Journal of Engineering Physics and Thermophysics, Vol. 77, No. 3, 2004

MODELING AND IDENTIFICATION OF THE PROCESSES OF HEAT EXCHANGE IN POROUS MATERIALS OF THERMAL PROTECTION OF REUSABLE AEROSPACE SYSTEMS

S. V. Reznik,[a] **W. P. P. Fisher,**[b]
D. Martines,[c] **L. Ya. Paderin,**[d]
N. V. Pavlyukevich,[e] **D. Petit,**[f] **and**
P. V. Prosuntsov[a]

UDC 629.7.018.3:536.24 + 536.33

The features of aerospace systems as transport facilities for exploration of near-earth space and high-velocity intercontinental transportation have been considered. Problems of complex investigations of the processes of heat exchange in porous materials of thermal protection of prospective reusable aerospace systems have been formulated.

Features of Aerospace Systems as Facilities for Orbital and Intercontinental Transport. Until recently, there have been significant differences in the technique of exploration of the air ocean and outer space. The hardware for firing into space and returning from space was initially *expendable,* since it was constructed on the basis of modified missiles, whereas vehicles for atmospheric flights — balloons, airplanes, gliders, and dirigibles — were not thought of as other than *reusable*. In designing transport facilities meant for atmospheric and space flight, the reliability of performing purpose-oriented functions and economic efficiency are equally important. For aircraft moving with a high velocity in the atmosphere, the two properties are directly related to the capacity of the structure for withstanding the action of thermal loads. The degree to which such a capacity is ensured is determined by the required service life, weight-size characteristics, and cost [1–3]. In recent years, the problem of overcoming a "thermal barrier" (this barrier was faced even in creating the first long-range ballistic rockets and supersonic airplanes [4]) has been solved due to switching increasingly more completely from expendable structural elements to reusable elements.

The high reliability of modern expendable launchers such as Soyuz, Molniya, Proton, and Zenit and descent spacecraft of the ballistic type has been attained owing to the development of the production technology and operation of many years. As far as the prospective launchers Angara (Russia), Atlas III and Atlas V (USA), GSLV Mk I-Mk III (India), Great March (CZ-5, China), and others [5] are concerned, it is planned that their high reliability will be ensured by the employment of stages of the same type. The introduction of combined methods of designing and production and testing and operation with a powerfully computer-aided life cycle (CALC technology) is considered to be a strong means.

The ratio of the payload mass to the launching mass attains 0.029 in modern Proton and Zenit launchers for a low near-earth orbit [6]. Theoretically, it can be more than doubled in expendable launchers. A substantial influence on the weight efficiency of launchers is exerted by the low (close to unity) values of the safety factors. The economic efficiency of the hardware for access to space can be spoken of only in terms of comparison by virtue of the uniqueness of launchers and descent spacecraft as expendable transport facilities. The cost of one kilogram of payload in a low near-earth orbit is 1000 to 5500 US dollars [6].

It cannot be said that the creators of launchers reject the idea of multiple employment of the matériel. This idea has already been realized in recoverable stages of the Russian launchers Énergiya and Angara. A number of large

---

[a] N. É. Bauman Moscow State Technical University, 5 2nd Baumanskaya Str., Moscow, 105005, Russia; email: sreznik@bmstu.ru; [b] EADS Space Transportation GmbH Group, Bremen, Germany; [c] PSA, Tabernas (Almeria), Spain; [d] N. E. Zhukovskii Central Aerohydrodynamics Institute, Zhukovskii, 140160, Moscow Region, Russia; [e] A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus; [f] École Nationale Supérieure de Mécanique et d'Aérotechnique, Futuroscope Cedex, France. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 77, No. 3, pp. 3–8, May–June, 2004. Original article submitted April 14, 2004.

1062-0125/04/7703-0471 ©2004 Plenum Publishing Corporation

European companies are jointly developing reusable launchers within the framework of the Everest program [5]. They are considering the designs of a two-stage fully reusable launcher, a two-stage launcher with a reusable first stage, and a launcher with reusable accelerators.

For aerospace systems — aerospaceplanes, aviation-space rocket complexes, and interorbital transport vehicles with aerodynamic deceleration — the multiplicity of employment of propellant tanks, engines, instruments, and other elements is an integral property of the structure. Aerospace systems can be classified according to the following features: partially reusable/fully reusable systems; single-stage/multistage ones; those with a horizontal/vertical start; orbital/suborbital systems; those with a ballistic/gliding descent; winged/wingless systems. The advantages of aerospace systems are high load-carrying capacity, velocity, and maneuverability, the possibility of taking-off from airfields and landing on them, and the capacity to deorbit bulk payloads [7, 8].

It was expected that preservation of the matériel of aerospace systems would significantly decrease the cost of delivery of payloads to the earth's orbit, which served as a strong incentive to create aerospace systems. According to optimistic evaluations, the cost of one kilogram of payload delivered by the Space Shuttle to a low near-earth orbit was expected to be 200 to 1000 US dollars, however, it currently exceeds 10,000 US dollars [6].

In a number of designs, the launching stage of an aerospace system represents a reusable winged hypersonic aircraft with a combined propulsion system changing over to jet, ramjet, or liquid-propellant rocket engines in a certain range of altitudes and velocities. In the future, such aircraft will play an independent role as a transport facility for high-velocity intercontinental cargo and passenger transportations [2]. In the latter case, aircraft will have flight trajectories different from those of the facilities for firing into space. Structural-layout solutions will be constructed on the basis of a fairly long duration of a hypersonic flight in the atmosphere (thousands of seconds) and the necessity of using air oxygen for a propulsion system. For aerodynamics reasons, structures with sharp foreparts of the fuselage, leading edges of the wing and the empennage, and shells of the engines' air intakes are being proposed, which will result in the appearance of local zones of extremely high thermal loads. The commercial appeal of this class of aircraft depends on the overall dimensions, and they in turn are reflected on the area of surfaces interacting with a high-velocity air flow. Evaluations show that in prospective aircraft, the area lies in the range from several tens to several thousands of square meters.

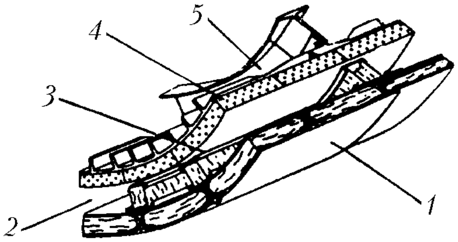
The *problem of thermal protection* remains the central problem of reusable launchers and aerospace systems.

Classification and Principles of Construction (Aufbau Principles) of Reusable Thermal Protection. Reusable thermal coatings must not irreversibly change their shape, size, and aerodynamic and thermal-protection characteristics from flight to flight because of fusion, ablation, shrinkage, swelling, and other physicochemical and structural transformations. Consequently, relatively heavy ablating polymer composite materials traditionally used in expendable rockets and descent spacecraft are not suitable for reusable thermal coatings. Thermal protection systems without an irreversible disturbance of the thermal stability of the structure can be subdivided into passive, active, and combined systems.

In passive systems that are the most developed, the transfer of heat into the bearing structure is blocked by the low thermal conductivity and high capacity of the material, backward scattering of the internal radiation flux on optical inhomogeneities, shielding, and reradiation by the internal layers and from the surface. Recombination on the surface is suppressed.

The main advantage of passive thermal protection systems is the relative simplicity of their technical implementation and the associated reliability of operation. Materials from SiO_2 and Al_2O_3 fibers, having a porosity of higher than 90% and possessing a high thermal and chemical stability, meet the stringent requirements imposed on their use in such systems. The fibers forming these materials are partially transparent to external radiation sources and to the intrinsic radiation in the visible range and in a part of the infrared range. In such materials, the energy is transferred by heat conduction, radiation, and convection simultaneously with the predominance of radiative-convective heat exchange, whereas the physicochemical transformations in the operating range of temperatures are excluded.

In active systems, use is made of a liquid or gaseous coolant. Supply of the coolant makes it possible to remove excess heat from the rear side or from the volume in pressure filtration through a porous material or through orifices, to take off the excess heat with the use of physicochemical transformations, and to create curtains on the surface heated. Active thermal protection systems are technically more complex, as a rule, than passive systems. The presence of vessels with a coolant, pipelines, pumps or pressure accumulators, and other accessories reduces their



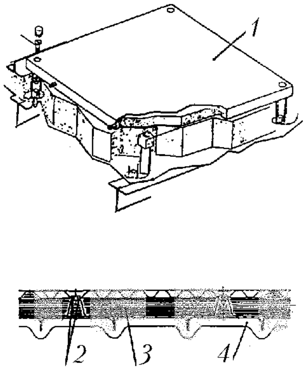


Fig. 1. Fragment of the fuselage of a prospective aerospace system: 1) metallic panels or panels from a carbon–carbon composite material, containing fibrous insulation; 2) channel for blowing; 3) aluminum frame; 4) foamed polyurethane; 5) shell of the cryogenic tank.

Fig. 2. Thermal-protection panel for the Hermes aerospaceplane: 1) front panel from a heat-resistant composite material; 2) junction; 3) multilayer heat insulation (foils and ceramic fibers); 4) internal heat insulation.

weight-geometric efficiency. However, they can ensure a reduction in the protected-surface temperature to an acceptable level, making it possible to employ the existing structural materials.

All thermal coatings are subdivided into two groups depending on the degree of their engagement in ensuring the bearing capacity of the structure. One recognizes thermal coatings with a bearing frame (of integral type) and attached ones that do not perform force functions. The latter include tile, flexible, and ribbed-tile thermal coatings developed for the first generation of aerospaceplanes.

Technical Requirements of Reusable Thermal Protection. Because of the pronounced difference in the level of aerodynamic and thermal loads on different surface portions of aerospace systems, thermal protection is of a combined character. For example, the most heated portions of the Space Shuttle and Buran, i.e., the nose spinner and the edges of the wings and the vertical stabilizer, are in the form of thin-walled shells from heat-resistant composites of the "carbon–carbon" type with internal thermal shields from high-temperature heat insulators. The windward part is fitted with ceramic tile thermal protection, whereas the leeward part is protected by ceramic ties and flexible sewn mats from heat-resistant cloths [3, 7, 8]. The tiles are intended for employment in 100 flights. By virtue of the pronounced difference in the thermal coefficients of linear expansion of the material of the bearing frame and the high-temperature heat insulator, the tiles are stuck to the bearing frame by means of damping substrates from fibrous material. However the ceramic tiles covering about 70% of the Space Shuttle and Buran area have a number of drawbacks, the most serious of which are brittleness, damageability, and the need for hydrophobic treatment before flight.

Because of the necessity of increasing the service life of thermal coatings, the earlier designs that were an alternative to a tile thermal coating have been improved in recent years. Thus, thermal coatings in the form of metallic panels from such materials as titanium, niobium, and nickel (Rene-41)-, and cobalt (L-605, Haynes-188)-based alloys filled with a fibrous high-temperature insulator (Fig. 1) were considered for prospective aerospace systems as far back as the 1970s [9]. Combination of the panels made it possible to distribute a part of the force loads on them, i.e., to create a thermal-protection structure of the integral type with a bearing frame efficient at surface temperatures to 1600 K. The high heat-insulating properties of the structure were ensured by fibrous materials of the Microquartz (ρ = 56.1 and 67.3 kg/m^3), Dynaflex (ρ = 96 kg/m^3), Protecalor (ρ = 20.8 kg/m^3), and Fiberfrax (ρ = 113 and 128 kg/m^3) types between load-bearing elements. The specific mass of the above thermal coatings was estimated at 5.9–22.9 kg/m^2. It was expected that a low-temperature insulation of cryogenic tanks of the foamed-polymethacrylamide type with a permissible temperature of 477 K would be employed as part of certain kinds of thermal coatings in addition to the high-temperature insulation; blowing of the insulation surface with dry gas was assumed to exclude freezing [10].

The ribbed-tile thermal coating developed in the 1980s for the Hermes aerospaceplane [11] represented an assembly of individual functional layers — the front layer in the form of an SiC–SiC composite material with an anti-

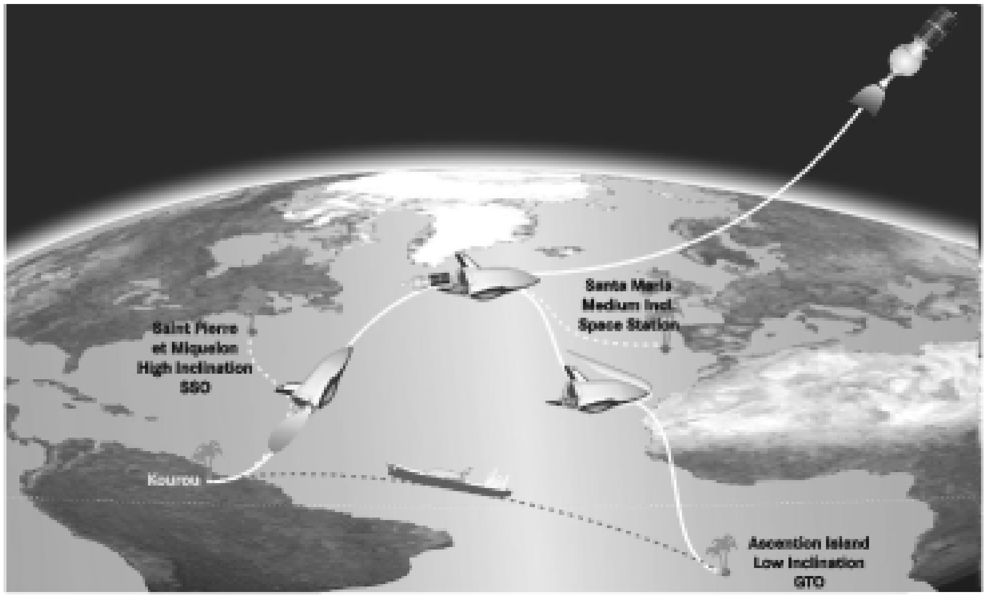


Fig. 3. Hopper single-stage aerospace system developed by the EADS Company.

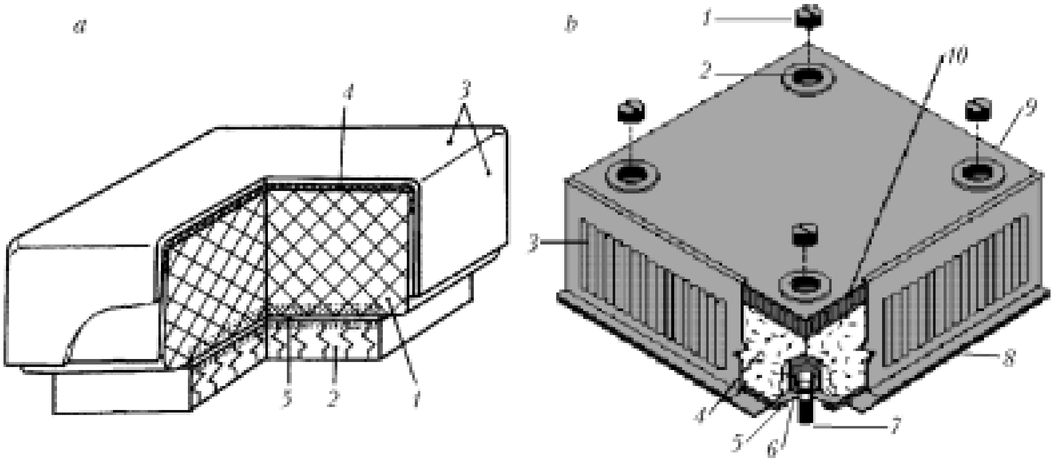


Fig. 4. Comparison of the thermal-protection elements: a) Space Shuttle and Buran; b) aerospace system under development; a) 1) tile from baked SiO_2 fibers; 2) damping substrate; 3) varnish coating; 4) glass coating; 5) glue layer; b) 1) stopper; 2) tube; 3) frame; 4) multilayer heat insulator from Al_2O_3 or SiO_2 fibers; 5) honeycomb titanium panel; 6) titanium foil; 7) mechanical fastening; 8) plate; 9) shaping strip; 10) honeycomb Inconel panel.

oxidant low-catalytic coating and heat-insulation layers from inorganic fibers separated by thin metallic shields (Fig. 2). Individual layers were held together by studs. The ribbed-tile elements allowed rapid installation and replacement. Another advantage of them is the possibility of varying the composition and thickness of the layers, given the universality of the structural base.

It was expected [12] that, as compared to the Space Shuttle, the Hermes thermal coating would correspond to the more stringent requirement imposed on deorbiting — to the longer lateral distance (2000 km) and smaller angles of attack and hence longer duration (of the order of 4000 sec). Three types of multilayer insulations were assumed to be necessary to obtain thermal protection optimum in weight at a permissible temperature of the frame surface of 473 K [12]. In an insulation of the A type, efficient at temperatures to 873 K, it was assumed to employ a 13-μm-thick aluminum foil in combination with felt from SiO_2 fibers of diameter 2 μm (ρ = 17 kg/m^3) with a distance of 5 mm between the shields. In an insulation of the B type for temperatures to 1073 K, one must employ a foil from gold-

TABLE 1. Characteristics of the Setups and Benches for Testing Specimens of Thermal Protection Materials

Characteristics	Name, owner			
	"Uran-1", A. V. Luikov Heat and Mass Transfer Institute, Minsk, Belarus	"Luch-2", A. V. Luikov Heat and Mass Transfer Institute, Minsk, Belarus	T-52A, N. E. Zhukovskii Central Aerohydrodynamics Institute, Zhukovskii, Russia	Solar furnace, solar platform, Almeria, Tabernas, Spain
Method of heating	Gas-discharge-plasma radiation	Combined (radiation and convection)	Contact	Concentrated solar radiation
Maximum dimensions of the specimen (length × width × height or diameter × length), mm	∅60 × 50	∅20 × 100	152 × 152 × 50	∅230 × 500
Power, kW	under 10	450	under 10	58
Maximum heat-flux density, W/m^2	$0.6 \cdot 10^7$	$1.5 \cdot 10^7$	$5 \cdot 10^6$	$3.0 \cdot 10^6$
Nonuniformity of the heat flux, %	15%	15%	1%	5% per ∅230 mm
Maximum duration of the test, min	10	10	under 600	300
Composition of the test atmosphere	Air	Air	Air, N_2, Ar, vacuum	Air, N_2, Ar, vacuum
Pressure of the test atmosphere, Pa	10^5	$1.2 \cdot 10^5$	$1–10^5$	$10^{-4}–10^5$
Diagnostic means	Optical pyrometer, thermocouples, heat flux sensors	Optical pyrometer, thermocouples, heat flux sensors	Thermocouples, sensors of heat and radiation fluxes	CCD camera – incident heat flux, Avio 2000 pyrometer, thermocouples

plated nickel; felt is analogous to an A insulation; the distance between the shields is 3 mm. In an insulation of the C type, intended for use at temperatures to 1673 K, felt from Al_2O_3 fibers (ρ = 48 kg/m^3) must combine with a platinum foil for a distance of 3 mm between the shields.

In selecting a thermal coating for prospective aerospace systems (Fig. 3), not only is the capacity itself for protecting against aerodynamic heating of importance but also (and primarily) the weight and operating characteristics of the coating. The main requirements [13] are the initial cost, the cost of a life cycle, and the capacity for integrating with the primary bearing structure, including cryogenic propellant tanks. It is required that the thermal coating withstand damage from falling tools in ground service and high-velocity collisions with separated structural elements in space and in the rain and operate under thermal, acoustic, and thermomechanical loads. Furthermore, the thermal coating must easily be inspected and repaired; it must offer freedom of application of water repellents in the period between flights.

New thermal coatings that are under bench and flight tests as applied to the single-stage aerospace systems in the USA [13–19] must meet the requirement enumerated. A rectangular or diamond-shaped thermal-protection element includes the front and rear honeycomb panels from a high-temperature metal alloy, held together with a box-shaped metallic frame (Fig. 4). The front panel acts as an antierosion shield with a low catalytic activity and a high emissivity. The rear panel is connected with the bearing structure by pins. The internal space of the element is filled with a multilayer (not bearing a force load) heat insulation based on SiO_2 and Al_2O_3 fibers with ρ = 24, 48, or 96 kg/m^3. A study has been made of metallic foams [18].

Complex Investigations of Porous Materials as a Component Part of the Problem of Designing of Thermal Protection. The use of porous materials, including those from partially transparent fibers, in reusable thermal coatings places a reliable mathematical description of the processes of combined, primarily radiative-convective, heat exchange among the main problems of thermal designing of such structures [20]. Thermal coatings from porous materials are designed at present predominantly with the use of mathematical models of effective thermal conductivity. However, the effective coefficient of thermal conductivity λ_{eff} is a property of not only a material; it represents the characteristic of the overall heat transfer of a specific structure under certain conditions of interaction with the ambient medium. Flight conditions can significantly differ in their heating rates, temperature levels and differences, and optical properties of the boundary surfaces and the levels and rates of change of the ambient pressure, which causes a difference of the temperature and barometric dependences of λ_{eff}.

To create thermal coatings with optimum weight-geometric and economic characteristics it is topical to determine with a required degree of accuracy the temperature and barometric dependences of λ_{eff} of the porous materials for operating conditions. Solution of this problem is complicated by the fact that neither experimental nor theoretical methods are self-sufficient. The drawbacks of experiment are the incompleteness of reproduction of the required conditions and measurement errors. Theoretical methods are limited by the inefficiently deep knowledge of physical phenomena, the approximateness of corresponding mathematical models and initial data, computational errors, and computer resources.

It seems that the problem can be solved with several mutually complementary methods.

The experience gained in the previous investigations of λ_{eff} shows that the most informative experiments are those simulating actual operating conditions. With account taken of the diversity of these conditions, it is expedient to cover the range of heating rates to 100 K/sec at temperatures of 300 to 2000 K in the range of pressures $1\text{–}10^5$ Pa. All these conditions together can be reproduced with a number of experimental setups (see Table 1). Methods of parametric identification of thermal processes, which are based on solution of inverse problems [21], should be used for processing of experimental data.

Theoretical methods of calculation of λ_{eff} assume, as a rule, the additivity of individual mechanisms of heat transfer (heat conduction, radiation, and convection) and knowledge of the structural characteristics of a material (porosity and particle-size distribution). These characteristics are usually determined experimentally by electron microscopy, absorption analysis, mercury porosimetry, and other methods.

Of great importance is determination of the radiative component of heat transfer in porous materials which absorb and scatter radiation in volume. In calculating the bulk optical properties of such materials, one must take account of the effects of mutual influence of individual scatterers (cooperative effect). To check the methods developed it is expedient to use data on the properties of partially transparent scattering materials.

Within the framework of the project uniting experts from Belarus, Germany, Italy, Russia, and France, the most important are the following problems:

(a) to generalize and systematize data on the results of investigation of different versions of thermal coatings based on porous materials;

(b) to develop mutually complementary computational-experimental methods of determination of λ_{eff} of porous materials in nonstationary regimes of heat exchange of specimens in a gaseous medium with a variable pressure with the use of mathematical models of combined heat exchange, the theory of solution of inverse problems, and the techniques of approximation of empirical dependences;

(c) to develop algorithms and computational programs (based on the methods and algorithms of solution of inverse problems) for identification of the parameters of heat exchange in a porous material by experimental data obtained in the tests of the specimens of materials;

(d) to modify experimental setups and to prepare and run tests of the specimens with simulation of operating conditions;

(e) to process experimental data and to derive and analyze the dependences of λ_{eff} of the porous materials for nonstationary regimes of heating of thermal coatings.

A combination of the advantages of bench tests with the potentials of modern methods of mathematical modeling and parametric identification of the processes of combined heat transfer offers the possibility of improving the accuracy of thermal designing and imparting greater stability to the action of ambient factors to thermal coatings from porous materials.

This work was carried out with financial support from INTAS, project No. 00-0652.

NOTATION

ρ, density of the material; λ_{eff}, effective coefficient of thermal conductivity.

REFERENCES

1. Yu. V. Polezhaev and F. B. Yurevich, *Thermal Protection* [in Russian], Énergiya, Moscow (1976).
2. A. I. Leont'ev, N. N. Pilyugin, Yu. V. Polezhaev, and V. M. Polyaev (Eds.), *Scientific Principles of Technologies of the XXIst Century* [in Russian], UNPTs Énergomash, Moscow (2000).
3. S. V. Reznik (Ed.), *Materials and Coatings under Extremal Conditions. Insight to the Future.* In 3 vols. Vol. 1 [in Russian], Izd. MGTU, Moscow (2002).
4. V. F. Gladkii, The mistery of the project of the R-3 rocket, Aviats. Kosmonavt., No. 11, 13–16 (2002).
5. I. Chernyi, High-power rockets for the near future, *Novosti Kosmonavt.*, **14**, No. 1, 30–32 (2004).
6. K. P. Feoktistov, *Space Techniques. Perspectives of Development* [in Russian], Izd. MGTU, Moscow (1997).
7. G. E. Lozino-Lozinskii and A. G. Bratukhin (Eds.), *Aviation-Space Systems* [in Russian], Collection of Papers, Izd. MAI, Moscow (1997).
8. M. Ya. Gofin, *Heat-Resistant and Thermal-Protective Structures of Space Shuttles* [in Russian], Moscow (2003).
9. H. N. Kelly, D. R. Rummler, and L. R. Jackson, in: *Proc. AIAA/NASA Conf. Adv. Technol. Space Syst.: Collect. Tech. Pap.*, Hampton, VA (1979), pp. 12–23.
10. A. H. Taylor, J. A. Cerro, and L. R. Jackson, Analytical study of reusable flight-weight cryogenic propellant tank designs, *Aérokosm. Tekh.*, No. 9, 101–111 (1986).
11. D. Chaumette and J. Cretenet, Hermes thermal protection system overview, *Acta Astronaut.*, **16**, No. 3, 391–399 (1987).
12. R. Veneri, P. De Filippis, and C. Williamson, Development of Hermes IMI High Temperature Flexible Insulation, *SAE Tech. Pap. Ser.*, No. 1494 (1989).
13. M. L. Blosser, C. J. Martin, K. Daryabeigi, and C. C. Poteet, Reusable metallic thermal protection systems development, in: *Proc. 3rd. Eur. Workshop on Thermal Protection Systems*, Noordwijk, The Netherlands, March 25–27, 1998.
14. K. Daryabeigi, Analysis and testing of high temperature fibrous insulation for reusable launch vehicles, *AIAA Pap.*, 1999, No. 1044 (37th AIAA Aerospace Sci. Meeting and Exhibition, Reno, NV, January 11–14, 1999).
15. K. Daryabeigi, Effective thermal conductivity of high temperature insulations for reusable launch vehicles, NASA/TM. 1999–208972.
16. D. E. Myers, C. J. Martin, and M. L. Blosser, Parametric weight comparison of advanced metallic, ceramic tile, and ceramic blanket thermal protection systems, NASA/TM. 2000–210289.
17. K. Daryabeigi, Thermal analysis and design of multi-layer insulation for re-entry aerodynamic heating, *AIAA Pap.*, 2001, No. 2834 (35th AIAA Thermophysics Conf., Anaheim, CA, June 11–14, 2001).
18. A. D. Sullins and K. Daryabeigi, Effective thermal conductivity of high porosity open cell nickel foam, *AIAA Pap.*, 2001, No. 2819 (35th AIAA Thermophysics Conf., Anaheim, CA, June 11–14, 2001).
19. J. T. Dorsey, C. C. Poteet, R. R. Chen, and K. E. Wurtser, Metallic thermal protection system technology development: Concepts, requirements and assessment overview, *AIAA Pap.*, 2002, No. 0502 (40th AIAA Aerospace Sci. Meeting and Exhibition, Reno, NV, January 14–17, 2002).
20. S. V. Reznik, Modeling and inverse problems of radiative and conductive heat transfer, in: *Proc. of the Eurotherm Seminar 68*, Poitiers, France, March 5–7, 2001, pp. 23–36.
21. O. M. Alifanov, P. N. Vabishchevich, V. V. Mikhailov, et al., *Principles of Identification and Design of Thermal Processes and Systems* [in Russian], Logos, Moscow (2001).