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# On-Ground Simulated Space Factors Influence on Physical Properties of Spacecraft Materials

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**The experience of the Special Research and Development Bureau (SRDB) in the areas of cryogenic vacuum and space materials science and scientific equipment and facilities building for the tasks of special materials science is presented. A series of specific results from SRDB-conducted experimental investigations of the influence of space environment factors effects on the physical and mechanical properties of space-application materials developed in former USSR and in present-day Ukraine and Russia are presented.**

## I. Introduction

THE materials used in field of cryogenic, vacuum, and aerospace engineering are employed under hard and unfavorable conditions. They are impacted by such outer space environmental factors as deep vacuum, electromagnetic radiation by the sun, high-power flux of corpuscular irradiation from radiation belts of the Earth, zero gravity, low temperatures, significant cyclic gradient thermal loadings, magnetic fields, notable static, dynamic, and reciprocal cyclic loadings, vibrations, and many other factors.

Each of the mentioned factors has its individual influence on the alteration of mechanical, optical, electric, thermophysical, tribotechnical, and other properties of materials, whereby the resultant effect of all these factors builds up in a nonadditive manner. Experience gained worldwide in orbit operation of various types of spacecraft shows that, in general, the real space environment has an aggressive effect on structural and functional materials, almost always leading to significant (or even complete) degradation of their performance capabilities.

Because of these circumstances, determination of serviceability, reliability, and lifetime properties of the materials being utilized under such severe conditions, as well as the creation of novel materials of outstanding performance characteristics, constitute a major technical and technological problem in cryogenic-vacuum and space-purpose materials science. These issues are especially important for the Ukraine, whose space industry is now faced with the tasks of certification of available materials, as well as the creation of novel domestic materials.

These technical problems can be solved with either of two approaches:

1) On-ground studies and investigations of the bulk of physical and mechanical properties of materials may be conducted, under conditions of simulated single- and multiple-factorial influences by the outer space environment.

2) Expose materials and structural elements under real conditions of the outer space environment, with a consequent set of investigations of the deterioration of materials physical and mechanical properties (to be implemented either aboard the orbiting spacecraft or eventually after landing).

The former approach, though associated with relatively inexpensive costs and short-time terms, would demand the researchers to retest the adequacy of this method compared to real effects of outer space environmental factors, in a real flight mission.

The latter approach, although it would require significant costs and lengthy time would provide researchers with trustworthy results.

Note that both of these approaches are complementary and, hence, the Special Research and Development Bureau (SRDB) simultaneously conducts its work efforts with both of these approaches together.

## II. Creation of Laboratory-Testing Simulating Facility Base

The task of implementing materials scientific investigations has required us to develop and fabricate an array of specialized cryogenic and vacuum machinery and a mix of simulation-purpose universal testing and research equipment, as well as to create a set of research and measurement methodologies for the complex physical and mechanical properties of materials to be studied in on-ground simulated conditions of the influence of outer space environmental factors (SEF).[1,2] An actively functioning, unique (across the Ukraine and the former USSR) specialized testing shop has been organized to conduct research and certification of cryogenic-vacuum and aerospace-purpose materials.

These unique facilities include the following apparatus:

1) The complex system of equipment intended for investigations of antiradiation resistance of materials provides the following simulated effects of radiation impact: down to $3\times10^{-4}$ Pa deep vacuum, extreme (80–400 K) temperatures, solar electromagnetic radiation in the visible waveband, ultraviolet (UV) radiation, vacuum UV (VUV) radiation, ultrasoft roentgen (x-ray) radiation (USX) within $\lambda = 1.24$–250-nm wavelength band, and fluxes of protons and electrons at 200-keV energy rate.

2) Testing rigs check materials for fatigue strength, cyclic crack propagation resistance, and wear resistance of materials under low (4.2–300 K) temperatures in cryogenic liquids (such as nitrogen, hydrogen, or helium), as well as in vacuum or in any gaseous media.

3) An array of test purpose cryogenic machinery investigates the set of quasi-static mechanical properties of materials, within the 4.2–300-K temperature range. This facility enables one to conduct simultaneously a measurement of magnetic- and electrophysical characteristics of a test object.

4) A low-temperature impact-testing machine tests various materials against mechanical bending, within the 4.2–300-K temperature range.

5) The space orbital flight simulator thermocycles in the temperature range 77–300 K.

In addition there are the commonly used structural methods of investigation, such as transmission and scanning electron microscopy, as well as techniques of low-temperature x-ray structural analysis.

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Along with designer developments being implemented to meet the tasks of aerospace materials science, the SRDB has developed a package of methodologies and principles of construing the test stand rig equipment. This is devised to enable accelerated complex testing procedures with onboard cryocoolers, whose planned nonstop performance lifetime in outer space is to last 10–20 years.[3,4] In other words, we cannot wait for decades to obtain real-time ground-based test results. Hence, the performance behavior of a machine supposed to operate in space for many years must be identified with the aid of accelerated simulation techniques. Note that no analogs to some items in these facilities exist elsewhere in the world.

These laboratory and testing facilities enable one to provide standard certification procedures for various structural materials, due to the following characteristics and under the following conditions: 1) a complete set of mechanical properties, over a broad range of temperatures (4.2–300 K) in vacuum, including static (as well as those within up to 4-T magnetic field), dynamic, and fatigue characteristics of strength and cracking resistance; 2) static, fatigue, and tribotechnical mechanical characteristics in vacuum, under impact of such radiation factors as VUV and USX irradiation; 3) electrophysical characteristics of polymeric film materials, as well as volt–ampere characteristics of solar cell batteries, under complex impact by outer SEF; 4) optical characteristics (of a test object in a vacuum chamber), such as absorption coefficient and blackness coefficient, before and after complex impact by outer SEF; 5) kinetics of mass loss by the method of nonstop weighing, as well as mass-spectrometric analysis of materials outgassing process in vacuum, under complex impact by outer SEF; 6) structural and phase state of materials during the process of low-temperature deformation; 7) micromechanisms of materials plastic deformation and failure under low temperatures; and 8) morphology of materials surface under low temperatures, before and after complex impact by outer SEF.

## III. Results in the Field of Cryogenic and Aerospace Materials Science

Trends in aerospace materials science include a range of versatile research, studies, and investigations, aimed at solving the problems of providing serviceability, reliability, and long life of a wide range of aerospace-purpose structural and functional materials and coatings under cryogenic and vacuum conditions. These include metals, alloys, composites, ceramics, types of glass, plastics, etc., to be employed under extreme operational and service conditions.

Significant experience has been gained after 40 years of complex research, studies, and investigations of the physical and mechanical properties of materials and heavy-duty components of space machinery,[5] under near-real conditions. It enables us to establish a set of substantiated physical criteria of evaluation, assessment, and selection of typical classes of structural and functional materials, worthy of being applied under the harsh conditions of operation in cryogenic and aerospace purpose facilities. These criteria are based on analysis of experimentally established interrelations among a wide spectrum of (both internal and external) factors and plotting a logical causal-sequential pattern devised as prehistory–structural–phase state–macroscopic properties–operational conditions–application.[6]

Applicability of this selected criteria, on success of solving a set of definite tasks in the creation of novel cryogenic and aerospace purpose materials, has been apparent. As a result, a relevant database of physical and mechanical properties of different classes of materials, to be utilized under severe conditions, has been collected. Here are several characteristic examples of these experimental investigations.

### A. Influence of Vacuum and Low Temperatures on Structural Materials Resistance to Fatigue Failure

Spacecraft intended for long duration missions (such as orbital stations, space shuttles, etc.) are subjected to multiple vibration loadings inflicted by launch and landing, in orbital flight, while docking with and undocking from relevant spacecraft, under orbit correction and at implementing different technological experiments onboard the ship. Therefore, to provide reliability and long life of spacecraft, structural materials of heavy-duty components (such as casing and body, aerials, solar cell batteries' armature, and others) should not only possess outstanding values of specific strength, but significant grade of resistance to fatigue destruction as well. In view of these preconditions, systematized research and investigations on the influence of SEF, such as deep vacuum and low temperatures, on ability of constructional materials to resist to fatigue failure, have been widely implemented.[7–12]

*Vacuum Influential Factor*

Analysis of the results from study of vacuum influential impact on the characteristics of fatigue strength and fatigue crack growth resistance of metals and alloys indicates a positive influence of vacuum on these processes.

Figures 1 and 2 show the characteristic feature curves of the vacuum influence on the fatigue factor, as well as kinetic diagrams of metallic materials fatigue destruction. Data presented in Fig. 1 were obtained in the course of testing a series of standard fatigue specimens, under a symmetrical cycle of tension–compression at 20-Hz frequency, where $\sigma$ is the amplitude of cyclic stress applied to the test specimens and $N$ is the number of loading cycles before the material's destruction under a given load. Figures 2–4 show a dependence of fatigue crack growth rate $V$ vs stress-intensity factor range, $\Delta K = K_{\max} - K_{\min}$. This testing has been carried out with standard middle-tension specimens for fatigue crack growth rate testing under symmetrical loading cycle at 20-Hz frequency.

It has been found that improved characteristics for fatigue destruction in vacuum are specified by quasi-uniform distribution of microplastic deformation within the surface layer of metal, owing to the change of conditions for oxygen atoms' absorption by the newly formed microsurfaces of slide steps.

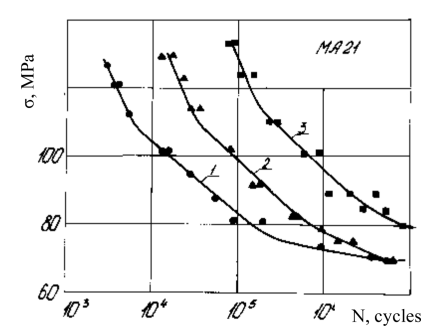


**Fig. 1 Fatigue strength for magnesium alloy Mg–5.4% Al–1.0% Zr–4.7%Cd–8.6% Li (MA21) measured 1, in open air; 2, in vacuum at 293 K; and 3, in vacuum at 11 K.**

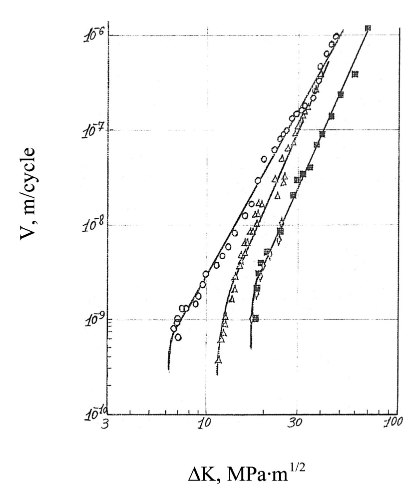


**Fig. 2 Kinetic diagram of fatigue failure for Fe–20% Cr–16% Ni austenite steel, measured in open air and in vacuum at different temperatures: ○, air, 293 K; △, vacuum, 293 K; ◇, vacuum, 93 K; and ■, vacuum, 11 K.**

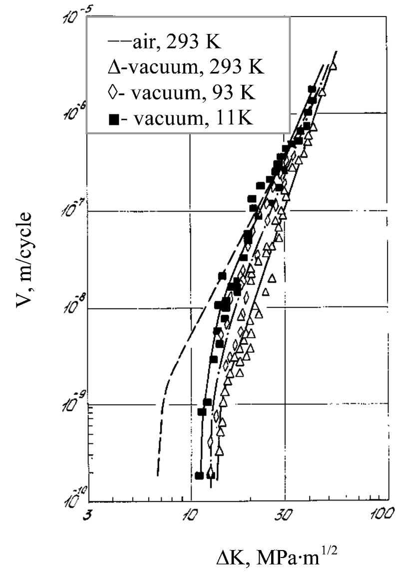


**Fig. 3 Kinetic diagram of fatigue-failure titanium alloy Ti–5% Al–2.5% Sn, obtained in open air and in vacuum at different temperatures: ——, air, 293 K; △, vacuum, 293 K; ◇, vacuum, 93 K; and ■, vacuum, 11 K.**

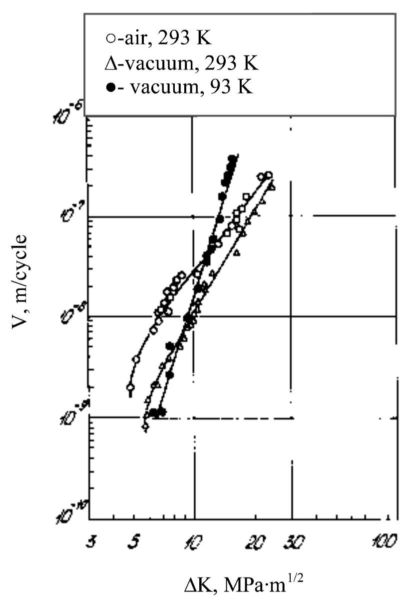


**Fig. 4 Kinetic diagram of fatigue-failure titanium alloy Ti–4% Al–5% Mo–5% V, obtained in open air and in vacuum at different temperatures: ○, air, 293 K; △, vacuum, 293 K; and ●, vacuum, 93 K.**

*Low-Temperature Influence*

The influence of low temperature on the characteristics of fatigue resistance and cyclic cracking resistance of metallic materials is in contrast to that of vacuum; it is ambiguous and depends on the type of crystal lattice structure and on the level of applied stresses.

The hexagonal-close packed (HCP)-lattice-structured alloys (basically, titanium- and magnesium-based compositions) are known for the fact that value of fatigue crack growth rate vs stress-intensity factor usually tends to rise with temperature decrease, whereas the rate of fatigue crack growth (within the near-threshold zone) tends to decelerate. However, in the high-amplitude area of the fatigue life kinetic diagram, temperature reduction can result in either deceleration (Fig. 3) or acceleration of the fatigue crack growth rate (Fig. 4).

The most acceptable structural materials, from the viewpoint of low-temperature cyclic cracking resistance ability, are structurally stabile face centered cubic (FCC)-lattice-structured alloys, which are characterized by enhanced resistance against fatigue destruction under low temperatures, irrespective of stress-loading level.

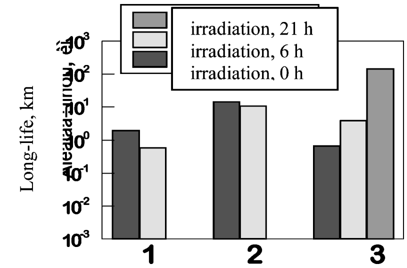


**Fig. 5 Influence of VUV irradiation on service lifetime of solid lubricant based on powdered $MoS_2$ and different bonding agents: 1, silicon-organic composition; 2, epoxy resin; and 3, inorganic material.**

### B. Influence of Ionization Radiation on Friction and Materials Wear Features

The influence of outer SEF is determined by observing the changes in tribotechnical attributes and properties of materials, such as friction coefficient, wear intensity, friction long life. Significant changes in these properties can results in operational failure of heavy-duty components of space machinery.

Rather serious problems may occur in serviceability of spaceships intended for the exploration of planets in our solar system. After a long-duration flight on a far universe mission, the spacecraft should maintain its capability of performing under the definite atmospheric conditions of planets and their satellites, such as Mars, Venus, and the moon.

Mechanical friction units of a spacecraft mechanism are influenced additionally by inherent exterior atmosphere of the spacecraft itself.

Research implemented by the SRDB[13,14] has revealed that impact by VUV radiation on solid lubricant coatings and antifrictional lubricants (comprising different natured bonding agents), which are widely used with space engineering equipment and facilities, results in irreversible change of a lubricant's service lifetime, when operated in vacuum.

In this manner, when being subjected to VUV radiation, the solid lubricant coatings with organic bonding agents (such as epoxy resin or silicon-organic composition) have demonstrated deteriorated frictional life, whereas inorganic bonding substance-based coatings (such as potassium silicate) have shown a fivefold enhancement of service lifetime (Fig. 5).

### C. Influence of Orbital Thermal Cycling on Mechanical Properties of Materials

Components of structures, instruments, and devices operated under orbital flight conditions are subjected to cyclic thermomechanical stresses that occur due to systematic sunshine–shadow revolution of a spacecraft in orbital flight. This phenomenon can inflict alterations in the structural status of materials and change their set of structurally sensitive physical and mechanical properties.

This section presents some results gained by the SRDB in research to determine the influence of simulated orbital thermal cycling on mechanical properties of typical structural materials utilized in cryogenic–vacuum and aerospace engineering, such as stainless steels.[15]

It has been found that the degree of phase stability of steel is a factor that crucially changes the character of the mechanical characteristics' dependencies on the quantity of thermal cycles. Hardening or softening of steel is dependent on the material's degree of phase stability (specified, for example, by availability of cooling martensite and/or deformation martensite), and subsequent testing temperature range (Figs. 6 and 7).

Structural investigations have indicated that an increase of yield stress, $\sigma_{0,2}$, for structurally unstable Cr18Ni8 stainless steel after thermocycling is related to the reduction of the initial value $d$ of steel grain due to the occurrence of interlayers of martensite phases (such as $\alpha$ cooling martensite and $\varepsilon$ deformation martensite). This process is routinely described by the Hall–Patch equation, the parameters of which are defined by strength of interface boundaries between

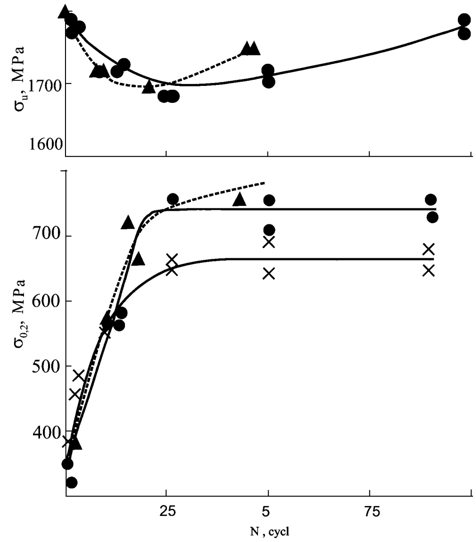


**Fig. 6 Yield point $\sigma_{0.2}$ and ultimate strength $\sigma_u$ vs thermocycles' number $N$ for stainless steel grade 18-8 at 77 K: ×, 300–77 cycling without loading; ▲, 300–77 K cycling under loading $0.8\sigma_{0.2}^{300\,\mathrm{K}}$; ●, 300–4.2 K cycling under loading $0.8\sigma_{0.2}^{300\,\mathrm{K}}$.**

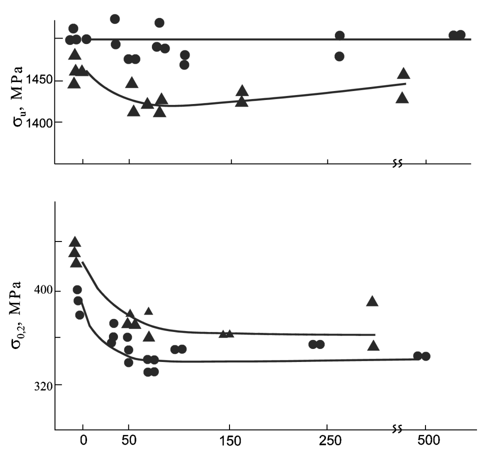


**Fig. 7 Yield point $\sigma_{0.2}$ and ultimate strength $\sigma_u$ vs thermocycles' number $N$ for stainless steel grade 18-10 at 77 K; ▲, 300–4.2 K cycling under loading $0.8\sigma_{0.2}^{300\,\mathrm{K}}$; ●, 300–77 K cycling under loading $0.8\sigma_{0.2}^{300\,\mathrm{K}}$.**

initial FCC $\gamma$ austenite and either newly born BCC $\alpha$ martensite or HCP $\varepsilon$ phase.

The softening of Cr18Ni10 stainless steel is related to the fact that the onset of the plastic yield process is not specified by initial-austenite deformation, but by a subsequent deformation caused by shift nature of $\alpha$ and $\varepsilon$ martensite under stresses whose values are less than the yield stress of initial austenite. Under thermal cycling and exterior stresses, a great number of stacking faults emerge within initial austenite (and remain in an unrealized state). These stacking faults act as areas of intensive $[\gamma \Rightarrow \varepsilon]$ transformation under subsequent low-temperature deformation. Simultaneously, within bands of $\varepsilon$ phase (being formed at thermocycling), there is an $[\varepsilon \Rightarrow \alpha]$ transformation, which also contributes to decrease of deforming stresses.

The effect of the rise of transformation intensity, after a predetermined quantity of preliminary thermal cycles (for steel of a given stability grade), is an explanation for the drop of ultimate strength with samples that have undergone thermocycling. Accumulation of $\varepsilon$ and $\alpha$ martensite in the course of thermocycling (in excess of the preplanned quantity of thermal cycles) reduces the transformation intensity under subsequent deformation, accumulation of inner stresses within residual martensite, and development of plastic deformation within newly formed and stronger body centered cubic (BCC) $\alpha$ martensite. All of these processes result in strengthening of thermocycled material.

In this manner, by the control of the intensity of strengthening $\alpha$ and plastifying $\varepsilon$ martensite generation, one is able to obtain the simultaneous effect of strengthening and plastification of structurally unstable types of steel. This effect is a fundamental concept for the method of cryogenic thermocycling process, which would ensure the possibility to create novel grades of steel of enhanced strength and plasticity.

### D. Influence of Accelerated Simultaneous Impact of Outer SEF on Physical Properties of Functional Materials

In an outer space mission, apart from the cosmic vacuum, every spacecraft is enveloped in the thinnest layer of inherent specific atmosphere originated mainly by emission of material micromasses from all of its components. Because of cosmic radiation, organic molecules of a spacecraft indigenous atmosphere undergo polymerization on the exterior surfaces of a space vehicle. This effect hinders and deteriorates the normal service of optical instrumentation, thermal regulation systems, and high-voltage electrotechnical and electronic devices employed in outer space conditions. For this reason, the SRDB has been conducting studies of mass loss, outgassing products composition, alteration of surface material morphology, and subsequent change of thermooptical radiation characteristics of functional materials and coatings in vacuum, under influence of radiation and low temperature.[16–18] Examples of SRDB's research are described next.

*Investigations of Mass Loss Kinetics*

The kinetics of mass loss has been studied by in situ weighing the materials inside the vacuum chamber of a laboratory SEF simulation complex, under simulated conditions of applied temperature and radiation factors. The electromagnetic weighing scales have a sensitivity of $10^{-4}g$. This weighing device is an optimal instrument for vacuum operation by providing remote control through the hermetically sealed shell of the vacuum chamber.

Figures 8a and 8b show the dependencies of mass loss kinetics (for a plastic lubricant used in spacecraft structural parts and

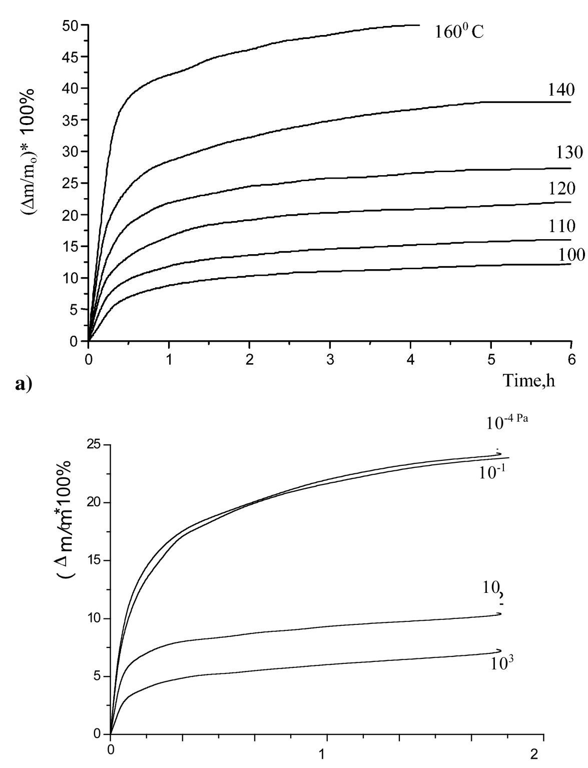


**Fig. 8 Characteristic curves of dependencies of mass loss kinetics for lubricant: a) various temperatures and $P = 10^{-4}$ Pa residual pressure and b) various residual pressures inside the vacuum chamber, at $T = 130$ K.**

mechanisms) during exposure to various temperatures and residual pressures inside the vacuum chamber.

As is obvious from Fig. 8a, kinetic curves $f(t)$, where $f$ is $(\Delta m/m_0) \times 100\%$ and $t$ is exposure period, within the $T = 100$–$140°C$ temperature range, reach the plateau in almost 4 h of experiment. At the same time, if a test sample is subjected to somewhat greater temperature (160°C), saturation does not occur even if the experiment lasts for over 6 h. It was shown that the fastest rate of mass loss can be identified within the entire range of temperatures during first 60 min of isothermal exposure. This rate is classified as an overallowable one. For reference, $10^{-7}$ g/cm$^2 \cdot$ s is an allowable rate of mass loss adopted for the effect of oil evaporation from unit lubricant surface.[19] However, with a longer exposure period, the rate of lubricant's evaporation gradually slows down, and in the case with 6-h experiment at $T = 120°C$, the rate reaches $0.8 \times 10^{-8}$ g/cm$^2 \cdot$ s. The critical temperature for the lubricant under study is $T = 140°C$. If the temperature range is assumed to be 160°C, the mass loss rate would dramatically elevate so that, after the first hour, the lubricant composition becomes denuded by the deficiency of about 47% its dispersion matter, that is, oil.

Data presented in Fig. 8b indicate that a decrease of residual pressure inside the vacuum chamber to $P = 10^{-1}$ Pa results in the rise of the lubricant's mass loss and, consequently, the deterioration of lubricant service conditions. Further decrease of residual pressure, even up to $P = 10^{-4}$ Pa, results in no obvious effect of the given lubricant's oil evaporation.

The use of mass-spectroscopy instrumentation in these experiments will enable identification of chemical compositions of volatile components being emitted under experimental test conditions. These data will aid in the understanding of the dynamics of the outgassing processes of the molecular flux of the testing materials, over a wide range of pressures.

*Influence of SEF Impact on Surface Structure and Optical Properties of Thermal Control Coatings*

The purpose of these studies is to investigate the influence of the simultaneous impact by simulated fluxes of protons and electrons, electromagnetic radiation by solar simulator, including the vacuum ultraviolet radiation, and vacuum on the spectral dependence of reflection coefficient $R(\lambda)$, integral coefficient of radiation, $\varepsilon$, and morphology of surface of metal–polymeric Teflon®-based thermal control coatings.

The surfaces of coatings were irradiated with an integral proton and electron fluxes with dose of $D = 6 \times 10^{15}$ cm$^{-2}$, that is, equivalent to the presence of the materials on geostationary Earth orbit (GEO), $H = 36{,}000$ km for 5 years. The sun simulator irradiation intensity at the wave length range of 200–2500 nm was $1.4 \times 10^3$ W/m$^2$ (one irradiation unit by the upper atmospheric sun), and the exposure duration was of 100 h. The irradiation dose in the range of vacuum ultraviolet (at $\lambda = 5$–$200$ nm) was 0.1 W/m$^2$, which corresponds to the presence of a material on GEO for 1 year.

Figure 9 shows characteristic diagrams of the alteration of the coating's reflection ability before and after impact by simulated

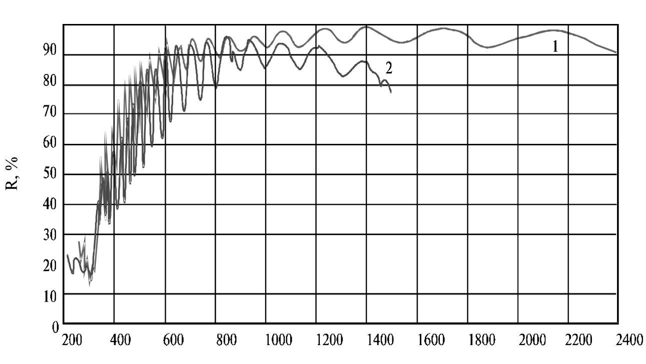


**Fig. 9 Characteristic diagrams of alteration of the coating's reflection ability 1, before and 2, after impact by artificial SEF.**

SEF. The impact by artificial SEF results in deterioration of the coefficient of coating's ability to reflect the light, and the value of this deterioration depends on dosage of irradiation.

Simultaneous impact by artificial SEF also produces structural changes within surface of coatings, manifested by occurrence of different flaws such as cracks, pores, rough skin areas, and laminations. This process is accompanied by an increase of integral radiation, that is, blackness coefficient, of the coatings.

The identified effects of surface-state deterioration (as well as decrease of reflection coefficient and increase of blackness coefficient) of the thermal control coatings are specified by Coulomb and recombination interactions between protons and electrons in the near-surface layer of material.

*Influence of VUV Radiation and Atomic Oxygen on Spacecraft Functional Materials*

Substantial factors of real space at near-Earth orbits are VUV components of solar radiation, as well as atomic oxygen. While designing the new models of spacecraft, the engineer has to be especially attentive and scrupulous when selecting construction and functional materials because of the deteriorating effect of atomic oxygen.

To address this concern, the process of oxidation of silver films in the atmosphere of atomic oxygen, under the impact of VUV radiation, has been investigated. A gas discharge-type hydrogen lamp was used as a source of irradiation. The integral intensity of the light flux of the lamp, within the 110–200-nm wavelength band, was $5 \times 10^{-3}$ W/cm$^2$.

It was shown that under the influence of short-wave UV radiation in oxygen-containing atmosphere, oxidation of silver films begins with formation of an amorphous oxide film, which is a place where crystalline nucleation centers of silver oxide start to appear. Growth of oxide islands occurs, usually perpendicularly toward the film surface, whereby the silver film undergoes destruction.

It was found that vacuum-deposited films of silver, subjected to irradiation by UV radiation of a hydrogen lamp within oxygen-containing atmosphere, lose their physical property of metallic conductivity. This feature enables one to employ silver condensates as sensors for detection of percentage of atomic oxygen in outer space while in orbital flight.

## IV. Conclusions

Currently, the SRDB has developed and fabricated a complex system of equipment (being a new generation of simulation facilities) intended for investigations of radiation resistance of materials. Under design and in manufacture is a stand rig facility for thermovacuum testing of full-scale space vehicles (for instance, microsatellites, etc.), which will possess a broad range of capabilities to simulate near-atmospheric sun radiation, reflected terrestrial radiation, orbital flight evolutions of a spacecraft, etc.

Along with these efforts, experts of the SRDB carry out a wide range of studies for novel perspective of space purpose materials developed by Ukrainian specialists.

Development and fabrication of simulated space-environment equipment, as well as SRDB activities in the area of space purpose materials science, are implemented by orders of the National Space Agency of Ukraine, together with Ukrainian aerospace industry enterprises, as well as contracts with space-oriented organizations in Germany, Russia, the United States, and China.

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