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ATOMIC OXYGEN IN LOW EARTH ORBITS, A RETROSPECTIVE REVIEW STUDY

The article presents a retrospective review of atomic oxygen (AO) research in low Earth orbit (LEO).The space environment of LEO is a barrier to all satellites passing through it. Several of its constituent parts pose a great danger to satellite materials and subsystems. Such orbits are convenient for remote sensing and experimental satellites. In order to maintain the operational level of spacecraft, it is necessary to carry out thorough studies of the LEO environment and its components. AO, which is a hyperactive state of oxygen, is considered one of the most dangerous components of the LEO environment. It can react with many materials and thereby change the physical, optical and mechanical properties that affect the functionality of the satellite. To maintain the satellite in its orbit with a certain margin of reliability, it is necessary to reduce the aggressive influence on it of the environmental components of LEO. Predicting the impact of AO on materials that will be used in space ensures their correct selection. The work provides some recommendations for the creation of AO facilities for testing materials exposed to the aggressive influence of the space environment.

Keywords: *Atomic Oxygen (AO), Low Earth Orbits (LEOs), Coronal Mass Ejections (CMEs), Space Environment.*

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1. INTRODUCTION. Space technologies benefit the Earth and human society in cases where they can be used to solve some life-support problems and gain experience in the use of planetary resources. In combination with terrestrial technologies, they are of undeniable interest both for the IT sector and for business. It improves global resource management and the protection of terrestrial resources.

1.1. Atomic Oxygen (AO). Atomic Oxygen is the most reactive gas in Low Earth Orbits (LEOs). It may affect the lifetime of the satellite or one or more of its components. It is produced either by photo-dissociation or by decomposition of the oxygen molecules O_2. The formation of AO depends on the presence of radiation of a wavelength shorter than 190 nm (especially the ultraviolet, UV, radiation) that has the ability to break the bonds of O_2.

Formation of AO occurs in the ionosphere by the photo-dissociation of the O_2 using the UV radiation in the LEOs as given by eq. 1 [1].

$$O_2 \xrightarrow{h\nu} \begin{cases} O + O, & 99\,\%, \\ O^{+} + O, & << 1\,\%. \end{cases} \qquad (1)$$

Production of AO occurs in response to cosmic rays that cause the decomposition of the neutral atmosphere. AO represents 80 % of the total composition in the upper atmosphere (area at an altitude of 200 to 800 km above the Earth's surface) [2]. AO exists, with different densities, in LEOs and HEOs (Highly Elliptical Orbits), as summarized in Fig. 1 [3].

Among all atmospheric constituents in orbits below 1000 km, AO is considered the most abundant species. Fig. 2 shows the variation of density ρ in cm^{-3} of atmospheric constituents with altitude h (km). The very high AO density is revealed in orbits at altitudes of 120 to 700 km [4].

Variation of AO flux F, atom/(cm^2s), with altitude h, km, as in Fig. 3, shows an inverse relation between AO flux and altitude, i.e., AO flux decreases with increasing altitude [4].

At altitudes of 150 to 500 km, the AO density is higher (10^7 to 10^{10} atoms/cm^3) than at altitudes about 1000 km (10^2 to 10^6 atoms/cm^3) [1].

1.2. AO and Solar Activity. There is a good coherence between solar activity and AO densities since the values of AO density and flux are higher during

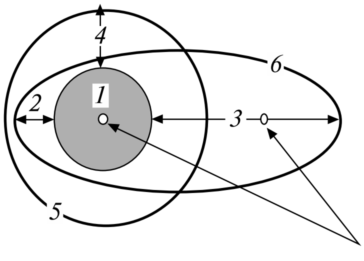

Figure 1. Orbits having AO presence: *1* — Earth, *2* — perigee, *3* — apogee, *4* — altitude, *5* — LEO, *6* — highly elliptical orbit, *7* — ellipse focal point

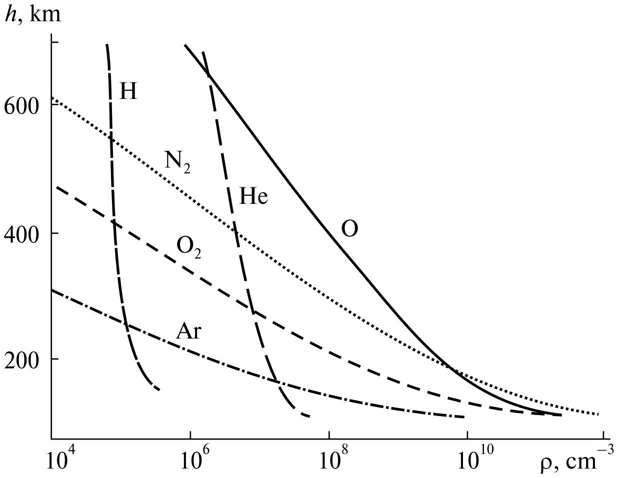

Figure 2. Variation of density ρ of atmospheric constituents with altitude h

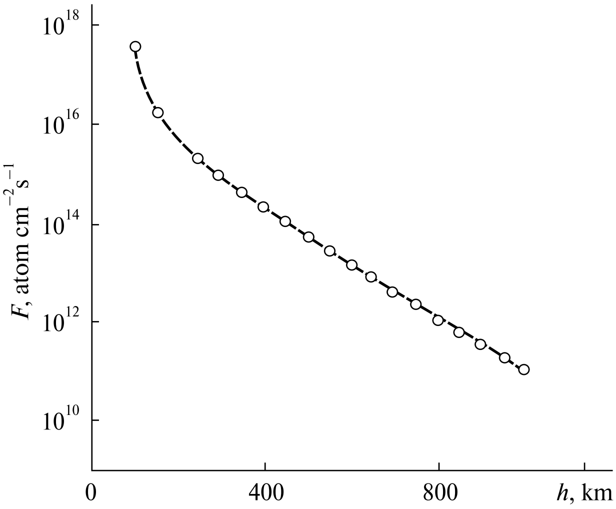

Figure 3. Variation of AO flux F with altitude h

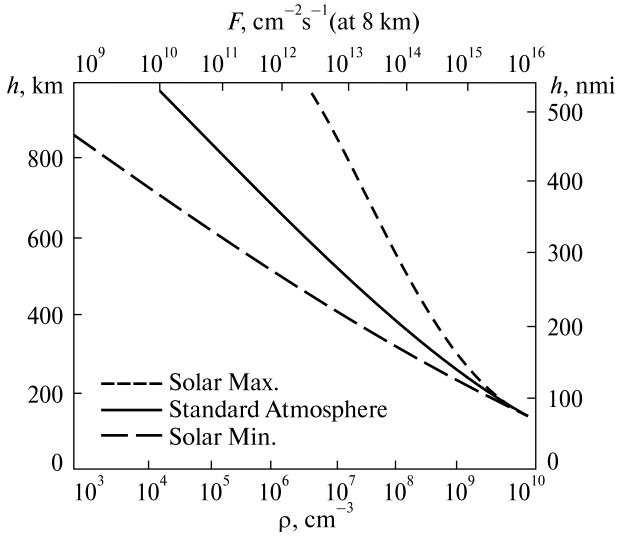

Figure 4. Variation of AO density ρ and flux F with solar activity

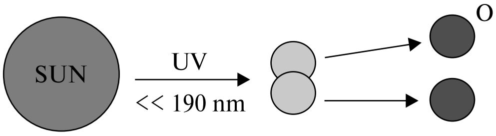

Figure 5. Photodissociation of molecular Oxygen

maximum solar activity rather than in its minimum, as follows from Fig. 4 [5, 6].

Although AO exists in LEO, PEO, and HEO, it is predominant in LEOs (altitude <<1000 km). The neutral oxygen atoms have a mean free path of the order 10^4 m at 400 km, which means that the re-association probabilities are very low [7].

Solar UV radiation (<< 190 nm) has enough energy to photodissociate O_2 forming free and hyper-energized AO, as shown in Fig. 5 [3].

It was stated by [3] that the formation of AO in LEOs occurs by the photodissociation of O_2 molecules. These molecules absorb the near solar UV radiation and then dissociate into free oxygen atoms O in the outer ionosphere (at altitudes higher than 80 km), as shown in Fig. 5.

The production rate of AO strongly depends on solar activity and UV radiation. AO fluxes are significantly related to the orbit and velocity vector of the spacecraft, as well as the incidence angle of AO on the surface. The reaction of AO with some materials creates excited state (short-lived) species that emit visible radiation near the incidence surface, forming the glow phenomena as described in [8—11].

At altitudes between 180 and 650 km, the solar radiation has enough energy to break the double bond of O_2 to form AO with a very low probability of O_3 formation, as shown in [11—13].

The AO flux depends on the solar activity cycle, seasonal cycle, geomagnetic behavior, orbital altitude, and inclination. Due to the orbital speed of spacecraft in LEOs (7-8 km/s), AO impacting energy ranges from 4 to 5 eV [14].These energy ranges are sufficient to break the chemical bonds of many materials that will lead to very high erosion rates in the case of the outer surfaces of satellites [15].

If the orbital velocity of a spacecraft is 8 km/s (related to the LEOs), it will be exposed to highly energetic AO of about 5 eV energy. Exposure to AO leads to a high erosion rate of materials such as organic films, composites and many polymers, as well as extreme mass loss and changes in the physical and chemical properties of the surface. These changes, directly and indirectly, affect the functionality of the spacecrafts and, thus, its lifetime [3].

1.3. AO and LEOs Environment. The space environment is composed of many components such as vacuum, pressure difference, radiation, solar and galactic cosmic rays, solar wind plasma, micrometeoroids and debris, etc. Each group of altitudes has its own components or parameters. Fig. 6 shows all the space environmental components distributed with different altitudes from the sea level up to the HEOs. It is clear that AO is more abundant in orbits with altitudes of 180 to 800 km [16].

It is reported that AO is the main component of the LEOs since it has a high corroding ability after combining it with the outer surface materials [17].

The space environment of a spacecraft is the environment to which the spacecraft is subjected. Each space environment has its own characteristics and conditions, which control the target of the mission, choice of materials, and construction of the spacecraft. There are four categories for the environment, which are summarized in Table 1 [18].

1.4. Effect of AO on materials. The AO interaction with the materials of the LEO satellite depends on the type of AO [6]:

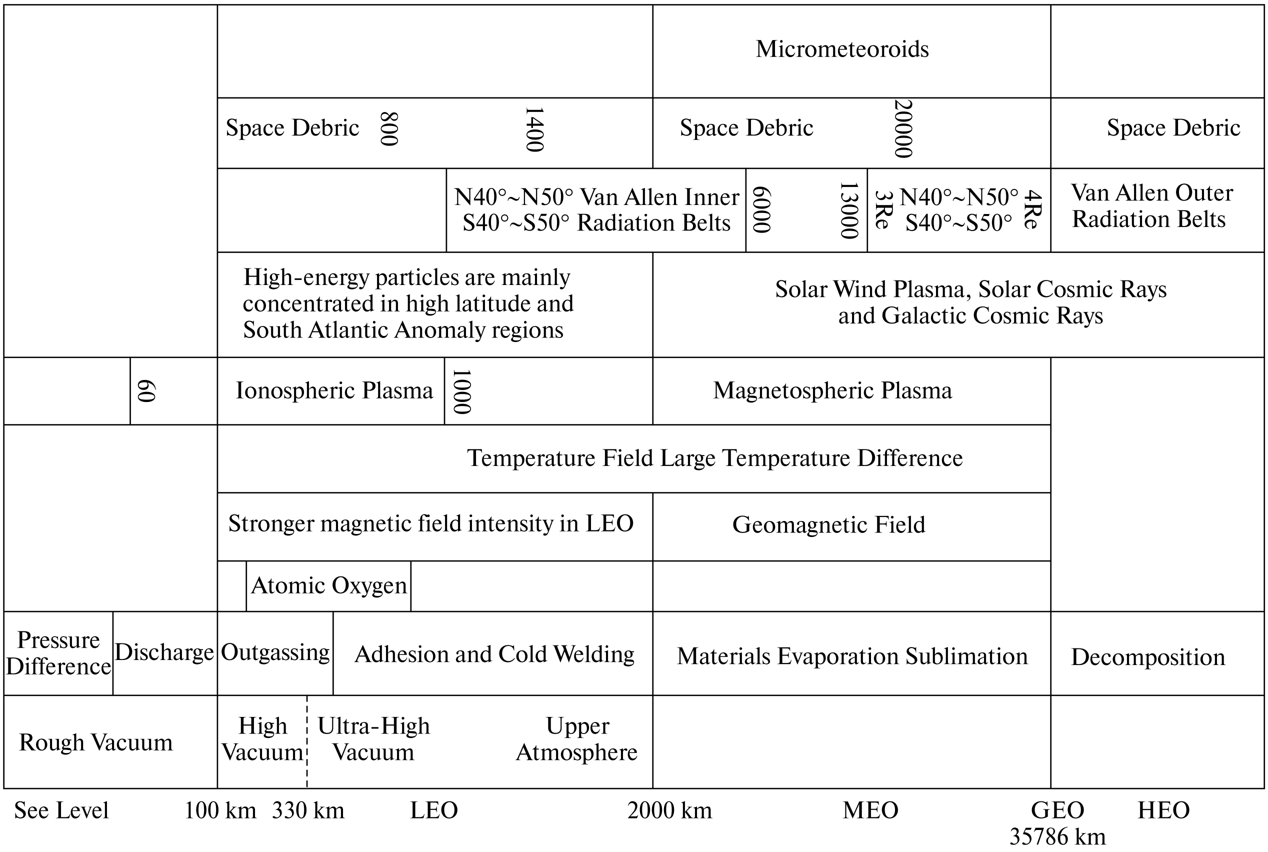

Figure 6. Space environmental components in all altitudes

Table 1. **Summary of four categories of environments**

Environment	Inclusion
Neutral environment	• It includes the residual atmospheric gas. • It is released through decomposition or outgassing, emitted during thruster firing, or deliberately vented from the spacecraft.
Plasma environment	• It includes the ambient plasma (that is created by hypervelocity impact with the spacecraft surfaces). Its components are corpuscular and electromagnetic.
Radiation environment	• It includes the ambient solar photon flux (that is reflected and emitted from the Earth). • It also includes electromagnetic waves (that are generated by the plasma environment) and photons emitted from nuclear sources of the spacecraft - Electromagnetic interference (EMI) is generated by the operation of spacecraft systems or arcing. • The corpuscular radiation environment consists of the ambient flux of particles (Electrons, photons, heavy ions, and neutrons) and any high-energy particles emitted by nuclear sources or reactors.
Particulate environment	• It consists of orbital debris, ambient meteoroids, and particulates (that are released by the spacecraft). It results in the dust on spacecrafts surfaces and materials decompositions (by thermal cycling or exposure to UV radiation)

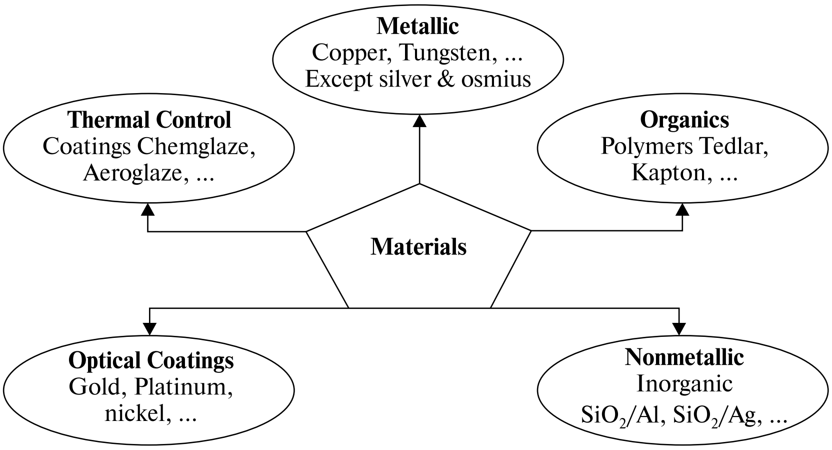

Figure 7. Types of materials to be used in space technology

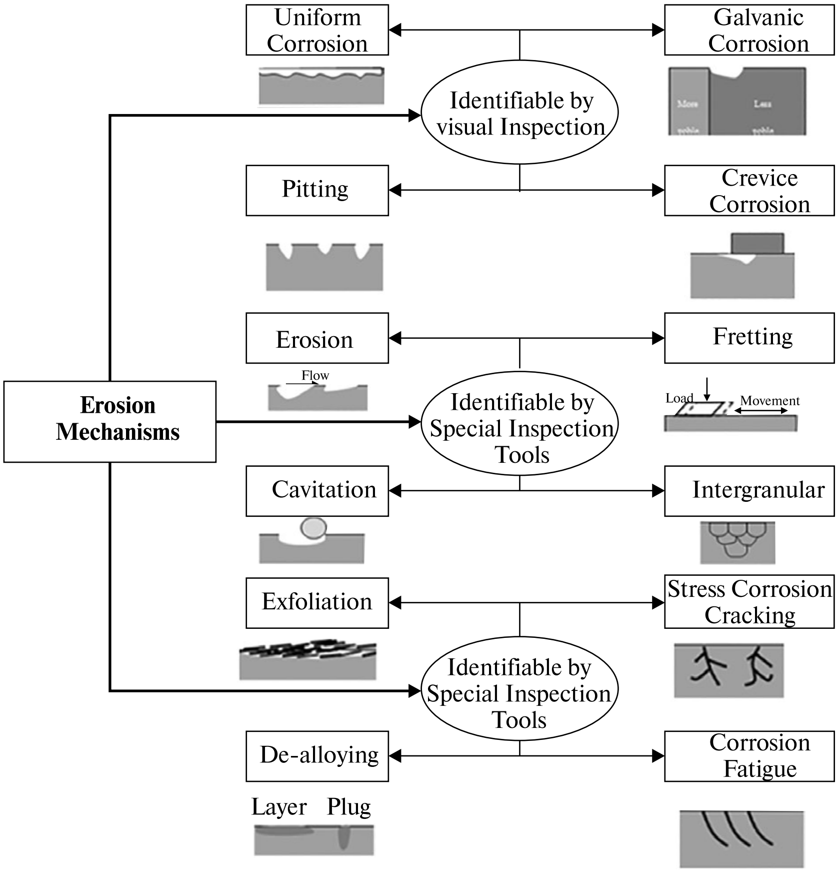

Figure 8. Erosion mechanisms

1 — Thermal AO; the interaction with material and degradation are a chemical process involving only chemical bonding changes, as the covalently bonded structure is broken apart, forming volatile products.

2 — Hyperthermal AO; impacts the material surface at 8 km/s. It causes erosion and degradation of organic polymers.

The interaction of AO with materials may form oxides for most organic materials or form volatile oxides at a continuous rate.

The interactions result in chemical composition change, mechanical degradation, mass loss, thickness loss, and/or erosion. Also, they generate a glow phenomenon that affects the visibility of the satellite's optical system.

2. AO AND MATERIALS. Types of materials to be used in space technology are summarized in Fig. 7.

AO may interact with materials via many mechanisms. These mechanisms are described in three categories mentioned by [6, 19], as shown in Fig. 8.

Based on the different types of materials to be used in space technology (Fig. 7) and the different mechanisms of AO interactions with different materials (Fig. 8), some notes for the results of AO interactions are summarized in Table 2.

The difference between different material samples before and after exposure of MISSE 2 PEACE polymers to the AO is shown in Fig. 9 [15].

Figure 9. Pre-flight and post-flight photograph of the MISSE 2 PEACE polymers experiment tray

Besides, the erosion of organic materials will cause condensable gas volatiles, which in turn can lead to the degradation and contamination of optical instruments [4, 15, 20].

To compare erosion rates of different materials, the efficiency of the reaction of AO erosion can be measured in the volumetric loss per incident oxygen atom, cm^3/atom.

Monte Carlo developed a two-dimensional model for AO interactions to predict the erosion of an oxidizable material under a non-reactive layer with an opening in it. This Erosion is obtained by direct arrival and by scattering inside the formed cavity [21].

3. AO PREDICTION. As an atomic species, O hasn't vibration-rotation spectra, but it has two fine structure lines: one is centered near 63 mm while the other is near 145 mm. The 63 mm line is optically thick and isn't observable in the upper mesosphere and lower thermosphere (MLT) from space. The 63 mm line was measured by rocket-borne instruments [22] and by high-altitude balloons [23]. The 145 mm line is optically thin, but it requires complex technology to be observed from a satellite. Thus, there aren't global observations of the O-atom concentration in the MLT obtained from direct observations of radiant emission from O itself [24].

When planning a space mission, especially in the LEOs, much attention must be focused on the AO and its erosion effects on the spacecraft's materials. For better understanding, NASA's space environment and experiment branch carried out many studies to investigate the AO erosion effect on materials in addition to the observable effects in ground-based experiments. Many studies have focused on the erosion depth of materials used in space [4, 25], and other studies have focused on the change of photoemission properties of materials [26, 27], and also some studies have concentrated on modeling AO exposure before and after the mission [28].

3.1. ATOMOX. Space Environment Information System (SPENVIS; web-site: http://www.SPENVIS.oma.be) provides the Atomic Oxygen Interaction Model (ATOMOX) to evaluate the AO flux, fluence and material erosion, based on reference atmosphere and wind model. The models are summarized in Table 3 [6]:

1. Mass-Spectrometer-Incoherent-Scatter (NRLM-SISE-00).
2. Marshall Engineering Thermosphere (MET-V 2.0).

Table 2. **Notes for AO interactions with different types of materials**

Type of material	Interactions with AO
Organic and Polymers	• Polymers and other organics are among the most vulnerable materials when exposed to AO. • Polymeric films may peel due to thermal cycling, which in turn opens new surfaces that can be attacked by AO. • AO interaction with polymers leads to the formation of volatile oxidation products on the surface. • Polymers with Cl and F have lower AO erosion yield. • Polymers with O have higher AO erosion yield. • AO interactions with change in surface texture will develop as the material oxidizes and becomes thinner. • Surface texture can change the optical reflectance of material from specular to diffuse and increase the solar absorptance of opaque materials. Surface texture can also be the cause of crack initiation or tearing of thin film polymers
Metallic: Except silver and osmium	• Silver and osmium react rapidly and are generally considered unacceptable for use in uncoated applications. • Silver was used as a surface for a passive recording of the AO impact. • Most alloys of aluminum have proven to be resistant to AO. • Optical properties (solar absorptivity or thermal emissivity) may change due to AO bleaching or radiation darkening. • Interactions with AO result in mass loss due to outgassing
Nonmetallic	• AO reaction efficiencies ranged from $0.4\text{-}2.3 \times 10^{-28}$ cm^3/atom for silicon oxides, magnesium fluoride, and aluminum oxides. • The most commonly used nonmetallic, inorganic material is Beta cloth. • It is a fabric woven from fine quartz threads. It resists mechanical wear as well as AO and AO+UV attacks. • Both the Teflon and other materials can be eroded by AO and AO+UV exposure. • Glass generally resists the AO attack well. • Many forms of Beta cloth are impregnated with Teflon or silicone-based materials to lubricate the threads, so the fabric bends easily during handling without the threads abrading each other. • Small decreases in reflectance were noted, except for MgF2-sapphire over silver, which had noticeable degradation.
Optical Coatings	• The performance of most optical systems depends on coatings of various types. • While most glasses generally resist AO erosion well, their coatings can be highly vulnerable. • Erosion of reflective surfaces could greatly roughen the mirrors which must reflect X-rays at grazing incidence angles. • The samples of fluorides of magnesium, calcium, and lithium plus sodium salicylate, a luminescing phosphor, showed no significant loss, but the sodium salicylate showed significant surface roughening and a 50-percent decrease in VUV luminescence. • The camera comprises nested grazing incidence mirrors with filters — such as carbon, beryllium and aluminum-bonded to a Lexan substrate. • To protect the wide-field camera's filters, several protective coatings were investigated before boron carbide was selected. • Defects were observed on all reflective surfaces except SiO2/AI where a small decrease in reflection was measured
Thermal coatings	• The Chem-glaze and Aero-glaze families of paints are widely used in various spacecraft applications. • Ceramic-based paints, such as Z-93, were found to be quite durable in the space environment, but these paints have their own problems with molecular contamination absorption and difficulty in applying. • In general, thermal control coatings with organic binders such as polyurethane should not be selected for long-term AO exposure. These binders degrade, leaving only pigment particles which then become a contamination hazard. • A zinc oxide with potassium silicate binder. It varies from Z-93 with finer zinc oxide particle size and a pigment-to-binder ratio adjusted for lower solar absorptance; exhibited no color change or surface texturing; slight quenching of fluorescence was noted. • Zinc ortho-titanate with potassium silicate binder. It was formulated similarly to zinc oxide developmental paint; no color or surface changes; black light fluorescence did not appear to change. • Doped silica black ceramic paint, which did not appear to be affected by exposure.

Table 3. **Comparison between ATOMOX models**

Model	Ionospheric layers	Description	Shortcoming
NRLMSISE	All	Empirical	None
MET-V	Thermosphere Lower & Upper (90—150 km)	Semi-empirical	The altitude range between 90 km and 2.500 km
IRI2001	E-Region	Empirical	Overestimation of electron densities in the upper topside (from about 500 km above the F peak upward)
DTMB78	Thermosphere	Thermopause temperature model and an analytical temperature profile	Not representative of low solar activity condition due to the dataset used, which in turn causes uncertain predictions during low solar activity
NeQuick v2.0	E, F1, and F2	Semi-empirical	Only electron as an ionospheric / atmospheric constituent

Table 4. **Fast Atomic Oxygen Testing Facilities — Development Efforts**

	Organization	Location AO	AO Formation	FAO Flux formation/delivery	References
1	Jet Propulsion Lab	Pasadena, CA	Ion source	Electrostatic acceleration/ laser	[31]
2	Jet Propulsion Lab	Pasadena, CA	Pulsed laser breakdown in O_2/laser Cont. sustained plasma	Detonation / blast wave expansion through a nozzle	[32]
3	Los Alamos National Laboratory	Los Alamos, NM	Cont. plasma — induced breakdown	Detonation / blast wave expansion through a nozzle	[33]
4	NASA-Langley Research Center	Hampton, VA	Oxygen dissociative adsorption 9 diffusion through AG	Electron-stimulated desorption	[34]
5	NASA-Lewis Research Center	Cleveland, OH	Ion source	Ion flux	[35]
6	NASA-Lewis Research Center	Cleveland, OH	Microwave plasma	Electrostatic acceleration	[36]
7	Physical Science Inc.	Andover, MA	Pulsed laser breakdown in O_2/laser Cont. sustained plasma	Detonation / blast wave expansion through a nozzle	[37]
8	Princeton Plasma Physics Laboratory	Princeton, NJ	RF plasma source	Electrostatic acceleration / neutral on a biased plate	[38]
9	Toronto University of 9Aerospace Institute)	Downs view, Ontario, Canada	Microwave plasma in He/O_2	Expansion through a skimmer	[39]
10	Zhukovskij Central Aviation Institute - TsAGi	Moscow	RF arc discharge plasma in He/O_2	Expansion through a skimmer	[40]
11	Inst. Nuclear Physics, MSU	Moscow	Oxygen plasma by spark discharge	Electrostatic acceleration / ion deflection	[41]

3. Drag Temperature Model (DTMB78).

4. International Reference Ionosphere (IRI2001) — (IRI is now outdated. It is functioning since 2020).

5. NeQuick Ionosphere Electron Density Model (NeQuickv2.0).

4. AO FACILITIES AND EXPERIMENTS. Based on the importance of AO and its effect on satellite materials, it is recommended to provide many facilities to simulate, investigate, analyze, test, and manufacture, practically, the behavior of AO interactions with all materials that can be used in all space technology purposes.

AO facility, generally, consists of type, mode and principle of operation, AO formation method, AO flux formation/delivery, mode, thermal vacuum

Table 5. **The Main Types of FAO Sources in LEO Space Environment Simulation Facilities Worldwide**

	Name, affiliation	Type, mode and principle of operation	AO Formation Method	FAO Flux Formation/Delivery	Mode	Energy of atomic O, eV	Flux density, $cm^{-2}s^{-1}$ cont/pulse	Flux structure, %	References
1	MSFC (USA)	Elec.-phys., pulse, plasma, rech.	RF plasma	Elec. accel., plate neutr. / Scattering	Pulsed	5	5×10^{15}	O -10 % + VUV (-200ES)	[42—44]
2	PSI (USA) ESTEC (Netherlands) NASA JPL (USA) CERT-ONERA, (France)	Gas-dynamic, pulse, laser	Laser breakdown in O_2/Laser sustained plasma	Detonation/ blast wave in supersonic nozzle	Pulsed	1-16	$5\times10^{15}/10^{17}$	O_2/O 10/90 (+UV/ VUV)	[45—49]
3	Montana State University (USA)	Gas-dynamic, pulse, laser	Laser: breakdown in O_2/ sustained plasma.	Detonation/ blast wave in supersonic nozzle	Pulsed	~5	$\sim10^{14}$	O_2/O ~60/40	[50]
4	LANL (USA)	Gas-dynamic, cont, laser	Laser breakdown Ar/O_2	Detonation/ blast wave in supersonic nozzle	Cont.	1-3	10^{16}	Ar/O_2/O 90/7/3	[51]
5	ITL/UTIAS (Canada)	Gas-dynamic, cont, UHF	Microwave plasma, He/O_2	Supersonic expansion	Cont.	1-3	10^{17}	He/O_2/O 97/1/2	[52]
6	Zhukovskij Central Aviation Institute -TsAGi (Russia)	Gas-dynamic, cont, HF	RF arc discharge, He/O_2	Supersonic expansion	Cont.	1-5	10^{16}	He/O_2/O 90/7/3	[53]
7	SOREQ NRC (Israel)	Electro-phys, cont, ionic	Ion source	Electrostatic accel. /decel.	Cont.	30-50	10^{14}	O - 100	[54]
8	Kobe Univ. (Japan)	Gas-dynamic pulse laser	Laser breakdown in O_2/Laser sustained plasma	Detonation/ blast wave in supersonic nozzle	Pulsed	4.5-5.1	$(0.3...6.5)\times$ $\times10^{14}$	O_2/O ~55/45	[55]
9	Inst. Nuclear Physics, MSU (Russia)	El-phys, cont, plasma +recharging	Oxygen plasma	Electrostatic accel. / Ion deflection	Cont.	5-80	10^{16}	O_2/O 15/80	[56, 57]
10	Moscow Phys. Inst. (Russia)	Gas-dynamic, pulse, spark	Oxygen plasma by spark discharge in O_2	Shockwave/ supersonic expansion	Pulsed	1-5	$5\times10^{15}/10^{18}$	O_2/O 2/98	[58]
11	Phill Lab, Cal. Univ. (USA)	Phys., diffusion - desorption	O_2 dissociation/ diffusion through Ag foil	Electron-stimulated desorption	Cont.	~5(4-6)	4.5×10^{13}	0-100	[59, 60]
12	Shanghai Univ, (China) (2001)	Electro-phys, pulse(?), plasma, recharging	RF plasma	Elec. accel., plate neutralization/ reflection	Pulsed	6-20	2×10^{16}	(NA)	[61]
13	Beijing Inst. of Spacecraft Env. Eng. (China) (1999)	Electro-phys, ionic decel., recharging	ECR-based ion source	Deceleration/ neutralization	Cont.	5-10	(NA)	(NA)	[62]
14	Lanzhou Inst. of Phys. (China) (1998)	Electro-phys, plasma, recharging	Microwave plasma	Electrostatic acceleration/ plate neutralization/ reflection	Pulsed	5-10	4×10^{15}	0-100(NA) 0+<0.1%	[63]

chamber, and other accessories (sample holder, quartz crystal microbalance (QCM), etc.

Many experiments are running to simulate the resistance of some materials (especially polymers that can be used in thermal control blankets) to the effect of AO. MDM2 (Material Degradation Monitor 2) is an experiment in which some materials were exposed onboard the International Space Station (ISS) that uses the Exposed Experiment Handrail Attachment Mechanism (ExHAM) developed by JAXA. MDM2 aimed at under standing surface reactions and degradation of the samples used in the MDM at a given AO fluence. In the MDM2, 16 samples of spacecraft material were exposed at an altitude of 400 km from May 26, 2015, to June 13, 2016, then returned for analysis [29].

Table 4 summarizes the development efforts of FAO testing facilities and Table 5 presents the main types of FAO sources in LEO space environment simulation facilities worldwide [30].

5. SUMMARY. AO is very dangerous atmospheric constituent since it has hazardous impacts on satellites and space technology of LEOs. It is formed by photodissociation of molecular oxygen. UV radiation and cosmic rays has a great ability to form AO by breaking the bonds of molecular oxygen. AO has the ability to react with almost all materials and it can change its physical, chemical, and optical properties. Many simulation techniques are required for more investigation to the interaction of AO with different types of materials (metallic, non-metallic, organic, thermal control coatings, and optical coatings). Surface material might be eroded by different mechanisms according to AO type (thermal and hyperthermal) and material type. ATOMOX models provide five different models to simulate the effect of AO on materials. The models are NRLMSISE, MET-V, IRI2001, DTMB78, and NeQuick v2.0. NRLMSISE is the only model that predicts the mass and thickness loss through all ionospheric layers. Other models have been developed to study and investigate reactions between AO and materials. Many facilities must be provided to enhance studying, understanding and testing the AO effect on materials. A continuous improvement for models and facilities is required to protect space missions from AO.

REFERENCES

1. Vest E. C. (1991). The effects of the space environment on spacecraft surfaces. *Johns Hopkins APL Technical Digest*, **12**(1), 46—54.
2. Banks B. A., Miller S. K. R. (2006). Overview of space environment effects on materials and GRC's test capabilities. NASA Seal/Secondary Air System Workshop. Vol. 1
3. Mundari N. (2011). *Effect of Atomic Oxygen Exposure on Spacecraft Charging Properties*. Diss. PhD thesis. Department of Electrical and Electronic Engineering, Kyushu Institute of Technology, Japan.
4. Bank B. B., de Groah K. K., Miller S. K. (2004). Low Earth Orbital Atomic Oxygen Interaction with Spacecraft Materials. NASA/TM-213400.
5. Samwell S. (2014). Low earth orbital atomic oxygen erosion effect on spacecraft materials. *Space Res. J.*, **7**(1), 1—13.
6. Mahmoud W. M., Elfiky D., Robaa S. M. (2021). Effect of Atomic Oxygen on LEO CubeSat. *Int. J. Aeronaut. Space Sci.*, **22**, 726—733. https://doi.org/10.1007/s42405-020-00336-w.
7. Harris I. L., Chambers A. R., Roberts G. T. (1998). Results from the space technology research vehicle 1a atomic oxygen experiment. *Spacecraft and Rockets J.*, **35**(5), 647—652.
8. Mende S. B., Swenson G. R., Clifton K. S. (1984). Space plasma physics: atmospheric emissions photometric imaging experiment. *Science,* **225**, 191—193.
9. Caledonia G. E. (1989). *Laboratory simulations of energetic atom interactions occuring in low Earth orbit.* Rarefied Gas Dynamics: Space Related Studies. Eds E. O. Munts, D. P. Weaver and D. H. Campbell. Progress in Astronautics and Aeronautics Ser., AIAA, Menlo Park, CA, **116**, 129—142.
10. Banks B. A., de Groh K. K., Miller S. K. (2005). Low Earth orbital atomic oxygen interactions with spacecraft materials. *Materials Research Society Symposium Proceedings*, 851.
11. Santiago-Prowald and Salghetti Drioli L. (2012). *Space Environment and Materials*. Space Antenna Handbook. W. A. Imbriale, S. (Shichang) Gao and L. Boccia. John Wiley & Sons, Ltd, **99**, 106—137.
12. Dickerson R. E., Gray H. B., Haight G. P. (1979). *Chemical Principles*. The Benjamin/Cummings Publishing Company Cummings, Menlo Park, 457. doi: 10.1109/ACCESS.2019.2927811.

13. Dever J., Banks B., de Groh K., Miller S. (2005). *Degradation of spacecraft materials.* Handbook of Environmental Degradation of Materials. William Andrew, Norwich, NY., 465—501.
14. Arnold G. S., Peplinksi D. R. (1986). Reaction of high-velocity atomic oxygen with carbon. *AIAA J.*, **24**(4), 673—677.
15. De Groh K. K., Banks B. A., Mccarthy C. E. (2008). MISSE 2 PEACE polymers atomic oxygen erosion experiment High Performance Polymers. *Int. Space Station J.*, **20**(4-5), 388409.
16. Lu Y., Shao Q., Yue H., Yang F., 2019: A review of the space environment effects on spacecraft in different orbits. *IEEE Access*, **7**, 93473—93488.
17. Dennison J. R., Bruson J., Swaminathan P., Wesley N., Frederickson A. R. (2006). Method of high resistivity measurement related to spacecraft charging. *IEEE transaction on plasma society*, **34**(5), 2204 2218.
18. Hasting D., Garrett H. (2004). *Spacecraft Environment Interaction*. Cambridge University press, Chapter 1, 1—11. ISBN 0-521-60756-6.
19. Rana A., Abdulmajeed M. (2016). Tribocorrosion, advancesin tribology. Ed. Pranav H. Darji. IntechOpen. https://doi.org/10.5772/63657.
20. Banks B. A., de Groh K. K., Backus J. A. (2008). Atomic Oxygen Erosion Yield Predictive Tool for Spacecraft Polymers in Low Earth Orbit. NASA/TM-215490.
21. Banks B. A., Stueber T., Miller S. K., Groh K. K. (2017). Monte Carlo Computational Modeling of Atomic Oxygen Interactions. https://ntrs.nasa.gov/api/citations/20170006849/downloads/20170006849.pdf
22. Grossmann K. U., Vollmann K. (1997). Thermal infrared measurements in the middle and upper atmosphere. *Adv. Space Res.*, **19**, 631—638.
23. Mlynczak M. G., Martin-Torres F. J., Johnson D. G., Kratz D. P., Traub W. A., Jucks K. (2004). Observations of the O (3 P) fine structure line at 63 mm in the upper mesosphere and lower thermosphere. *Geophys. Res. J.*, **109**, A12306. doi:10.1029/2004JA010595.
24. Mlynczak M. G., Hunt L. A., Mast J. C., Marshall B. T., J. M. R., Smith A. K., Siskind D. E., Yee J-H., Mertens C. J., Martin-Torres F. J., Thompson R. E., Drob D. P., Gordley L. L. (2013). Atomic oxygen in the mesosphere and lower thermosphere derived from SABER: Algorithm theoretical basis and measurement uncertainty. *Geophys. Res.: Atmospheres J.*, **118**(11), 5724—5735. https://doi.org/10.1002/jgrd.50401
25. Bourassa R. J., Gillis J. R. (1992). Atomic oxygen exposure of LDEF experiment trays. *NASA Contractor Report*.
26. Samaniego J. I., Wang X., Andersson L., Malaspina D., Ergun R. E., Horányi M. A. (2018). Investigation of coatings for Langmuir probes in an oxygen-rich space environment. *Geophys. Res.: Space Phys. J.*, **123**, 6054—6064. https://doi.org/10.1029/2018JA025563
27. Samaniego J. I., Wang X., Andersson L., Malaspina D., Ergun R. E., Horányi M. A. (2019). Investigation of coatings for Langmuir probes: Effect of surface oxidation on photoemission characteristics. *Geophys. Res.: Space Phys. J.,* **124**, 2357—2361. https://doi.org/10.1029/2018JA026127.
28. Schumm G., Bonnell J. W., Wygant J. R., Mozer F. S. (2020). Calculation of the atomic oxygen fluence on the Van Allen Probes. *Geophys. Res.: Space Phys. J.,* **125**, e2020JA027944. https://doi.org/ 10.1029/2020JA027944
29. Kleiman J., Iskanderova Z., Gudimenko Y., Horodetsky S. (2003). Atomic oxygen beam sources: a critical overview. *Materials in a Space Environment*, **540**, 313—324.
30. Goto A., Umeda K., Yukumatsu K., et al. (2021). Property changes in materials due to atomic oxygen in the low Earth orbit. *CEAS Space J.,* **13**, 415—432. https://doi.org/10.1007/s12567-021-00376-2
31. Orient O. J., Chutjian A., Murad E. (1990). Collision of O-(2P) Ions and O (3P) Atoms with Surfaces. Materials Degradation in Low Earth Orbit (LEO). Eds V. Srinivasan and B. A. Banks. A Publication of TMS (Minerals, Metals, Materials), 87—95.
32. Brinza D. E., Coulter D. R., Chung S. Y., Smith K. O., Moacanin J., Liang R. H. (1989). A Facility of Studies of Atomic Oxygen Interactions With 3rd Materials. *Proc. Int. SAMPLE Electronics Conf.*, 646—652.
33. Cross J. B., Cremers D. A. (1986). High Kinetic Energy (1—10 eV) Laser Sustained Neutral Atom Beam Source. *NIMB13*, 658—662.
34. Outlaw R. A. (1989). Producing essentialy pure beam of atomic oxygen — by providing material which dissociates molecular oxygen and dissolves atomic oxygen into its bulk. US Patent, 4, 817—828.
35. Banks B. A., Rutledge S. K., Paulsen P. E., Stueber T. J. (1989). Simulation of the Low Earth Orbital Atomic Oxygen Interaction with Materials by Means of an Oxygen Ion Beam. *NASA TM-101971.*
36. Ferguson D. C. (1990). Atomic oxygen effects on refractory materials,materials degradation in Low Earth Orbit (LEO). *Annual Meeting of the Minerals, Metals, and Materials Society*, 97—105.
37. Caledonia G. E., Krech R. H. (1990). Studies of the interaction of 8 km/s oxygen atoms with selected materials. *Annual Meeting of the Minerals, Metals, and Materials Society*, 145—154.
38. Cuthbertson J. W., Langer W. D., Motley R. W. (1991). Atomic oxygen beam source for erosion simulation. *Annual Meeting of the Minerals, Metals, and Materials Society*, 77—86.

39. Tennyson R. C., Morison W. D. (1990). Atomic oxygen effects on spacecraft materials. *Annual Meeting of the Minerals, Metals, and Materials Society*, 59—76.
40. Nikiforov A. P., Scurat V. E. (1993). Kinetics of polyimide etching by supersonic beams consisting of atomic and molecular oxygen mixtures. *Chemical Phys. Lett.*, **212**(12), 43—49.
41. *New Scientific Technologies in Industry*. Encyclopedia. Chief ed. K. S. Kasayev (2000). Space Environment Effects on Spacecraft Materials and Equipment. Eds L. S. Novikov, M. I. Panasyuk. Moscow: Entsitech, 17 [in Russian].
42. Finckenor M. M., Edwards D. L., Vaughn J., Schneider T. A., Hovater M. A., Hoppe D. T. (2002). Test and analysis capabilities of the space environment effects team at Marshall Space Flight Center. *NASA/TP –2002-212076*.
43. Dooling D., Finckenor M. M. (1999). Material Selection Guidelines to Limit Atomic Oxygen Effects on Spacecraft Surfaces. *NASA/TP-1999-0064119*, 209—260.
44. Cuthbertson J. W., Langer W. D., Motley R. W. (1990). Atomic Oxygen Beam Source for Orbital Environments. *Materials & Manufacturing,* **5**(3), 387—396.
45. Krech R. H., Caledonia G. E. (1993). AO Experiments at PSI. *Report PSI*.
46. Caledonia G. E., Krech R. H., Green B. D. (1987). A High Flux Source of Energetic Oxygen Atoms for Material Degradation Studies. *AIAA J.*, **25**, 59—63.
47. Caledonia G. E., Krech R. H., Green B. D., Pirri A. N. (1990). US Patent Number 4,894,511, Jan. 16 1990.
48. Cazaubon B., Paillous A., Siffre J., Thomas R. (1996). Five-Electron-Volt Atomic Oxygen Pulsed-beam Characterization by Quadrupolar Mass spectrometry. *Spacecraft and Rockets J.*, **33**(6).
49. Grossman E., Guzman I., Viel-Inguimbert V., Dinguirard M. (2003). Modification of 5 eV Atomic-Oxygen Laser Detonation Source. *Spacecraft and Rockets J.*, **40**(1), 110113.
50. Zhang J. G., Donna J., Minton T. K. (2002). Reactive and inelastic scattering dynamic of hyperthermal oxygen atoms on a saturated hydrocarbon surface. *Chem. Phys. J.*, **17**(13), 6239—6251.
51. Cross J. B., Spangler L. H., Hoffbauer M. A., Archuleta F. A. (1987). High intensity 5 eV CW laser sustained O-atom exposure facility for material degradation studies. *SAMPE Quarterly,* **18**(2), 41—47.
52. Morison D., Tennyson R. C., French Y. B. (1988). *Microwave Oxygen Atom Beams Source*. Fourth European Symp. on Spacecraft Materials in Space Environment. CERT, Toulouse, France, 435—441.
53. Scurat V. E., Nikiforov A. P., Ternovoy A. I. (1994). *Investigations of reactions of thermal and fast atomic oxygen (up to 5 eV) with polymer films.* Proc. 6th Int. Symp. on Materials in a Space Environment, ESTEC, Noordwijk, The Netherlands, 183—187.
54. Vered R., Lempert G. D., Grossman E., Haruvy Y., Marom G., Singer L., Lifshitz Y. (1994). *Atomic Oxygen Erosion on Teflon FEP and Kapton H by Oxygen from Different Sources: Atomic Force Microscopy and Complementary Studies*. Proc. 6th Symp. on Materials in Space Environment. ESTEC, Noordwijk, The Netherlands, 175 179.
55. Tagawa M., Kumiko Y., Nobuo O., Hiroshi K. (2000). Volume diffusion of atomic oxygen in.-SiO2 protective coating. *High Performance Polymers*, **12**(1), 53—63.
56. Titov V. I., Solovyev G. G., Tarasov J. I., Chernik V. N., Naumov S. F., Demidov S. A., Kutlaliev A. I. (1991). *«Complex-2» Low Earth Orbital Environment Simulation Faculty for Materials Durability Evaluation*. Proc. 5th Int. Symp. on Spacecraft Materials in Space Environment. Cannes, 4345.
57. Chernik V. N. (1997). *Atomic Oxygen Simulation by Plasmadynamic Accelerator with Charge Exchange SP-399*. Proc. 7th Int. Symp. Materials in Space Environment. Toulouse, 237—241.
58. Danilichev P. V., Kudryavtsev N. N., Mazyar O. A., Smirnov N. V., Suhov A. M. (1993). Pulsed Source of Fast Molecular Flux on the Base of Electromagnetic Shock Tube. *Pribori i Tehnika Eksperimenta*, № 4, 151—155 [in Russian].
59. Outlaw R. A., Davidson M. R. (1994). Small Ultrahigh vacuum compatible hyperthermal oxygen atom generator. *J. Vac. Sci. Technol.*, **12**(3), 854—860.
60. Shively J., Miglionico C., Roybal R., King T., Robertson R., Baird J., Davis S., Stein C. (1997). Combined Effects of the Lower Earth Orbit Environment on polymeric materials. High temperature and environmental effects on polymeric composites. Vol. **2**. ASTM STP1302, 223—242. DOI: 10.1520/STP11377S
61. Jia-nian S., Yan-fa H., Long-jiang Z., Meishuan L. (2001). The generation and control of high flux neutral atomic oxygen beam. *High Power Laser and particle Beams*, **13**(2), 228—232.
62. Sun G., Tong J., Li J. (1999). The deceleration and neutralization systems for microwave discharge atomic oxygen simulation. *Chinese Space Sci. and Technol.* (1000-758X), **19**(6), 5357.
63. Wang J., Yu Z., Cai C., Li H., Zhang J. (1998). Coaxial atomic oxygen simulation facility and its properties. *Chinese Space Sci. and Technol.* (1000-758X), **18**(5), 50—55.

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АТОМАРНИЙ КИСЕНЬ НА НИЗЬКИХ НАВКОЛОЗЕМНИХ ОРБІТАХ: РЕТРОСПЕКТИВНИЙ ОГЛЯД

У статті подано ретроспективний огляд досліджень атомарного кисню (АО) на низьких навколоземних орбітах (LEO). Космічний простір LEO є перешкодою для всіх супутників, які перебувають в ньому. Кілька його складових частин становлять велику небезпеку для матеріалів і підсистем супутників. Такі орбіти зручні для дистанційного зондування та експериментальних супутників. Для підтримки рівня працездатності космічних апаратів необхідно виконувати ретельні дослідження стану середовища LEO та його компонентів. АО, який є гіперактивним станом кисню, вважається одним із найнебезпечніших компонентів середовища LEO. Він може реагувати з багатьма матеріалами і тим самим змінювати фізичні, оптичні та механічні властивості, які впливають на функціональність супутника. Для підтримки супутника на його орбіті з певним запасом надійності потрібне зменшення агресивного впливу на нього екологічних компонентів LEO. Прогнозування впливу АО на матеріали, які будуть використовуватися в космосі, гарантує їхній правильний вибір. В роботі надаються деякі рекомендації щодо створення установок АО для тестування матеріалів, що піддаються агресивному впливу космічного середовища LEO.

Ключові слова: атомарний кисень (АО), низькі навколоземні орбіти (LEO), викиди корональної маси (CME), космічне середовище.