the flux density not exceeding 5×10^{12} cm^{-2}s^{-1} (which is approximately equivalent to 10^2 Gy/s). For low-energy electrons (with energies less than 100 keV), the total absorbed dose on the material surface was approximately equal to the annual surface dose on an orbit that crosses the radiation belts of the Earth. For electrons with the energy greater than 100 keV, these doses exceeded the annual level on such orbits by approximately 2 times The dependence of the optical parameters on the irradiation time for each material was determined for four values of the fluence of electrons, similarly to what is planned to be done in the case of electromagnetic solar radiation. After irradiation, the samples were also placed into an environmental container filled with inert gas.

Irradiation of materials with accelerated protons was conducted for protons with the energies 50, 150, 300, 500 keV, with the fluence reaching $\Phi_e \approx 2\times10^{16}$ cm^{-2} and the flux density not exceeding 5×10^{12} cm^{-2}s^{-1}. For protons in the energy range 150 to 500 keV, the total dose absorbed on the material surface was approximately equal to the annual level absorbed on orbits crossing the radiation belts. The dependence of the optical parameters on the irradiation time for each material was determined for four values of the fluence of protons. For the energies 150, 300 and 500 keV, measurement of α_S took place directly in the vacuum chamber. In order to study the effect of 'bleach,' the results of measurements in vacuum were compared to those obtained after storage of the samples in air and in an inert medium.

The following optical parameters were measured:

- for opaque reflective materials (thermal control coatings, etc.):

α_S, ρ_λ, ρ_S, ε, BRDF (measurements carried out for two angles of incidence of the ray: 0 and 70°), change of appearance and color (by eye)

- for transparent scattering materials (fabrics, etc.)
  ρ_λ, α_S, T_λ, T_S, ε, change of appearance and color (by eye)
- for transparent materials (non-metallized polymer films and glasses, etc.)
  ρ_λ, α_S, T_λ, T_S, ε, D, D/x, change of appearance and color (by eye)
- for mirror surfaces (metallized polymer films, polished metal surfaces, etc.)
  ρ_λ, α_S, ρ_λ, ρ_S, ε, BRDF (measurements carried out for two angles of incidence of the ray: 0 and 70°), change of appearance and color (by eye)

3. List of materials for testing

A list of the materials tested is given below (tabl. 1). The listed materials are generally available and widely used in spacecraft. Test results for these materials in laboratory and in-flight conditions have been published in Russian and foreign scientific literature. One of goals of the work was the systematization of the known data and obtaining new ones for the listed materials.

The TCC samples in question are cured films of lacquer-paint coatings on a metal substrate. The substrates have the shape of discs with a diameter of 30 mm and a thickness of 1 mm and are made of the aluminum-based alloy AMg6. Before the lacquer-paint coatings were sprayed onto the discs, the latter had been preprocessed. The side of the substrate receiving the coating was sandpapered using No. 6 emery paper and subsequently blown out with compressed air. All the substrate surfaces were washed and degreased with acetone of the "ch" brand.

A thermal control coating is a film of the corresponding enamel sprayed onto a layer of priming. AK-07 brand priming (technical standard GOST 25718-83) was applied to the preprocessed substrate surface in a single layer and subsequently let dry for 30 — 40 minutes at a temperature of 20 ^{0}C to 25 ^{0}C in air. KO-0148 brand priming was applied to the substrate surface in a single layer and subsequently let dry for 30 — 40 minutes at a temperature of ca. 60 ^{0}C in air.

The lacquer-paint materials were applied to the substrate surfaces by pneumatically spraying them on with the ambient air temperature being from 20 ^{0}C to 25 ^{0}C. The TCC enamels were applied to the priming in several layers with subsequent drying-out of every layer for ca. 30 minutes until the layer became visibly dull (mat).

The TCC were given a finishing drying-out by leaving them in air for five days at a temperature of 25 ±2 ^{0}C. Data on the TCCs are given in Table 2.

4. Data base structure and content

The following results, contained in the published sources listed below, have been selected for entering into the DB:

- pristine optical and thermophysical parameters of TCCs, fabrics, metallized and non-metallized glasses and polymer films, solar arrays, structural and optical materials, lacquer and paint coatings, MLIs, pigments used in TCCs;
- results of laboratory tests for the listed materials under the action of UV radiation, accelerated electrons and protons;
- results of laboratory tests for TCCs in conditions modeling those in orbits that cross and do not cross the radiation belts of the Earth;
- results of in-flight tests for materials in LEOs (Salyut-6, Salyut-7, Almaz, Mir);
- results of in-flight tests for TCCs in HEOs and GEOs on board the space vehicles Molniya, Raduga, Gorizont and others with exposure times in open space of up to 10 years and estimates of the change of α_S for up to 10 years in GEOs, based on the data of laboratory tests;
- results of laboratory tests of light resistance for materials used on the external surfaces of spacecraft with exposure times in open space of up to 15 years;
- kinetic models of degradation for TCCs under the action of UV, atomic oxygen, electrons and protons;
- study results of the kinetics of 'bleach' for TCCs after irradiation with UV, electrons and protons;
- others.

Table 1.

List of materials to perform experimental investigations

№	Russian Material Designation	Type of Material	Application of Material	Chemical Composition of Material
1	EKOM-1 white	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of space vehicles (SVs) in conditions of low-earth orbits (LEOs). Has a limited use for small operating times in geostationary earth orbits (GEOs) and high-ellyptical earth orbits (HEOs).	• Acrylic copolymer; • Pigment ZnO.
2	AK-512 white	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs. Has a limited use for small operating times in GEOs and HEOs.	• Acrylic copolymer; • Pigment TiO_2; • Inorganic filler (Alum earth (Al_2O_3*$3H_2O$)).
3	KO-5191 white	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs. Has a limited use for small operating times in GEOs and HEOs.	• Polysiloxane binder; • Pigment ZnO.
4	40-1-28 white	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs. Has a limited use for small operating times in GEOs and HEOs.	• Organosilicon resin KO-116 (polymethylsiloxane); • Pigment ZrO_2.
5	TRSO-TsM white	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs. Has a limited use for small operating times in GEOs and HEOs.	• Water solution of potassium silicate; • Pigment ZrO_2.
6	EKOM-1P silver	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs. Has a limited use for small operating times in GEOs and HEOs.	• Acrylic copolymer; • Aluminum powder; • Pigment ZnO.
7	EKOM-2 black	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs, GEOs and HEOs.	• Acrylic copolymer; • Pigment: a mixture of oxides of Fe, Cu, Mn + carbon.
8	AK-512 black	TCCs (Enamel)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs, GEOs and HEOs.	• Acrylic copolymer; • Pigment: a mixture of oxides of Fe, Cu, Mn + SiO_2.

№	Russian Material Designation	Type of Material	Application of Material	Chemical Composition of Material
9	SOT-1S-100	TCCs (Metallized film)	Used as a coating on the external surfaces of radiators of SVs in conditions of LEOs, GEOs and HEOs.	• Tetrafluoroethylene-hexafluoropropylene copolymer of the F-4MB brand with the thickness 100 mcm with a silver coating with the thickness 0.1-0.15 mcm; • protective layer over silver: nichrome of the Kh20N80 brand and EP-730 lacquer; • external surface of the film covered with a conductive transparent coating of indium oxide doped with stannum oxide (ITO).
10	PM-1EU-OA		Used as part of multi-layer insulation (MLIs) and in on-board cable networks in GEOs and HEOs.	Polyimide film with the thickness 12 mcm with one-sided vacuum spraying-on of a layer of aluminum.
11	RAM-1	Fabric	Used for facing MLIs in GEO conditions.	• Polyimide film of the PM-1EU-OA brand with the thickness 12 mcm with one-sided vacuum spraying-on of a layer of aluminum; • reinforcing layer: T-06 light-weight fabric of arimide fibers; • binding agent between the film and fabric: polyamidoimide resin of the PI-LK-4TP; • conductive optically transparent coating of indium oxide doped with stannum oxide (ITO) on the external surface of the polyimide film.
12	RAM-2		Used for facing MLIs in LEO conditions.	• Polyimide film of the PM-1EU-OA brand with the thickness 12 mcm with one-sided vacuum spraying-on of a layer of aluminum; • reinforcing layer: polyether fabric; • binding agent between the layer and fabric: thermally resistant copolymer; • conductive optically transparent coating of indium oxide doped with stannum oxide (ITO) on the external surface of the polyimide film.

№	Russian Material Designation	Type of Material	Application of Material	Chemical Composition of Material
13	NIIKAM-DPL	Non-Metallized film	Used for creating inflatable transparent devices in LEO conditions.	• Polyimide film of the PM-1EU brand with the thickness 20 mcm; • adhesive layer: NIIKAM-AK-1 glue; • polyethyleneterephtalate film of the PET-M brand with the thickness 12 mcm; • conductive optically transparent coating of indium oxide doped with stannum oxide (ITO) on the external surface of the polyimide film.
14	Arimide fabric 5359-87	Fabric	Used as part of MLIs, in on-board cable networks, as part of blinds in LEO, GEO and HEO conditions.	• Based on arimide (polyimide) threads.
15	Arimide frame fabric 56420		Used for facing MLIs and for thermal insulation of propulsion devices in GEO conditions.	• Arimide threads; • skeleton cell with the dimensions 10×10 mm made of copper silvered wire wound onto an arimide thread.
16	Arimide frame fabric SCh 5365-89		Used in soft blinds of optical telescopes functioning in GEOs and HEOs.	• Arimide threads; • skeleton cell with the dimensions 10×10 mm made of copper silvered wire wound onto a black arimide thread.
17	TSON-SOT M bts		Used for facing MLIs and in on-board cable networks in LEO, GEO and HEO conditions.	• Alumina borosilicate glass fibres STMK; • skeleton cell with the dimensions 10×10 mm made of copper silvered wire wound onto a capron thread.
18	FP-BSFR 100-208	Solar Arrays	Used as part of solar arrays in GEOs and HEOs.	Solar array cells based on crystalline silicon with a back side reflective coating and protective glass coatings K-208 with the thickness 100 mcm glued to the front and back surfaces.
19	FP-BSFR 200-208		Used as part of solar arrays in GEOs and HEOs.	Solar array cells based on crystalline silicon with a back side reflective coating and protective glass coatings K-208 with the thickness 200 mcm glued to the front and back surfaces.
20	FP 100-208		Used as part of solar arrays in LEOs.	Components of solar arrays based on crystalline silicon having bilateral sensitivity, with glued the K-208 glass protective coatings of 100 mkm thickness on the front and rear surfaces.
21	FP 200-208		Used as part of solar arrays in LEOs.	Components of solar arrays based on crystalline silicon having bilateral sensitivity, with glued the K-208 glass protective coatings of 200 mkm thickness on the front and rear surfaces.
22	FP-BSFR 200-215		Used as part of solar arrays in GEOs and HEOs.	Solar array cells based on crystalline silicon with a back side reflective coating and protective glass coatings K-215 with the thickness 200 mcm glued to the front and back surfaces.
23	FP 200-215		Used as part of solar arrays in LEOs.	Components of solar arrays based on crystalline silicon having bilateral sensitivity, with glued the K-215 glass protective coatings of 200 mkm thickness on the front and rear surfaces.

Table 2

TCC brand	Priming, thickness	Enamel thickness, mcm	Russian technical standard (GOST or TU)
EKOM-1	AK-070 8 - 10 mcm	90 - 100	TU 2313-416-07500935-00
AK-512 white	AK-070 8 - 10 mcm	80 - 100	GOST 23171-78
KO-5191	AK-070 8 - 10 mcm	110 - 120	TU 1-595-9-51-97
40-1-28	KO-0148	190 - 200	TU 92-932-1-290-98
TR-SO-TsM	No priming	210 - 230	TU 92-932-2-269-96
EKOM-1P	AK-070 8 - 10 mcm	60 - 70	TU 2313-332-07500935-01
EKOM-2	AK-070 8 - 10 mcm	60 - 80	TU 2313-294-07500935-99
AK-512 black	AK-070 8 - 10 mcm	60 - 70	GOST 23171-78

A structure of the Database has been developed that allows to systemize and to represent as fully as possible the above-mentioned test results in electronic format. The developed version of the DB structure includes fifteen tables and eight forms.

The table of materials contains the following information fields: auto-number (unique identifier), name of the material, type of the material, chemical composition of the material, peculiarities of the fabrication method of the material, application of the material, reference to the state standard for the manufacture of the material.

The materials are divided into seven types. The materials that do not come under any of the itemized types are presented in the 'others' category: fabrics, MLIs, thermal control coverings, solar arrays, structural materials, optical materials, others. TCCs are subdivided into the following classes: enamels, silicate coverings, galvanochemical coverings, metallized films, non-metallized films, metallized glasses, non-metallized glasses. Structural materials used on the external surfaces of spacecraft are subdivided into five types: glass plastics, thermoplastics, carbon plastics, metals, alloys. The table of the type of tests includes: in-flight tests, laboratory tests, prediction results. The factors of the space environment are divided into following classes: electrons, protons, ultraviolet solar radiation, infrared and visible solar radiation, vacuum ultraviolet, soft X-ray radiation, combined action of electrons and protons, combined action of electrons, protons and ultraviolet solar radiation, atomic oxygen, combined action of atomic oxygen and ultraviolet solar radiation, thermocycling, contamination, complex action of the space environment factors.

The list of optical and thermophysical parameters is given in tbl_Parameters: solar absorption, spectral absorption coefficient, solar reflectance, spectral reflectance, solar transmittance, spectral transmittance, coefficient of heat emission, spectral coefficient of heat emission, optical density, relative optical density reduced to the unit of the sample thickness, change of material color and appearance, Bi-directional Reflectance Distribution Function (BRDF), coefficient of thermal conductivity, coefficient of thermal diffusivity, specific heat capacity, melt temperature, density. Orbits (tbl_TypeOrbits), taking into account the operating conditions of spacecrafts in them, are divided into types as follows: Low Earth Orbit (LEO, 200 - 600 km, i = 0 - 90), Low Earth Orbit (LEO, 600 - 1000 km, i < 65), Middle Earth Orbit (MEO, 1000 - 36000 km, i < 90), Polar Orbit (POL, 600 - 1000 km, i > 65), Geostationary Earth Orbit (GEO, 36000 km, i = 0), High-elliptical Earth Orbit (HEO, 500 - 40000 km, i = 65).

The table tbl_References contains a list of the information sources, including the imprint of the publications, such as the author's name, title, and the publisher.

The results of material tests have been distributed into six tables in accordance with the division of materials into six types. Test results for each of the six material types are entered into a separate table linked to the other tables. The structure of the data tables is presented in Figure 1 with TCCs as an example. For the other types of materials, the structure of tables is similar.

For the presentation of the test results, 6 forms have been developed, each of them linked to one of the 6 data tables which, in turn, correspond to the 6 types of materials (fabrics, MLIs, TCCs, solar arrays, optical and structural materials). Figures 2 show example of record from the TCC data table in a data forms. The data form has a similar appearance for the other types of materials.

Some results of testing TCC samples are presented in Figures 3, 4 and in Table 3 as an example.

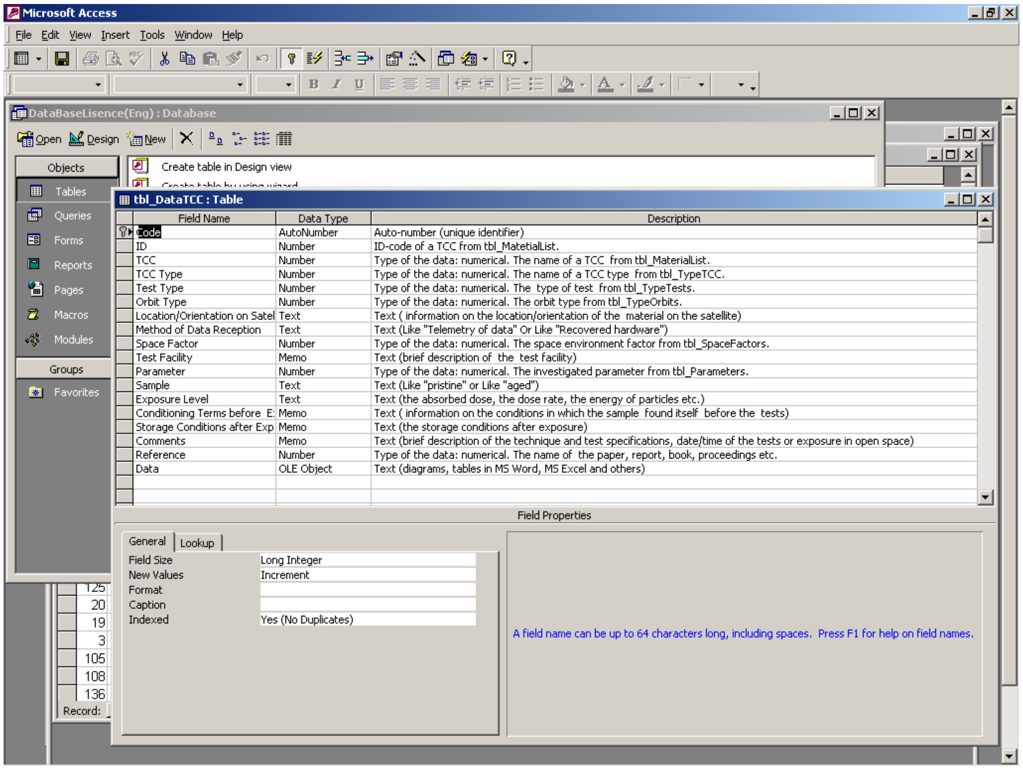

Figure 1. The structure of the data tables.

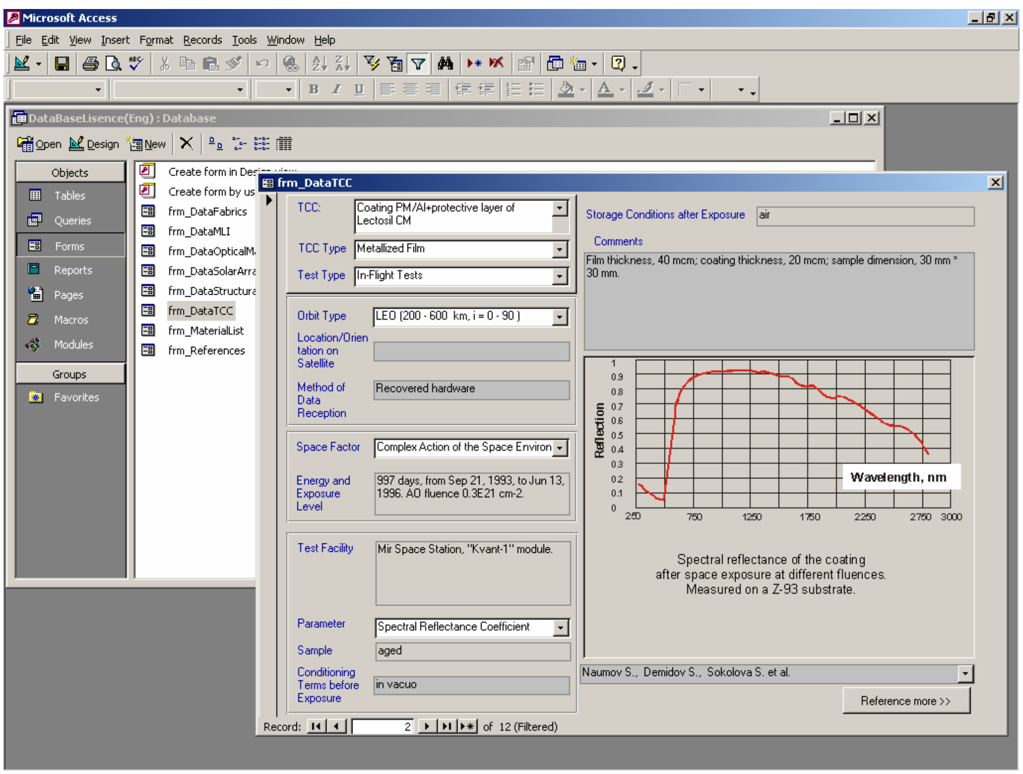

Figure 2. Example of record from the TCC data table in a data forms.

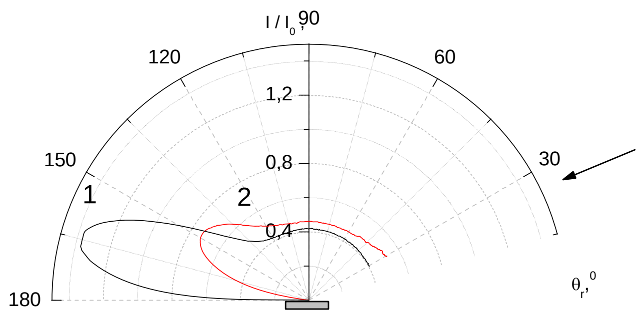

Figure 3. Reflection indicatrices for enamel: AK-512 (white) at $\theta_i = 67^0$ before (1) and after (2) electron action (40 keV).

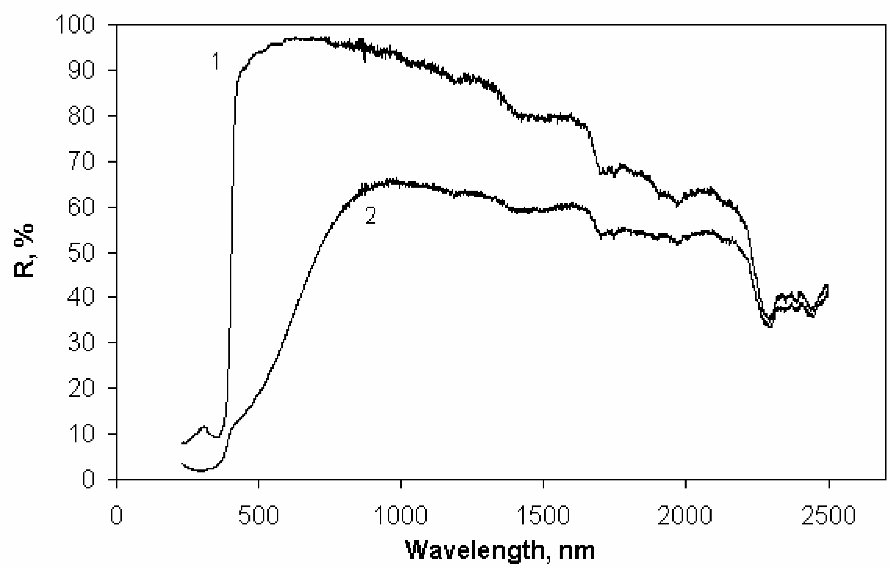

Fig. 4. Reflectance spectrum of the AK-512 enamel (white), pristine (1) and irradiated with protons (2). *Ep*=150 keV, proton flux intensity 5×10^{12} p/cm^{2}s, absorbed fluence 2×10^{16} p/cm^2

Table 3.

Values of the solar absorptance of enamels before and after exposure to electrons and protons

	Pristine	Electrons, 40 keV, 10^{17} cm^{-2}	Electrons, 100 keV, 2×10^{16} cm^{-2}	Electrons, 200 keV, 2×10^{16} cm^{-2}	Protons, 40 keV, 10^{16} cm^{-2}	Protons, 150 keV, 2×10^{16} cm^{-2}	Protons, 300 keV, 2×10^{16} cm^{-2}	Protons, 500 keV, 2×10^{16} cm^{-2}
EKOM-1 (white)	0.257	0.399	0.256	0.251	0.456	0.559	0.691	0.577
TRSO-TsM (white)	0.052	0.199	0.074	0.139	0.565	0.561	0.525	0.652
AK-512 (white)	0.173	0.306	0.226	0.244	0.584	0.583		0.544
40-1-28 (white)	0.071	0.516	0.164	0.322	0.562	0.537	0.533	0.237

Acknowledgements

The author should express profound gratitude and acknowledgement for the support and participation in the work to the employee of Metatech Corporation J. Walton, employee of Ball Aerospace Corporation T. King, employees of AFRL K. Higgins, Q. Dierks, L. Hrivnak, B. Johnson, T. Medland, and also employees of MIFI, NIIYaF MGU, and IKI RAN, who took part in performing testing, without which it would not be possible to complete the present work.

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