COMBUSTION OF SOLID NONMETALLIC MATERIALS IN MICROGRAVITY

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ABSTRACT

Research into the burning characteristics of various substances and materials in zero gravity, or to be precise in microgravity ($g \approx 0$), is known as one of the critical directions of combustion theory. Efforts in this area are required to solve practical problems concerning fire safety of space vehicles (SV)[1-4]. Research of the combustion behaviour of materials in microgravity has been considerably intensified in connection with designing the International Space Station (ISS) and other planetary facilities[5-9]. This work presents the Russian research findings relating to the material combustion behaviour in microgravity. These findings have determined a new avenue of SV fire safety engineering. Microgravity has been therewith produced using an airborne laboratory, a free falling container, and a land-based apparatus “Two-dimensional channel”. With the help of this equipment a burning process has been simulated by eliminating natural convection in a two-dimensional horizontally moving gaseous layer in an experimental apparatus “Skorost” aboard the Mir space station.

RESEARCH FINDINGS OF GASEOUS PHASE COMBUSTION BEHAVIOUR IN MICROGRAVITY

Some burning characteristics of materials have been registered experimentally in the airborne laboratory, which are critical to designing a physical model in microgravity, developing research methods and interpreting the results obtained. These burning characteristics are: (a) a spontaneous cessation of a sustainable burning of materials in microgravity without a forced gaseous flow; (b) an extinguishing time increase of small fire sources; (c) a more stable smouldering as compared to a gaseous phase combustion; (d) an abrupt change in the acceleration due to gravity vector within 0.05 to 0.08 s does not result in knocking down a flame; (e) self-extinction of combustibles takes place only at an acceleration due to gravity after-effect equalling 2 to 4% of the normal terrestrial acceleration.

Valuable results were obtained with the help of the free falling system[2-4]. Figure 1 shows photographs of burning paper without a gaseous flow at C_{ox} = 30% (oxygen concentration in the mixture) before and after the system transition to microgravity. Photographs 1 to 8 correspond to the burning process at g = 9.8 m/s. The flame spread over a horizontal specimen at a rate of 4.6 cm/s. Starting with Photograph 9 the system transition to microgravity takes place. An extinction process is shown to have two phases. During the first phase (Photographs 9 to 16) a rapid decrease of a natural convection flow rate occurs within 0.25 s. After that the front flame was withdrawn from the material surface, the flame spread was no longer sustained over the material. The second phase involved a gradual flame temperature decrease. This stems from the cessation of a convective oxidiser flow into a burning area and heat losses to the environment. The shape and geometry of a glowing region up to a complete glowing termination remain practically the same.

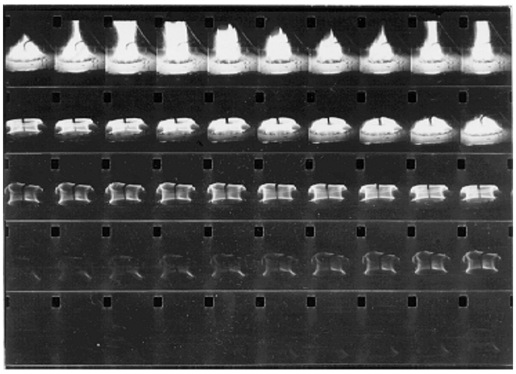


Figure 1: Motion picture diagram of paper extinction at microgravity transitions obtained in the free falling container at C_{ox}=30%.From right to left, downward, 64 frames/s.

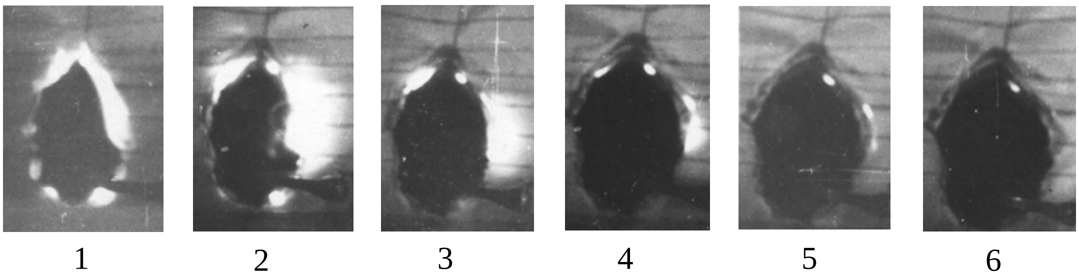


Figure 2: Motion picture diagram of nylon fabric at microgravity transitions obtained in the free falling container at C_{ox}=30%. 1 – burning at g=981 cm/s^2 within 4 seconds 2-6 – extinction process 0.1 s, 0.2 s, 0.4 s, 0.5 s and 0.6 s after the transition to microgravity. The fabric is thoroughly extinguished 0.7 s after the transition.

Figure 2 shows nylon fabric extinction in the free falling system, which differs substantially from the earlier mentioned process. A specimen was placed vertically in an internal container. Photograph 1 depicts the burning at g = 9.8 m/s. The fire spreads peripherally around a hole in the melted nylon. The flame, 4 s after the ignition, spreads up and down the specimen at a rate of 1.8 cm/s and 0.5 cm/s correspondingly. After the transition to microgravity (Photo 2) the flame was no longer available over the specimen. Separate flame areas became spherical (Photos 2 and 3). After that the burning of large fire sources comes to an end (Photos 3 to 5). Small fire sources are the last to stop burning (Photos 5 and 6) as in the case of those in the airborne laboratory. This is explained by a diffusion oxidiser flow increase with a flame front curvature rise.

During the transition-to-microgravity stage of the experiments with a forced gaseous flow along the specimen surfaces at a rate of 10 to 20 cm/s, the flame had not suffered considerable change, and its extinction had not occurred. The combustible system behaviour discrepancy has indicated the presence of a threshold burning gas flow rate, V_l.

Figure 3 shows C_{ox}-V_l relationships for a 1 mm thick organic glass (PMMA), obtained using the 2-dimensional channel (1) and the free falling container (2). Some variation of Curves 1 and 2 is due to a limited experimental time in the free falling container. Sustainable burning was observed with atmospheric parameters higher than those indicated by the curves. The curve minimum determines lower and upper burning rate limit values. A flame has been located only within the front part of the specimen at a lower burning rate. The right-hand part of the C_{ox}-V_l relationship corresponds to an upper burning rate limit at the moment of flame break-down by the flow. The minimum in microgravity in Curves 1 and 2 is equal to 16±0.2%, which almost coincides with C_l = 15.5±0.2% for the same material (C_l - an oxygen index on ignition of the material from underside) at g = 9.8 m/s^2. So, using V_l, conditions are possible in SV airtight compartments whereby combustibles become noncombustible materials in a planetary flight.

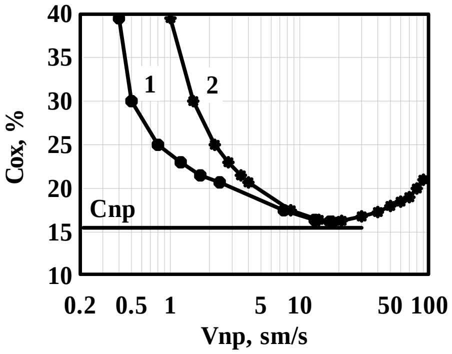


Figure 3: V_l-C_{ox} dependence for PMMA 1 – the Two-dimensional channel 2 – the Two-dimensional channel 2 –the free falling container.

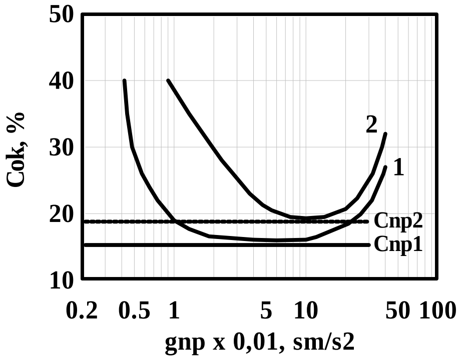


Figure 4: g_l-C_{ox} dependence for (1) PMMA and (2) Genitaks.

Combustion with spherical flame symmetry

Experiments have been performed for two cases. Firstly, small fire source tendency to a continuous extinction in microgravity has been considered (Figure 2). Secondly, there are theoretical prerequisites[10] for when a diffusion system in a spherical symmetry is capable of sustainable burning without convection, namely in microgravity. The ignition of an 8 to 10 mm diameter organic glass ball specimen in the free falling container has been witnessed. Tests have been conducted at low-pressure values ($P_{amb} \approx 1.2$ to 1.8 kPa) and high values of C_{ox} = (40 to 99%) when a spherical flame shape has been observed[11] at g =9.8 m/s^2. The spherical shape has been found to remain after the transition to microgravity at P_{amb} less than 1.8 kPa and C_{ox} higher than 40%. According to these findings, a sustainable gaseous-phase combustion behaviour can occur due to molecular diffusion. Losing its original stretched shape, the flame has been extinguished in similar tests at P_{amb} = 0.1 MPa and C_{ox} = 16% after the burning system transition to microgravity. This is due to molecular diffusion that does not provide a sustainable burning in microgravity at high pressures and without a forced gaseous flow. This is confirmed by experiments with paper, nylon, PMMA and other materials.

Combustion of materials at various accelerations due to gravity

The availability of V_l is due to the fact that in zero gravity there are no natural convection flows whereas a molecular diffusion at high pressures does not provide an oxidiser for a burning reaction. With the increase of g there has emerged a natural convection movement, which is able to maintain a combustion process and to produce a flow similar to V_l. Thus, there are prerequisites for a limit burning material acceleration (g_i). Research into g_i has been performed with the help of the free falling system having a centrifuge in the inner container. Values of g_l have been defined as a sum of centripetal and Coriolis acceleration vectors. Figure 4 shows a C_{ox}-g_i dependence for PMMA (Line 1) and for Getinaks (Line 2) and also C_l values for these materials at g=9.8 m/s^2 ($C_{l\,1}$ and $C_{l\,2}$ lines). There are lower and upper limit acceleration values by analogy with the C_{ox}-V_l dependence (Figure 3).

Smouldering in simulated microgravity

Cotton cord smouldering tests have been carried out using the land-based apparatus “Two-dimensional channel”. Tests were no possible in the free falling system due to slow cord response times. Table 1 gives V_l values for the cord at various C_{ox} values.

Table 1: V_l for the cord at various C_{ox} values.

Oxygen concentration, $C_{ox,\%}$	30	25	23	21	19	17	15	14.3
V_l values for the cord, cm/s	0.2	0.3	0.34	0.36	0.4	0.6	3.2	8.3

The cord smouldering behaviour is seen to be characterised by extremely low V_l values. Estimates have shown that they are due only to the molecular diffusion, where possible smouldering cannot be excluded at high C_{ox} and $g \approx 0$.

In-flight material combustion aboard the Mir space station

The study of in-flight material combustion behaviour aboard the Mir space station was conducted in 1994, 1996 and 1998 with the help of a specially designed apparatus “Skorost ”. The participation of Russia in engineering the International Space Station (ISS) substantially promoted space-borne experiments.

The main goal of space-borne experiments was to verify the statement that steady-state gas diffusion burning in microgravity is impossible. Also, V_l values were specified for various materials in microgravity to determine the behaviour of a flame and of a condensed phase at different values of gas flow rate.

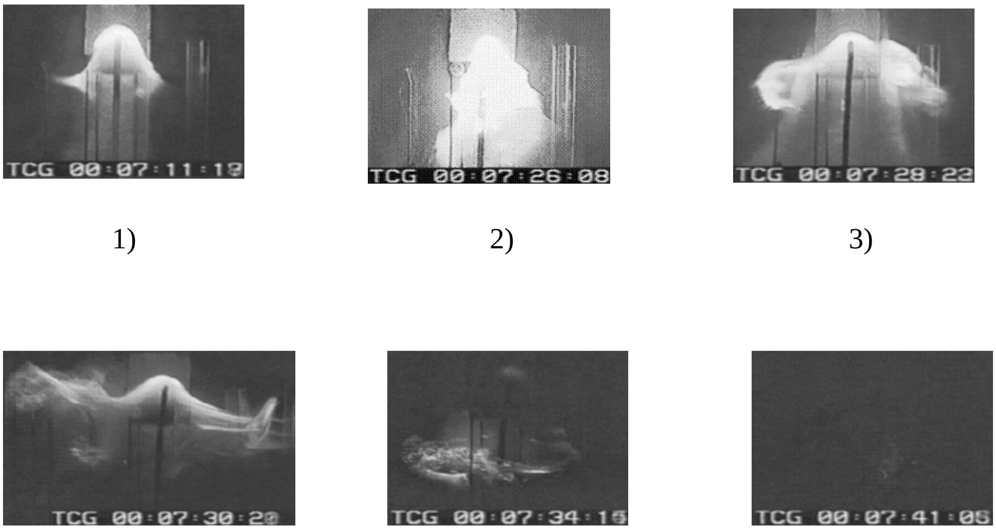
The experimental apparatus “Skorost” consists of a combustion chamber, filters, a flow meter, ventilators, connecting pipelines, a control board, and a video camera. The apparatus was placed in a Kvant module aboard the Mir. The Skorost is designed to carry out space-borne long-term fire tests in a gas flow having precision-set speed and oxygen concentration parameters.

Qualitatively and partially quantitatively, the obtained results have confirmed almost all assumptions of physical combustion models in microgravity based on ground research. In particular, they have confirmed the possible progressive burning of materials in microgravity at gas flow rates higher than V_l. In all experiments with the ventilator turned off at different combustion stages, the cessation of flame burning has been recorded.

Figure 5 illustrates the process described above with the video recording of PMMA tests at a gaseous ambient pressure, P_{amb} = 88 kPa and C_{ox} = 23.1%. On ignition of a specimen, a bell-shaped flame burning was observed at a flow rate of 6.4 cm/s (Photo 1). The flow rate was increased up to 15 cm/s, 15 seconds after a steady-state burning, resulting in flame elongation and flame temperature rise (judged from its brightness, Photo 2). Under these conditions the specimen had been quickly heated over a large length. At that moment the ventilator was switched off, a pulsating mushroom blue flame was produced (Photos 3 to 6). PMMA buoyant decomposition products were seen to flare up. After several flashes the flame had started to decrease in diameter and it extinguished. It took 14 seconds to extinguish the specimen, including 7 to 9 s for disconnecting the ventilator.

The observed phenomena are very important from scientific and practical standpoints. They characterise a solid material extinction process in zero gravity at a flow rate much higher than the lower burning limit value V_l, representing an intensive burning and heating-up of the specimen. An abrupt flow rate decrease after disconnecting the ventilation caused the transfer of pyrolysis products from the specimen to the area with an oxidiser. Due to an endothermic decomposition process, the specimen surface was cooled and the flow of pyrolysis products decreased. The colour change from orange to red and then to blue demonstrates the transition from heated-up specimen conditions to the extinction through limited burning conditions.

Similar observations were made with polyethylene specimens, which melt on burning. Figure 6 depicts a video recording at P_{amb} = 94 kPa and C_{ox} = 22.5%. A bright yellow flame indicates soot formation and an incomplete combustion at a flow rate of 8.5 cm/s (1). With the ventilation disconnected, the flame is blue (2, 3). The flame starts vibrating indicating near-limit conditions (2 – a short flame, 3 – a long flame). Such a phenomena manifests itself with any measurements of solid material combustion limits, and if a specimen is overheated[12]. In this case the flame vibration before extinguishment lasted 11 seconds.

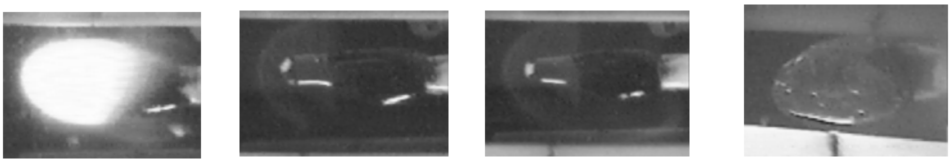


1) 2) 3)

4) 5) 6)

Figure 5: Space-borne measurements of non-plastized organic glass combustion and extinction characteristics in microgravity at C_{ox} = 23 %:

1) burning at V_f=6.4 cm/s, 2) a flow rate is increased up to 15 cm/s, 3) specimen ventilation is off and the flame is withdrawn from its surface, 4) further propagation of the flame, 5) a spherical flame is produced, 6) blue flame indicates the last extinction phase.



1) 2) 3) 4)

Figure 6: Polyethelene combustion and extinction process.
A bright yellow flame (1) indicates a soot formation and an incomplete combustion at a flow rate of 8.5 cm/s. The flame is of blue color (2,3) with the ventilation off. The flame starts vibrating which is characteristic to near-limit conditions (2 – a short flame, 3 – a long flame). A polyethelene melt drop is transparent on burning and nontransparent after cooling (4).

Data on a flame spread velocity in the gas flow direction and data on the flame geometry have been obtained during cotton cord tests at P_{amb} = 88 kPa and C_{ox} = 23.1%. The results are given in Table 2.

Table 2: Flame spread velocity and flame geometry.

Conditions and parameters of cord burning	Test number				
	1	2	3	4	5
Gas flow rate, cm/s	20	12	5	3	2
Cord flame spread rate, cm/s	0.39	0.33	0.30	0.26	0.25
Flame length and diameter, cm	1.6/0.9	1.6/1.0	1.7/1.0	1.5/1.1	1.3/1.1

As shown by the video recordings, in the beginning, a flame accompanied by a glowing front is spreading along the cord surface. The flame and the glowing are propagating at a steady, almost equal, rate.

With the help of the Two-dimensional channel, experiments aboard the Mir have confirmed high V_l values for certain materials. The space-borne test results have revealed a unique PMMA specimen ability of burning in microgravity at a flow rate of approximately 0.5 cm/s. This is lower than the free falling container results and the Two-dimensional channel measurements at the same oxygen concentration (C_{ox} = 21.5%). This may be explained by the physical characteristics of the burning material. Figure 7 shows a PMMA burning diagram at a flow rate of 0.5 cm/s and C_{ox} = 21.5%, obtained in the Skorost at the 9th minute before the Extinction. Decomposition area 3 is 4 mm in length. Front area 4 is the seat of a boiling melt. The boiling area and the lower flame tip are at the same level. The lower flame tip is bent 2 to 3 mm outwards at the expense of a massive outcome of pyrolysis products. A decomposing part of the specimen holds its shape and geometry for a long time, resulting in a thorough warming-up of the front part of the specimen. In so doing, a burning propagation along the specimen is defined as quasi-steady.

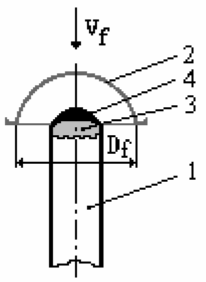


Figure 7: PMMA burning pattern at a flow rate of 0.5 cm/s, C_{ox}=21.5%, obtained in the Skorost at the 9th minute before the extinction. 1) specimen, 2) a spherical flame, 3) pyrolysis area, 4) boiling area.

The flame burning of the front of the specimen was observed at near-limit values. This is where the length of the decomposing specimen and the flame downstream length are confined. The organic glass is characterised by a low surface temperature (700 K), at which a material decomposition takes place at burning limit values. Flame temperature at burning limit values are much higher (1500 K)[11,13]. This provides for a stable and intensive flow of pyrolysis products into the burning area. Due to the observed characteristics, conditions are formed in which a flame is produced at the burning surface of the organic glass having a surface 10 times larger than the decomposing specimen surface. A flame on a comparatively large area consumes the oxidiser from a gas flow. The heat produced by the flame is directed towards a considerably less decomposing area on the specimen surface. Ground experiments with several dozen materials have demonstrated that the given physical behaviour is inherent only to PMMA. The burning conditions of other materials are less favourable because of the change of one or more of the mentioned burning characteristics.

Experiments aboard the Mir have been carried out with polyacetal, polyethylene and plasticised PMMA which melt on burning. Their combustion area in microgravity is presented as a gradually enlarging melt drop, moving downstream as the specimen melts. This defines their non-steady combustion behaviour. A burning melt drop in microgravity is securely kept by a solid material surface. Flame self-extinction has been observed in all tests of three melting flammable materials with the ventilator off in the combustion chamber.

Lower limit V_l value space-borne measurements have been shown to be close to the Two-dimensional measurements.

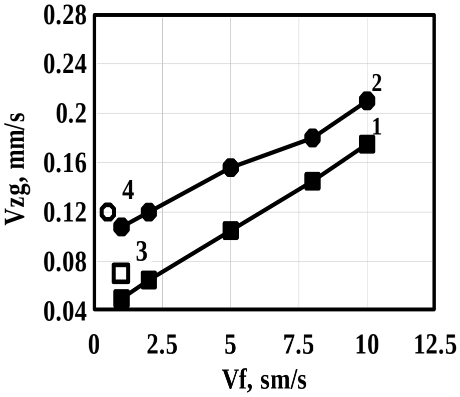


Figure 8: Two-dimensional channel (1,2) and Mir (3,4) measurements of a propagation velocity of a polyacetal burning area at C_{ox}: 1,3 – 22.5%, 2,4 – 23.6%.

Figure 8 depicts the results of measurements of a propagation velocity of a polyacetal burning area obtained with the help of the Mir and the Two-dimensional channel. The results are in a close agreement. On the basis of these results, burn-through rates of these materials have been arrived at.

CONCLUSIONS

This study has shown that any material displays a number of burning characteristics in microgravity. It was shown that a rather quick extinction of a flame occurs when a burning material has all forced or natural convection removed. Also, any burning material exhibits a limit flow rate, dependent on the atmospheric oxygen concentration. However, physical burning characteristics of various materials differ considerably depending upon the inflow direction, geometry, material capability of producing an incombustible residue or melting, oxidiser parameters, etc. The research findings have allowed a new engineering background to be developed to provide better fire safety of manned space vehicles.

REFERENCES

1. Kimzey I.H.. Flammbilitu cluring weightlessness Institute of Environmental Scinces. Annual Techn.Meet Proceedings San Diego. Colif. 1966. Mount Prospect. p. 433-437.

2. Melikhov A.S., Potyakin V.I.. About limited conditions of burning of solid materials in weightlessness. Chemical physics of burning processes and hazard. Material of the Sixth symposium on combustion and hazard. Chernogolovka, 1980, -no. 48-51.

3. Melikhov A.S., Potyakin V.I., Ryzhov A.M., Ivanov B.A.. About limited regimes polymer burning in absence of natural convection. Physics of burning and hazards, 1983, no.4, - no. 27-30.

4. Potyakin V.I., Melikhov A.S., Ivanov B.A.. About conditions of existence of spherical flame under acceleration of gravity. Chemical physics of burning processes and hazard. Chernogolovka, 1986, - no. 85-88.

5. Ivanov A.V., Alymov V.Ph., Smirnov A.B., Melikhov A.S., Bolodian I.A., Potyakin V.I. et al. Preliminary Results Of The Third Test Series Of Nonmetal Material Flammability Evaluation In SKOROST Apparatus On The Space Station Mir. Proceedings of the Fifth International Microgravity Combustion Workshop, Cleveland, Ohio, May 1999.

6. Melikhov A.S., Bolodian I.A., Potyakin V.I., Ivanov A.V., Alymov V.Ph., Smirnov A.B. et al. The Study Of Polymer Material Combustion In Simulated Microgravity By Physical Modeling Method. Proceedings of the Fifth International Microgravity Combustion Workshop, Cleveland, Ohio, May 1999.

7. Olson S.L., Ferkul P.V. and T'ien J.S.. Near-Limit Flame Spread over a Thin Solid Fuel In Microgravity. - Proceedings of Twenty Second Symposium /International/ on Combustion, 1988, pp. 1213-1222.

8. Dietrich D.L., Ross H.D., Frute D.T., T'ien J.S. et al. Candle Flames in Microgravity. - Proceedings of Fourth International Microgravity Combustion Workshop held in Cleveland, Ohio, May 14-21, 1997, pp.237-241.

9. T`ien J.S, Sacksteder K., Ferkul P.V., Bedir H., Shih H-Y., Greenberg P.S., Pettegrew R.D., Piltch N., Frate D., Solid Inflammability Boundary at low Speed (Sibal). NASA CP 10194 1997.

10. Zeldovich Ya.B., Barenblat G.I., Librovich V.I., Makhviladze G.I.. Mathematical theory of combustion and hazard. -M.: Science, 1980.-c. 263-272.

11. Melikhov A.S., Potyakin V.I., Flankin E.V. Limited conditions of polymer burning under lower pressures. Physics of combustion and hazard. 1982, N3. -c. 44-47.

12. Melikhov A.S., Bolodian I.A., Tretiyakov V.A. and others. Researches of limited conditions of burning of materials in surroundings with different oxygen content. Fire precautions. no. 9. -M.: Stroiizdat. 1974. -c. 21-29.

13. Bolodian I.A., Dolgov E.A., Zhevlakov A.F., Melikhov A.S., Potyakin V.I.. About limited conditions of polymer burning. Physics of combustion and hazard. 1979, no. 4, -c.63-65.