IMPACT OF SPACECRAFT AND ISS ENGINES ON EXPERIMENTAL SAMPLES OF VARIOUS MATERIALS MOUNTED ON THE OUTER SURFACE OF THE ZVEZDA MODULE

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Abstract
The work presents a study of the influence of the spacecraft and ISS engines during the correction of the station’s orbit. The zones of action of the gas jets and their impact on the environment and the surfaces of the experimental samples of various materials mounted on the outside of the Zvezda module were determined.

Introduction
Studying the effect of space conditions on various materials leads to the development and use of new materials. The continuous search for new alloys with specific properties leads to the selection of the main material in our work to be aluminum strengthened with diamond powder and Tungsten. The material is of considerable interest for its use in space technology and, in particular, for space instrument making. That is why the conceptual project is realized in cooperation with a leading country in this branch – the Russian module of the International Space Station (ISS), in which division, the team actively participates with the DP-PM block, as part of the OBSTANOVKA experiment. Block DP-PM is a container with dimensions 185 mm × 70 mm × 10 mm. In the core of the container, there are 10 pcs. cylindrical specimens made of high-strength B95 aluminum alloy reinforced with nanodiamond powder and tungsten (~0.1%) (Fig.1).

Method
The experiment to study the influence of the space environment on the structure and properties of various samples was conducted in the period from 04/19/2013 until 10.08.2015. The operation of the DP-PM block from its placement...
on the outside of the Zvezda module until its delivery to Earth is carried out in accordance with the documents of Product 17KS #12801. P42422 [1].

The purpose of the experiment is the study of light composites based on high-strength aluminum alloys and the change of their structures during prolonged stay in the conditions of outer space. The resistance of these composites with respect to solar and space radiation and vacuum, as well as the mechanisms of influence of extreme conditions on the strength and fatigue of the test specimens: the degree of stress of the structure, the tensile strength, the microhardness and the aging coefficient, were investigated.

In Fig. 2 shows the exact location of the DP-PM block on the surface of the ISS [1, 2].
After completion of the planned period, the DP-PM block is dismantled from the outer surface of the ISS and the cosmonauts place it in a work bag (Fig. 3, a). Then, in the transition compartment of the Zvezda module, the cosmonauts put it in a special soft container (Fig. 3, b). In preparation for returning to Earth with the “Soyuz-TMA” spacecraft No. 716, the container was additionally placed in an airtight transport package (Fig. 3, c). In this type, the DP-PM block was handed over for conducting research at the Space Research and Technologies Institute at the Bulgarian Academy of Sciences (SRTI–BAS).

Fig. 3. Different types of packaging for transporting a DP-PM block: a) Work bag; b) Special soft container; c) Airtight transport package

Upon external inspection of the samples (Fig. 4), it was found that their surfaces are heavily blackened, which suggests an atypical impact on them in the conditions of the space vacuum and weightlessness of this orbit. Our working hypothesis was that the condition of the surface of the samples was due to the impact of the gas jets from the various engines used in the control and correction of the ISS, both during the docking of the ships coming from Earth and their separation from the ISS.

Fig. 4. Appearance of the samples from block DP-PM during research at SRTI–BAS
After March 2011, a total of 15 pressurized modules were added to the ISS: Zarya, Zvezda, Destiny, Unity (Node1), Harmony (Node2), Tranquility (Node3), Columbus, Leonardo, Japanese, Quest, Cupola, Poisk, Rassvet and Pierce. To these modules we can add all three pressurized docking adapters. We note that after the completion of the flights of the "Space Shuttle" program, the orbit of the station was raised from 350 km to 390-420 km [3].

In order to study the influence of the gas jets of the engines on the samples, in addition to their location, also the modes of docking (de-docking), control and corrections of the ISS by the ships and the Zvezda module were taken into account.

The scheme presented below (Fig. 5) depicts the main components of the station and the ships arriving (departing) to it, as well as the location of the main and correction engines (red arrows) [4].

![Fig. 5. Schematic of the main components of the ISS and the spacecraft docked to it](image)

The height of the station's orbit is constantly changing due to the influence of solar activity and friction with the rarefied atmosphere, which leads to the gradual deceleration of the movement and loss of height. Atmospheric drag lowers the altitude on average by about 2 km per month [6, 7].

The graph of the change in the height of the ISS, including the period of the experiment, is shown in Fig. 6 [4].

The ISS's orbit is adjusted several times a year to compensate for friction, to avoid larger and larger pieces of space junk, and for other reasons. Orbit correction is done using the ISS's own engines. Until 2000, the engines of the Zarya functional cargo model were used for this purpose, and then - of the Zvezda service model. The engines of the arriving transport ships are also used for orbit correction, which also
refuel the ISS [5]. Up to a certain period of time, the correction in the orbit consists only of compensating for the decrease in altitude.

Research shows that using Space Shuttle craft to maintain an 350 km high orbit of the ISS required 8 600 kg of fuel for one year. When increasing the height of the station's orbit to 400 km, the required fuel is 3 600 kg. During this period, the fuel for control and orientation was 1 926 kg [4]. The increased altitude allows for a substantial reduction in the amount of fuel required to maintain this orbit. At the same time, it enables increased supplies of water and food products, as well as other payloads. The ISS completes a complete orbit around the Earth in about 92 minutes. From launch to February 5, 2023, the station has completed 138 805 complete orbits.

During the period of the experiment, the following spacecraft have flown to the ISS and docked with the station: “Soyuz”, “Progress” and “Cygnus”, and the results are shown in Tables No. 1, No. 2 and No. 3.

Table No. 1. “Soyuz” spacecraft flights

<table>
<thead>
<tr>
<th>№</th>
<th>Mission Name</th>
<th>Board number</th>
<th>Launch date</th>
<th>Date of landing</th>
</tr>
</thead>
<tbody>
<tr>
<td>141</td>
<td>Soyuz TMA-09M</td>
<td>709</td>
<td>05/29/2013</td>
<td>11/11/2013</td>
</tr>
<tr>
<td>142</td>
<td>Soyuz TMA-10M</td>
<td>710</td>
<td>09/26/2013</td>
<td>03/11/2014</td>
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<tr>
<td>143</td>
<td>Soyuz TMA-11M</td>
<td>711</td>
<td>11/07/2013</td>
<td>05/14/2014</td>
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<tr>
<td>144</td>
<td>Soyuz TMA-12M</td>
<td>712</td>
<td>03/26/2014</td>
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</tr>
<tr>
<td>145</td>
<td>Soyuz TMA-13M</td>
<td>713</td>
<td>05/28/2014</td>
<td>11/10/2014</td>
</tr>
<tr>
<td>146</td>
<td>Soyuz TMA-14M</td>
<td>714</td>
<td>09/26/2014</td>
<td>03/12/2015</td>
</tr>
<tr>
<td>147</td>
<td>Soyuz TMA-15M</td>
<td>715</td>
<td>11/24/2014</td>
<td>06/11/2015</td>
</tr>
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Table No. 2. “Progress” spacecraft flights

<table>
<thead>
<tr>
<th>By №</th>
<th>Mission Name</th>
<th>Board number</th>
<th>Launch date</th>
<th>Date of landing</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>Progress M-19M</td>
<td>419</td>
<td>04/24/2013</td>
<td>06/19/2013</td>
</tr>
<tr>
<td>143</td>
<td>Progress M-20M</td>
<td>420</td>
<td>07/28/2013</td>
<td>02/11/2014</td>
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<tr>
<td>144</td>
<td>Progress M-21M</td>
<td>421</td>
<td>11/26/2013</td>
<td>06/09/2014</td>
</tr>
<tr>
<td>145</td>
<td>Progress M-22M</td>
<td>422</td>
<td>02/05/2014</td>
<td>04/18/2014</td>
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<tr>
<td>146</td>
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<td>423</td>
<td>04/09/2014</td>
<td>08/01/2014</td>
</tr>
<tr>
<td>147</td>
<td>Progress M-24M</td>
<td>424</td>
<td>07/24/2014</td>
<td>10/27/2014</td>
</tr>
<tr>
<td>148</td>
<td>Progress M-25M</td>
<td>425</td>
<td>10/29/2014</td>
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<tr>
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<td>02/17/2015</td>
<td>08/14/2015</td>
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<tr>
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<td>05/08/2015</td>
</tr>
<tr>
<td>151</td>
<td>Progress M-28M</td>
<td>428</td>
<td>07/03/2015</td>
<td>12/19/2015</td>
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</table>

Table No. 3. “Cygnus” spacecraft flights

<table>
<thead>
<tr>
<th>By №</th>
<th>Mission Name</th>
<th>Spacecraft name</th>
<th>Launch date</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cygnus Orb-D1</td>
<td>George Lowe</td>
<td>09/18/2013</td>
<td>First Cygnus spacecraft mission. The first Cygnus docking mission with the ISS was delayed due to a computer problem, but was successful.</td>
</tr>
<tr>
<td>2</td>
<td>Cygnus Orb-CRS-1</td>
<td>Charles Fullerton</td>
<td>01/09/2014</td>
<td>First logistics mission of a Cygnus spacecraft</td>
</tr>
<tr>
<td>3</td>
<td>Cygnus Orb-CRS-2</td>
<td>Janice Voss</td>
<td>07/13/2014</td>
<td>During the launch attempt, there is a catastrophic anomaly and the launch vehicle explodes</td>
</tr>
<tr>
<td>4</td>
<td>Cygnus Orb-CRS-3</td>
<td>Donald Slayton</td>
<td>10/28/2014</td>
<td>First mission of an enhanced version of Cygnus</td>
</tr>
<tr>
<td>5</td>
<td>Cygnus Orb-CRS-4</td>
<td></td>
<td>11/19/2015</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 7 shows the structure of the “Soyuz” spacecraft and the location of the engine bay [14].

The propulsion module of the “Progress” spacecraft, like that of the “Soyuz”, is located at the rear of the spacecraft. The module consists of the ship's main engine and navigation engines used for automatic docking with the ISS and for correcting the station's orbit when the ship is docked with it. On these ships, only one set of orientation engines type OE (8 units) with a thrust of 1.5 kgf, a KTDU-35 brake-engine unit with a thrust of 417 kgf and 14 engines for docking and orientation (EDO) with a thrust of 10 kgf were installed. Fuel for KTDU-35 is asymmetric dimethylhydrazine (ADMH) and oxidizer-nitric acid. EDO and OE work with hydrogen peroxide [14].
The combined propulsion system, which is used in many cases for orbit correction and control of the ISS [15] consists of two 2×312 kgf thrusters, 32×13.3 kgf thrusters for orientation, 302 kg of propellant (ADMH) and 558 kg of oxidizer (nitrogen tetraoxide).

The “Cygnus” spacecraft consists of two main components - a service module and a cargo module. The service module has a gross weight of about 1800 kg and is powered by Japanese rocket engines (BT-4 of the Aerospace company) running on ethylhydrazine and dinitrogen tetroxide [16]. Each motor develops a thrust of 46 kgf (Fig. 8).

After detaching aboard the Antares rocket, “Cygnus” approaches the ISS and when within a few meters of the station, the craft is engaged by the Canadarm-2 mechanized arm and docked with the Harmony module. “Cygnus”
does not have the ability to return cargo to Earth, but it can be filled with debris to burn up with it as it enters Earth's atmosphere.

From the beginning of the creation of the station until October 2022, the orbit of the ISS has been corrected 327 times, of which 176 times with the engines of the transport spacecraft “Progress”, which shows the importance and frequency of the correction.

For the period of positioning of the samples on the outer surface of the Zvezda module (28 months) a total of about 4 550 kg was used. (spacecraft “Progress” – 3 248 kg; modules Zvezda, “Cygnus”, etc. about 1 302 kg) for correcting the orbit of the ISS for control necessary for avoiding space debris and preparing the station for docking and undocking of arriving and departing spacecraft [4].

![Fig. 9. Concentration of the components of the space environment at altitudes from 100 to 1000 km](image)

As noted, the fuel used is unsymmetrical dimethylhydrazine ADMH, codenamed “heptyl”, which is a high-boiling component of rocket fuel (boiling point above 0 °C). Nitrogen tetroxide (AT) is used as an oxidizer of ADMH – pure or in a mixture with nitric acid. Cases of using pure acid and liquid oxygen are known. To improve the properties, it can be used in a mixture with hydrazine, known as aerosine
[11]. It self-ignites upon contact with nitric acid and dinitrogen tetroxide-based oxidizers, which simplifies construction and provides easy starting and re-engagement of rocket engines. ADMH is thermally stable up to +350 °C.

In the range from +350 to +1000 °C, dimethylhydrazine decomposes into ammonia, amines, hydrocyanic acid, hydrogen, nitrogen, methane, ethane, resinous and other substances, and at increased temperature it decomposes into nitrogen and hydrocarbons with the release of heat, an increase in the volume and creation of jet force from the nozzles.

Taking into account that the impact process on the surface of the spacecraft takes place even with very small amounts of atoms of the elements at different altitudes of the trajectory of the spacecraft (Fig. 9), (well systematized and summarized in [12], where cited and the results of the team from SRTI–BAS [1]), we can conclude that in the given case there are far more intense impact processes taking place, albeit short-lived, as a result of the spread of gases from the engines.

The gas jets coming out of the nozzles of the engines spread almost instantaneously in the three-dimensional space, which is determined by the practical vacuum around the station (Fig. 10 a, b) and depending on the spatial position of the station and the direction of the change in the speed of the ISS, as well as from the engines that are used, the studied samples are subjected to an impact, causing processes (oxidation) on their surfaces.

![Fig. 10. Propagation of the gas jets from the engine nozzles in the three-dimensional space around the ISS](image-url)
In fact, contrary to the initial impression that the gases from the exhaust gases from the engine nozzles always remain behind the board of the ISS, thanks to their relative motion they spread partially on the surface of the station, which is also the reason for the condition of the surfaces of the examined samples (Fig. 11 a, b).

Fig. 11. Different flow of the samples, depending on the position of the motors used for correction

Conclusion

It can be assumed that the change of the surface of the samples is due precisely to the large amount of fuel that was used during the experiment, which turned into gases from the nozzles of the engines of the spacecraft’s “Progress”, “Soyuz” and “Cygnus” during their docking (undocking) and the module Zvezda in ISS orbit correction and control.

These assumptions are also confirmed by the research carried out in the project on the changes on the surfaces of the studied samples, as well as by the composition of the substances obtained during their cleaning.

The difference in the type and the results of the accompanying studies in the design of the surfaces of the samples (respectively, face–back) in the conclusions made, are obviously due to the different conditions of impact and oxidation by the gas jets, determined by their location.

References

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ВЛИЯНИЕ НА РАБОТАТА НА ДВИГАТЕЛИТЕ НА КОСМИЧЕСКИТЕ КОРАБИ И НА МКС ВЪРХУ ОПИТНИТЕ ОБРАЗЦИ ОТ РАЗЛИЧНИ МАТЕРИАЛИ, МОНТИРАНИ ВЪРХУ ВЪНШНАТА ПОВЪРХНОСТ НА МОДУЛА „ЗВЕЗДА“

П. Гецов, Д. Теодосиев, Н. Загорски, Г. Мардиросян, Д. Зафиров

Резюме

В работата е представено изследване на влиянието на двигателите на космическите кораби и Международната космическа станция при корекция на височината на орбитата на станцията. Определени са зоните на действие на газовите струи и тяхното въздействие на околната среда и повърхностите на експерименталните образци от различни материали, монтирани на външната страна на модула „Звезда“.