On the issue of selecting burned materials in rocket vehicle designs

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Abstract. The concept of selecting materials for the design of separable parts of missiles with a property that ensures their rapid disposal by burning after the mission is completed is considered. The characteristics of incinerated materials are presented. The choice of materials based on the proximity of thermal and strength characteristics to existing structural materials used in the production of traditional head fairings is made.

1. Introduction
One of the main problems associated with reducing the man-made impact of missile launches on the environment is the presence of separable parts. This problem leads to the need to allocate significant areas of exclusion zones on the territories and water areas of the Earth's surface for fall areas [1, 2]. Development of materials and structures of technical systems for various purposes with a certain property is a promising direction in materials science and engineering. It allows their rapid disposal by incineration after the mission. And is in demand in terms of reducing the man-made impact on the environment. For example, for unmanned aerial vehicles used in reconnaissance and covert surveillance tasks; for strategic missiles and launch vehicles - this is the possibility of burning the separating parts of the steps on the trajectory of their descent, for example, interstage compartments, leaf of nose fairings [3-6].

2. Problem statement
A preliminary analysis of the materials and structures currently used for separating parts of missiles has shown that, in particular, traditional unsaved head fairings are made of three-layer shells. The construction of which includes an aluminum honeycomb filler and external-inner layers made of polymer composite materials with high temperature resistance. The polymer composite material includes carbon filaments with a binder made of epoxy glue [7]. Preliminary theoretical and experimental studies to assess the possibility of burning materials that are part of traditional unsaved head fairings have revealed a number of problems. For example, it is difficult to implement combustion conditions, including: melting of aluminum and its oxidation, the need to create a high temperature for combustion of the carbon sheet, which is part of the outer and inner layers [8, 9].

Thus, for the design of head fairings that allow their combustion after completing the mission, it is required to select a material that allows the manufacture of three-layer casings with given strength and mass characteristics and having a certain heat of combustion.

Basic assumptions:
– the structure of the combustion head fairing structure does not include metal elements that are part of real head fairings: power frames, hatches, elements of the mounting system, etc.;
– the configuration of the incinerated structure is determined from the condition of providing strength similar to the strength of a traditional head fairing;
the thermophysical characteristics of the materials that make up the structure to be burned should, if possible, be close to the same thermophysical characteristics of the materials used in the existing head fairings made of traditional polymer composite materials reinforced with carbon fibers, from which the head fairings of modern missiles are made.

The list of tasks, the solution of which is necessary for the selection of materials and the development of a combustion structure:

– analysis of the operating conditions of the structure;
– selection of material compositions for the production of a combustion structure based on comparison of strength, mass and energy characteristics.

3. Theory

Analysis of the operating conditions of the structure

The analysis of operating conditions is shown in Fig. 1, where the results of trajectory parameters of the head fairing flap [10] made of traditional materials are presented as an example. The results of determining heat flows are obtained on the basis of a physical and mathematical model of the movement of the flaps of the burned head fairing. The latter was considered as a point with mass and midsection equal to the fold of traditional unsaved head fairings for Soyuz-type launch vehicles [11]. Accounting for heat entrainment from the surface of the flaps of the burned head fairing was carried out taking into account experimental estimates of the Nusselt numbers given in [12]. The parameters under study are given at the time of separation from the launch vehicle for one of the Soyuz launch vehicles launch programs being implemented.

\[ q_k - q_a^\alpha - q_a^\sigma > 0 \], \hspace{1cm} (1)

As follows from the results, a positive balance between the heat input and heat transfer from the surface of the leaf of the burned head fairing:

\[ q_k - q_a^\alpha - q_a^\sigma > 0 \]

it takes place on a small part of the descent trajectory to heights of \(~55\) km.

The required amount of heat \(Q_{EMF}\) spent on heating the flaps of the burned head fairing to the ignition temperature is estimated from the solution of the equation:
\[ c \cdot m \cdot \frac{dT}{dt} = Q_k - Q_{kt} + Q_{EM}, \]  

(2)

with initial conditions:

\[ T_0 \] – the initial mass average temperature of the flap of the combustion head fairing (K);

where: \( c \) – the heat capacity of the flap of the combustion head fairing (J·kg⁻¹·K⁻¹); \( m \) – the weight of the flap of the combustion head fairing (kg); \( T_w \) – the temperature of the flap of the combustion head fairing (K); \( Q_k \) – the amount of heat supplied to the combustion head fairing flap due to aerodynamic heating (W), can be determined using the relation:

\[ Q_k = S \cdot q_k; \]  

(3)

\( S \) – the surface area of the flap of the combustion head fairing (m²); \( q_k \) – the convective heat inflow \[ [12] \] (W·m⁻²), can be determined using the relation:

\[ q_k = 0.635 \cdot 10^{-3} \cdot 2^{0.5} \cdot \rho^{0.5} \cdot \rho_{0}^{0.5} \cdot d^{-0.5} \cdot V^{2.862}; \]  

(4)

\( d \) – the characteristic size of the flap of the combustion head fairing (m); \( \rho \) – the density of the atmosphere at altitude (kg·m⁻³); \( \rho_{0} \) – the density of the atmosphere at sea level (kg·m⁻³); \( Q_a \) – the amount of heat carried away by the oncoming aerodynamic flow (convective and radiant components) (W), can be determined using the relation:

\[ Q_a = S \cdot \left( q_a^c + q_a^\sigma \right); \]  

(5)

\( q_a^c \) – the convective heat flux (W·m⁻²);

\[ q_a^c = \alpha \cdot (T_\infty - T_w); \]  

\( q_a^\sigma \) – the radiant heat flux (W·m⁻²);

\[ q_a^\sigma = \sigma \cdot \varepsilon \cdot (T_\infty^4 - T_w^4); \]  

\( T_\infty \) – the average ambient temperature (K); \( \alpha \) – the heat transfer coefficient (W·m⁻²·K⁻¹); \( \varepsilon \) – the degree of blackness of the material of the flap of the combustion head fairing; \( Q_{EM} \) – the amount of heat supplied to the flap of the combustion head fairing from internal heat release (W):

\[ Q_{EM} = S \cdot q_{EM}; \]  

\( q_{EM} \) – the amount of heat flux density of the internal heat source (W·m⁻²).

For Fig. 2 shows the results of calculating the total heat inflow. The addition of heat increment from an internal heat source with a heat flux density of 0.91 MW·m⁻² (for a time interval from 180 s to 205 s) is taken into account. Also, in Fig. 2 shows the average mass temperature of the leaf of the burned head fairing over the time of movement on the descent trajectory.
The dotted line in Fig. 2 denotes the calculated values of heat flows for the physical and mathematical model of heating used, described by equation (2), when all the heat is instantly transferred to the heated body.

The choice of material for the manufacture of a combustion structure is proposed to be carried out on the basis of the following criteria:

– the value of the strength characteristics of the material and the structure to be burned as a whole should not exceed the permissible intervals of strength loading at all stages of operation;

– the proposed material must have sufficient heat resistance throughout the entire operation stage and at the same time have the highest value of the heat of combustion;

– the value of the mass of the structure to be burned should not exceed the value of the mass of the traditional unsaved nose fairing by more than 15 ... 20%.

**Choice of material for external and internal layers**

Traditional unsaved head fairings, made of three-layer casings, technical characteristics of the materials used as outer and inner layers are given in table. 1. The operating temperature range of the shell, consisting of these materials is from minus 60 °C to plus 150 °C [13]. Based on the characteristics presented in table 1, the following technical characteristics of a polymer composite material of the KMU-4L-2M type were obtained:

– breaking stress at tension 0,9 GPa, at compression-0,9 GPa;

– the Poisson's ratio of 0.3;

– density of 1450 kg·m⁻³.

**Table 1. Technical characteristics of outer shell materials**

| Name of the material | Working temperature, °C | Density, kg·m⁻³ | Poisson ratio | Modulus of elasticity, GPa | Ultimate strength, MPa |
|----------------------|--------------------------|-----------------|--------------|---------------------------|------------------------|
| Carbon tape LU-P/0,1-A | -50… +400                | 1490            | 0.24         | 280                       | 3000                   |
| Binder               | -60… +150                | 1000            | 0.31         | 4                         | 46                     |

In table. 2 shows the technical characteristics of the materials under consideration [14] possible to replace the existing polymer composite material type KMU-4L-2M.
Table 2. Technical characteristics of the proposed materials for use in the outer shell

| Name of the material                           | Working temperature, °C | Density, kg·m\(^{-3}\) | Poisson ratio | Modulus of elasticity, GPa | Ultimate strength, MPa |
|------------------------------------------------|-------------------------|------------------------|---------------|---------------------------|------------------------|
| Polyetherketone (PEEK)                         | -60…+360                | 1320                   | 1.5…18.6      | 52…214                    |
| Polyphenylene sulphide (PPS)                   | -60…+220                | 1520                   | 2.2…5.5       | 69…124                    |
| Polyester (PET)                                | -60…+160                | 1350                   | 13…15         | 172…190                   |
| Polybenzimidazole (PBI)                        | -60…+400                | 1300                   | 4…6.5         | 120…160                   |
| Polyamidimide (PAI)                            | -60…+250                | 1400                   | 0.32-0.38     | 2.5…8.8                   |
| Polyamide 66 (PA)                              | -60…+250                | 1050                   | 0.7…3.3       | 40…86                     |
| Modified Polyphenylene oxide (PPO)             | -50…+150                | 1100                   | 2…5.4         | 40…90                     |
| Polymethylmethacrylate (PMMA)                  | -40…+90                 | 1150                   | 3…5           | 56…70                     |
| High-strength polystyrene (PS)                 | -60…+120                | 1050                   | 1.5…5.2       | 30…105                    |

Further selection of material from the table 2 is carried out after evaluating the strength characteristics obtained from the calculation of bending and stretching of a standard sample with dimensions of 100x100 mm with a fixed load of 1000 N (see table 3).

Table 3. Results of strength calculations of the proposed materials

| Name of the material                          | The thickness of the plate, cm | Breaking bending stresses, MPa | Breaking tensile stresses, MPa |
|------------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| KMU-4L-2M (monolayer)                         | 0.1                           | 281.9                         | 98.2                          |
| Polyetherketone (PEEK)                        | 0.2…0.45                     | 13.5…70.5                    | 21.7…49                      |
| Polyphenylene sulphide (PPS)                  | 0.3…0.4                      | 16.8…30.8                    | 24.5…32.6                    |
| Polyester (PET)                               | 0.22                          | 58.7                          | 44.5                          |
| Polybenzimidazole (PBI)                       | 0.28…0.33                    | 25.5…36.2                    | 29.6…35                      |
| Polyamidimide (PAI)                           | 0.25…0.38                    | 18.7…45.5                    | 25.7…39.2                    |
| Polyamide 66 (PA)                             | 0.35…0.6                     | 7.2…22.8                     | 16.3…28                      |
| Modified Polyphenylene oxide (PPO)            | 0.3…0.41                     | 16.8…30.5                    | 23.9…32.6                    |
| Polymethylmethacrylate (PMMA)                 | 0.36                          | 21.8                          | 27.2                          |
| High-strength polystyrene (PS)                | 0.3…0.45                     | 13.5…30.5                    | 21.7…32.6                    |

The results presented in table 3 show that the proposed materials are not inferior in strength characteristics to the currently used polymer composite material of the KMU-4L-2M type. In particular, the increase in the thickness of the presented polymers (table 2) helps to reduce the maximum deflection and normal bending stresses, as well as reduce the effective tensile stresses.

Further analysis of the materials under consideration is based on the estimation of the value of the mass ratio of the material from table 2 to the mass of the polymer composite material of the KMU-4L-2M type and the value of the heat of combustion [15-19], shown in Fig. 3. Thus, the largest increase in mass has a polymer type of polyamide 66, polyetherketone and polyphenylene sulphide; the smallest-polyester, polyethylene and polystyrene. An important note when choosing these materials is that they are combustible materials in contrast to the polymer composite material type KMU-4L-2M. The highest heat of combustion is provided by the materials polyethylene and polyester, polyphenylene oxide and polybenzimidazole.
Figure 3. The values of the ratio of the mass of the burned materials to the mass of the polymer composite material of the KMU-4L-2M type (histogram) and the heat of combustion (line, kJ·g⁻¹)

Selecting the filler material

In traditional unsaved head fairings, the filler is located between the outer and inner layers. In accordance with the previously stated concepts [6], the heat release source is a filler, and since the heat release density of the internal source must be at least 0.91 MW·m⁻² (Fig. 2), it is proposed to consider a mixture of materials for the filler: a polymer and a self-burning component. The material for the initiation of combustion is not considered in this work.

Table 4 shows possible materials [20, 21] for their use as a replacement for existing fillers used in traditional unsaved head fairings. The operating temperature range of the filler material is in the range from minus 40 to plus 200 °C. From the presented materials, the most interesting from the point of view of combustibility [22-25] are polymer materials: polyethylene, polyethylene terephthalate and polysulfone.

Table 4. The strength characteristics of the available materials for filler

| Name of the material                  | Working temperature, °C | Density, kg·m⁻³ | Poisson ratio | Modulus of elasticity, GPa | Ultimate strength, MPa |
|---------------------------------------|-------------------------|-----------------|--------------|-----------------------------|------------------------|
| * Fiberglass                          |                         |                 |              |                             |                        |
| SPP-1P-4.2                            | -30...+160              | 50...60         | 0.35         | 19...22                     | 1.5...2.5              |
| SSP-7P-3,5                            | -30...+300              | 60...70         | 0.35         | 19...58                     | 1.8...3.0              |
| * Polimersotoplast (PSP)             | -60...+250              | 20...160        | 0.35         |                             | 0.3...11.8             |
| * Aluminium alloy                    |                         |                 |              |                             |                        |
| AMG                                   | -80...+200              | 2640            | 0.3          | 70000                       | 125...200              |
| D16AT                                 | -80...+250              | 2780            | 0.3          | 69000                       | 180...285              |
| * Steel 03H11N10M2T (VNS17)          | -160...+400             | 7850            | 0.27         | 205000                      | 1180...1400            |
| * Titanium alloy (OT4-1)              | -30...+300              | 4500            | 0.32         | 110000                      | 590...785              |
| * Polyvinyl chloride (PVC)            | -60...+60               | 90...480        | 0.4          | 5...43                       | 0.2...1.2              |
| * Polyurethane foam (PU)              | -60...+200              | 100...400       | 0.33         | 1...12                      | 0.15...1.2             |
| * Polystyrene (PS)                    | -60...+240              | 50...500        | 0.1...0.35   | 2...10                      | 0.2...2.4              |
| Polystyrene (PE)                      | -60...+150              | 920...1400      | 0.35-0.46    | 1600...2000                 | 10...50                |
| Polystyrene terephthalate (PET)       | -60...+160              | 1300...1400     | 0.38         | 3500...4500                 | 50...140               |
| Polysulfone (PSF)                     | -100...+290             | 1250            | 0.38         | 2500                        | 70...80                |
| Phenylon C                            | -80...+220              | 1350            | 0.37         | 3220                        | 100...140              |

*used at the moment, the materials of the fillers
The choice of possible materials is based on a comparison of the strength characteristics of the traditional design of the filler (honeycomb) of the head fairing with the characteristics of the design of the incinerated filler. The traditional design of the filler consists of a honeycomb aluminum foil with a thickness of $\delta = 0.04$ mm and a height of the filler $h = 30$ mm. The design of the combustible aggregate for the combustible design of the head fairing is similar to the traditional one, i.e. in the form of honeycombs with the same dimensions. Estimates of the strength characteristics of the combustible aggregate honeycomb structure for the combustible head fairing structure are given in table 5.

**Table 5.** Results of strength calculations of the proposed filler materials

| Name of the material                  | Breaking compressive stresses, MPa | Destructive shear stresses, MPa | Breaking bending stresses, MPa |
|--------------------------------------|------------------------------------|-------------------------------|--------------------------------|
| Polyvinyl chloride (PVC)             | 13                                 | 13209                         | 8.98                           |
| Polyurethane foam (PU)               | 3.9                                | 12452                         | 2.64                           |
| Polystyrene (PS)                     | 3.3                                | 12193                         | 2.25                           |
| Glass fiber (SSP)                    | 7                                  | 12645                         | 4.76                           |
| Polimersotoplast (PSP)               | 18                                 | 12645                         | 12                             |
| Aluminum honeycomb filler (D16T)     | 6906                               | 12193                         | 4604                           |
| Polyethylene (PE)                    | 581                                | 13613                         | 387                            |
| Polyethylene terephthalate (PET)     | 1258                               | 12968                         | 838                            |
| Polysulfone (PSF)                    | 738                                | 12968                         | 492                            |
| Phenyolone C                         | 938                                | 12856                         | 625                            |

The results of calculations shown in table 5 show that the materials considered are not inferior in strength characteristics to aluminum honeycomb filler (when calculating the shift). The results of calculations for compression and bending showed low values of destructive stresses, due to the fact that the calculation was carried out at the same thickness of the filler cells. Increasing the thickness of the honeycomb cells of the filler will increase the values of destructive stresses for the materials under consideration.

In fig. 4 shows a comparison of the density of the honeycomb structure of fillers made from the materials presented in table. 4 and tab. 5. The currently used aluminum alloy D16AT, used for aluminum honeycomb filler, has the highest density. The lowest density is possessed by promising glass fiber reinforced plastics and polymersotoplastics, however, due to their incombustibility, they are not considered as a combustible filler.

For the considered construction of the combustible aggregate, it is proposed to consider the materials polyethylene, polystyrene and polysulfone, since these materials have a relatively low density and a sufficiently high (up to $47.1 \text{ kJ} \cdot \text{g}^{-1}$ for polyethylene) heat of combustion [26].
4. Discussion of results

The parameters of the combustion process of the combustion head fairing structure obtained on the basis of thermodynamic analysis show satisfactory characteristics and practical feasibility of the proposed method for creating combustion head fairings. Aggregate combustion can be initiated in various ways (gas burner, electric spirals, solid ignition initiators). The process of ignition, pyrolysis, and combustion under various factors (low pressure, absence of an additional supply of an oxidizer) are not presented in this work.

The mass of the combustion head fairing structure with an area of 0.01 m$^2$ is $\sim 0.084$ kg. In this case, the mass of the filler (polystyrene $\sim 0.004$ kg), and the mass of the outer and inner layers $\sim 0.08$ kg (polyethylene). The mass of a similar three-layer plate for a traditional head fairing is $\sim 0.075$ kg.

5. Conclusion

The above analysis of the operating conditions of the traditional nose fairing showed that for the combustion of the existing structure, the aerodynamic flow is insufficient and additional internal heat sources with a density of at least 0.91 MW · m$^{-2}$ are required.

The choice of materials for the outer / inner layers and the filler of the combustion head fairing structure is considered separately. Based on the presented estimates of the strength, mass and energy characteristics of possible materials, the choice fell on polystyrene for the filler and polyethylene for the outer and inner layers.

The development of a methodology for the design of combustible structures, including the choice of design parameters of the shell, while the choice of materials and structures, is the next stage of research.

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