Management of processes of space debris capture and processing into fuel

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Abstract. The processes of space debris capture and processing into fuel are considered. The mentioned processes have a number of limitations on the choice of materials to be recycled (space debris) and on the creation of spacecraft for space debris utilization (hereinafter - space debris collector). Management of space debris capture and utilization processes is inseparably connected with pseudo-liquid fuel, received by the collector from space debris. Pseudo-liquid fuel is finely dispersed garbage in the environment of hydrogen (fuel) and oxygen (oxidizer). To control the processes of space debris capture and utilization into fuel it is necessary to determine the choice of materials of the spacecraft capture device and manufacturing of internal systems. Efficiency of space debris capturing and utilization into fuel management will be provided by fulfilling a number of fundamental requirements in addition to those of the work: orbital altitude of space debris collector is conditioned by space debris location in space (orbit altitude, inclination); space debris is captured only from certain materials and alloys (metallized space debris); space debris is captured by the network at the intersection of the target orbit at small angles; material and structure of the tether is selected based on maximum tension and absence of breaks.

1. Introduction

Space debris is end of life satellites remaining in orbit, upper stages and booster rockets, dumped fuel tanks, fragments of destroyed objects, as well as springs, bolts, nuts, plugs etc [1].

Space debris is classified as cosmogenic and anthropogenic. Cosmogenic space debris, including meteors (sometimes even asteroids and comets), micrometeorites, cosmic dust, etc. have accompanied
mankind throughout its history. Whereas the problem of man-made space debris gained its official status only in the 80s of XX century due to the growing trend of space activities of mankind. Today, the technogenic space debris (hereinafter referred to as space debris) is a danger of collision with functioning spacecraft and falling of unburned large debris to the ground.

According to the space debris catalogs NASA, Discos (ESA), ASPOS ECP, there are about 20,000 registered space objects with the size greater than 10 cm. The cause of early destruction of the object may be a collision with a particle smaller than 0.1 cm at a speed of 10 km/s. The collision probability of a spacecraft with the area of 6 m, at an altitude of 900 km, is equal to $10^{-6}$ over 90 years, with the space debris growth of 6-12% per year [2].

In this connection the concept of space debris processing into pseudo-liquid fuel, which is a mixture of gas and fine metallized powder that behaves like a boiling liquid (pseudo-liquid) is proposed [3].

One of the first models for calculating elements of structures operating in aggressive hydrogen-containing media, taking into account changes in material properties over time, was the model proposed in the works of V.V. Petrov, I.G. Ovchinnikov, A.B. Rassada [4-6]. In accordance with the studies carried out for the construction of mathematical models of behavior of materials in a corrosive environment, it was proposed to use the theory of structural parameters of Yu.N. Rabotnov, taking into account the physical and chemical effects on the surface and in the volume of deformable solid [4, 7].

One of the directions of research in this area is the choice of materials for spacecraft manufacturing, materials processed into pseudo-liquid fuel, and management of processes of space debris capture and utilization.

2. Process and Material Requirements

Space debris is classified into large objects (spent life spacecraft, stages of launch vehicles), medium objects (space probes, operational debris, spent life micro-, nano spacecraft) and small objects (debris of spacecraft, rocket stages, protective shells) figure 1 [8].

![Figure 1. Classification of space debris and possible counteraction methods. The arrows show the types of spacecraft - potential replenishment of space debris population on different types of orbits. Above the line, some orbital parameters are shown, below the line - some ways to counteract the space debris threat. Quantitative distribution of materials, which mainly consist of space debris to be eliminated, is shown in figure 2.](image-url)
According to the same study [9], space debris mainly consists of metal alloys based on aluminum, titanium, magnesium and steel, whose ignition temperature and density is 660° (2.7 g/cm$^3$), 1200° (4.5 g/cm$^3$), 1500° (1.74 g/cm$^3$) and 1365.5° (7.8 g/cm$^3$), respectively.

Materials based on plastic (2.2 g/cm$^3$) and silicon (1.4 g/cm$^3$) are not taken into account due to the fact that pseudo liquid fuel has a metallized base.

The relationship between stresses and deformations is constructed within the framework of A.A. Ilyushin's theory of small elastic plastic deformations [10]. The stress intensity is expressed by a function of strain intensity, hydrogen concentration and parameter $\xi$. The chosen method for solving the problem of hydrogenation effect on the stress-strain state of titanium alloy is a numerical method based on substitution of derivatives by difference schemes.

In the study [6] the preliminary distribution of space debris decay fragments was obtained: fragments of launch vehicle bodies - 90% of average density and high density 10% (number); payload fragments - 70% of low density, 27% of average density, and high density 3%. Obviously, low-density fragments can disintegrate in orbit much faster than high-density fragments.

The existing concepts of space debris removal can be classified into the methods of space debris removal (Nobu Okada - Japan, Jan Wörner - ClearSpace-1, EU, RemoveDEBRIS - USA) and destruction directly in orbit (Lei Lan, Jingyang Li, Hexi Baoyin, Tsinghua University, Beijing, China) [11, 12].

Based on the analysis of the subject area, the choice of materials for manufacturing of internal spacecraft systems for space debris utilization has not been revealed, which affects the management of the processes of space debris capture and utilization into fuel.

The space debris trap consists of deformable dome-shaped network and cone-shaped network connected with each other by tethers converging-spending with possibility of closed cavity formation.

The space debris disposal system consists of the following components: a trap, a two-roller crusher, a drum-ball mill, a membrane electrode unit, a water regenerator, a control device, a fuel tank and motors [13].

3. Research of materials for space debris capture and processing

Let us present histograms, built according to data sampling from NORAD space debris catalog as of 19.09.2020 by orbit altitude figure 3, its inclination figure 4 and eccentricity figure 5.
Figure 3. Distribution of observed space debris objects of NORAD catalog by orbital altitude. The red line shows the trend of orbital altitudes from 400 to 4000 km but the most concentration is observed at altitudes of 800-1500 km.

Figure 4. Distribution of observed space debris objects by inclination of the NORAD catalog orbit. The red line shows the orbital inclination trend of 72°-28° with the largest number of objects inclination range of 65°-72°.

Figure 5. Distribution of observed space debris objects by orbital eccentricity of NORAD catalog. The red line shows the orbital eccentricity trend 0.04-0.16, however the overwhelming majority of space objects have orbital eccentricity in the range 0.02-0.1
Let's present a scheme of pressure and rotation distribution in the space debris collector's grinding system (two-roller shredder and drum-ball mill) in figure 6 [8, 13].

![Pressure and rotation distribution in the space debris collector's grinding system](image)

Figure 6. Pressure and rotation distribution in the space debris collector's grinding system (double roller grinder and drum-ball mill). The straight arrows show the pressure on the system elements, the curved arrows show their rotation.

On the basis of the work [13, 14] let's present the table 1 which contains the data concerning the two-roller shredder.

**Table 1.** Compression strength of the material being shredded, pressure, power.

| Parameters \ Materials | Strength limit, MPa | Pressure two-roller shredder, MPa | Power twin-roller shredder, kW | Wall pressure drum-ball mill, MPa | Power drum-ball mill, kW |
|------------------------|---------------------|----------------------------------|-------------------------------|-------------------------------|------------------------|
| Aluminum (Al)          | 150-200             | 82.12-109.5                      | 2.26                          | 3.23*10^{-5}                 | 1.32                   |
| Titanium (Ti) and      | 600                 | 328.5                            | 4.58                          | 4.25*10^{-5}                 | 2.31                   |
| Magnesium (Mg)         | 35-100              | 19.16-54.75                      | 0.87                          | 2.90*10^{-5}                 | 0.30                   |
| Steel                  | 400-500             | 219.0-273.75                     | 3.52                          | 3.72*10^{-5}                 | 1.90                   |

Based on the table, it can be concluded that the internal systems of the space debris collector (double roller grinder and drum-ball mill) require the selection of materials that meet the requirements presented. Obviously, the twin-roller mill must consist of more robust materials than the drum-ball mill.

Scientists such as V.V. Beletsky, E.M. Levin, Y.M. Zabolotnov, F. Zimmermann, Jin Tumphin, Ju Genjong, etc. developed the mechanics of orbital cable systems, for which the following physical principles are relevant: gradient of gravity, the law of momentum conservation, the law of tension change, the laws of electrodynamics [15].

On the basis of the study [1], Kevlar was chosen as the rope material (density of rope material $\rho = 1.44$ g/cm$^3$, modulus of elasticity of rope $E = 70500$ MPa), and the network material, due to its strength - titanium alloy.

On the basis of all the above the requirements to processes and materials are obtained and summarized in table 2.

**Table 2.** Process and material requirements.

| Space debris location | Two-roller shredder | Drum-ball mill | Network | Tether |
|-----------------------|---------------------|----------------|---------|--------|
| 800 ≤ h ≤ 1200km, 62° ≤ i ≤ 78°, 0.02 ≤ e ≤ 0.24 | Diamond-coated titanium alloy | Tungsten needles | Titanium alloy | Kevlar |

The data in table 2 are in line with the requirements. To determine the stresses and horizontal movements along the edges of the rope at the point of attachment of the dome network and the winch...
on the conical network, the deformation diagrams are constructed, as shown in figure 7 and 8, respectively. The rope has a mathematical representation in the form of a cylindrical shell.

![Figure 7](image)

**Figure 7.** Voltages $\sigma_{22}$ at the point of the cable edge (by thickness).

The degree of penetration of hydrogen-containing medium in thickness is obtained from the solution of diffusion equation. Here $\lambda$ - concentration of hydrogen-containing medium, $q$ - uniformly distributed axially symmetric transverse load, $D$ - diffusion coefficient

![Figure 8](image)

**Figure 8.** Horizontal movement in the rope.
As a result of the study confirmed the hypothesis that for some period corresponding to large gradients of hydrogen concentrations, there is an intensive change in the nature of the stress-strain state, reaching 20% for movements in the compressed and 24% in the stretched areas.

4. Process control technology

Deployment of the rope is based on the law of tension change and is subject to the influence of a number of parameters (cross-sectional area, length, mass of the rope, the mass of the network, the force of tension), which we agree to designate as parameters of the rope material.

The mass equation of the rope looks like

\[ m_T = \rho \cdot r_k. \]  (1)

where: \( r_k \) - the total length of the cable.

Suppose a cable is deployed evenly, then we have the law of tension change:

\[ T = 3 \cdot m_T \cdot \omega^2 \cdot r. \]  (2)

where: \( \omega \) - angular velocity of the rope system in orbit, \( r \) - the length of the let out cable.

The mathematical model of orbital tether system deployment obtained on the basis of Lagrange equations of the second kind has the following form [15]:

\[
\ddot{l} = l \cdot \dot{v}^2 - \frac{\mu}{l^2} \left( 1 + \frac{3}{2} \cdot \frac{M_2}{M} \cdot \frac{r^2}{l^2} \cdot (3 \cdot \cos^2 \phi \cdot \cos^2 \theta - 1) \right)
\]

\[
\ddot{u} = \frac{1}{M \cdot r^2} \left( 3 \cdot \frac{\mu}{l^3} \cdot M_2 \cdot r^2 \cdot \cos^2 \phi \cdot \sin \theta \cdot \cos \theta - 2 \cdot M \cdot l \cdot \dot{l} \cdot \dot{u} \right)
\]

\[
\ddot{r} = \frac{1}{2 \cdot M_2} \cdot \left( \dot{r}^2 \cdot \left( \dot{\phi}^2 + \dot{u} + \theta \right) \cdot \cos^2 \phi + \frac{\mu}{l^3} \cdot \left( 3 \cdot \cos^2 \phi \cdot \cos^2 \theta - 1 \right) - \varepsilon \cdot \sigma^2 \cdot (r - \bar{r}) + 2 \cdot \varepsilon \cdot \varsigma \cdot \dot{r} \right)
\]

\[
+ \frac{1}{2 \cdot M_2} \cdot \left( \dot{r}^2 \cdot \left( \dot{\phi}^2 + \dot{u} + \theta \right) \cdot \cos^2 \phi + \frac{\mu}{l^3} \cdot \left( 3 \cdot \cos^2 \phi \cdot \cos^2 \theta - 1 \right) - \dot{r}^2 \right) \cdot \frac{\partial M_2}{\partial r} + \frac{T}{M_2}
\]

\[
\ddot{\phi} = -\ddot{u} - 2 \cdot (\ddot{u} + \theta) \cdot \left( \frac{\dot{r}}{r} - \dot{\phi} \cdot \tan \varphi \right) - 3 \cdot \frac{\mu}{l^3} \cdot \sin \theta \cdot \cos \theta - \frac{1}{M} \cdot (\ddot{u} + \theta) \cdot \dot{\phi} \cdot \dot{r} \cdot \frac{\partial M_2}{\partial r}
\]

where: \( M_2 \) is the mass of the space debris collector with a tether and a network, \( l \) - radius - vector of the center of mass, \( u \) - latitude argument, \( \theta \) - angle of deviation from the vertical, \( \varphi \) - angle of deviation from the orbital plane, \( \varsigma \) - damping factor of the tether material, \( S \) - cross-section area of the tether, \( \bar{r}, r \) - respectively the length of the stretched and not stretched tether.

Figure 9 shows the maximum allowed intersection angle of the orbit, at which the velocity of space debris capture in orbit does not lead to the destruction of the space debris collector (the final orbit is outside the initial one).
Figure 9. Maximum allowed speed for space debris capture. Angle $\alpha$ - minimum angle of interorbital transition at the speed, $\beta$ - optimal angle of interorbital transition at the speed, $\gamma$ - maximum angle of interorbital transition at the maximum allowable speed, $\delta$ - angle of space debris collector destruction at the rate of destruction.

Space debris capture process management is carried out in two stages taking into account the selected sensors of spacecraft health and payload [16, 17]. The process of space debris processing into fuel management is depicted on figure 10 and 11.

Figure 10. Some points related to the management of space debris capture by the network. Space debris detection is carried out according to the catalogs and the place of increased space debris location.
Space debris detection is carried out according to the catalogs and the place of increased space debris location.

![Diagram of space debris management stages]

**Figure 11.** Stages of management of space debris processing into fuel.

The stages of space debris processing into fuel management are divided into preliminary stages, where the captured objects are analyzed, processed into fuel and used as intended.

The spacecraft sensors are divided into two types: health sensors and payload sensors. Health sensors monitor the performance of the spacecraft itself and are responsible for the location of the spacecraft and its internal systems. Payload sensors are designed to detect the metallized part of space debris, suitable for further processing. The processing of space debris into pseudo-liquid fuel is carried out in three stages, following which the work of the space debris collector without damaging it.

5. **Conclusion**

Space garbage is of cosmogenic and technogenic nature. As part of the development of human space activities, the problem of the growing population of technogenic space debris must be solved. A spacecraft that processes space garbage into fuel has been proposed; to ensure its operation meeting the presented requirements, a number of tasks have to be solved.

In this work the choice of space debris materials and management of processes of space debris accumulation and processing into fuel are considered.

Space debris has been classified and possible ways of its control have been presented, which made it possible to formulate the requirements to the materials of both the spacecraft itself and the recycled debris. This made it possible to analyze the composition of the debris (alloys based on aluminum, titanium, magnesium and steel) and to determine the largest accumulation of space debris on the Earth's orbits (800 ≤ h ≤ 1200km, 62° ≤ i ≤ 78°, 0.02 ≤ e ≤ 0.24).

The behavior of the cable system in space is considered, which allowed to develop the control process of network opening. It is suggested to determine the maximum allowable angle of orbit intersection. Control over space debris capture and processing process is developed.

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