KAPITEL 3 / *CHAPTER 3* [3]
RESEARCH OF MECHANISMS OF DESTRUCTION AND PROTECTION COMPLEX THERMODYNAMIC SYSTEMS

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Introduction

An extremely important property of technical objects is the ability to perform specified functions, to maintain the values of all operational indicators during operation and within certain limits, which ensure the performance of the required functions under specified load conditions. When designing technical facilities, much attention is paid to their reliability, but failures are not always avoidable [1-8]. They lead to huge losses of money, effort, and time, and sometimes to human casualties. Therefore, the problem of creating reliable technical facilities and their systems is relevant. This can be explained by the complexity of technical facilities, special operating conditions, thermal and thermomechanical loads, and the increasing complexity of tasks.

Currently, when creating and improving technical facilities, a reasonable combination of calculation and organizational and technical methods is used to study the mechanisms of destruction and ensure the reliability of systems. Calculation methods are used to select the most acceptable technical solutions for the created systems and products in terms of reliability. However, it is not so easy to ensure the calculated values of reliability and service life indicators when implementing a project in real structures and systems of technical facilities. For this purpose, a special set of methods and means of protection of technical systems and products is used, which allows to realize the design characteristics and minimize the probability of failures with severe consequences. The successful use of basic and protective materials primarily depends on how well the behavior and properties of materials under various thermodynamic conditions are studied. Reproducing such conditions is usually a very complex technical task that requires significant costs.

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3.1. General provisions, terms and definitions

A thermodynamic system is a set of material bodies that are in energetic interaction.

The **fracture mechanism** is a schematic model of the behavior of a heat-shielding coating in a high-temperature and high-speed gas flow, indicating the number and type of the most important physical and chemical processes that accompany the removal of the coating mass [4]. The destruction mechanism is necessary for calculating and comparing the characteristics of heat-shielding coatings under different conditions. Five conditional mechanisms are distinguished: evaporation, melting, and mass removal under thermal, thermo-erosion, and oxidizing effects of a gas flow.

Thermal destruction means the removal of mass under purely thermal influence. An example of such impact is radiant (radiation heating). Thermoerosion destruction means the removal of mass under the thermal and gas-dynamic influence of the incoming gas flow (friction stress on the surface). All three mechanisms are characteristic of material surface destruction in an air or carbon dioxide stream: thermal, thermo-erosion, and oxidation. The identification of these five mechanisms of material destruction in a high-temperature gas stream is arbitrary, but this approach facilitates the analysis of the processes of heating and mass removal of heat-shielding materials.

Thermal protection is a certain way of blocking or reducing the flow of heat from the environment to the body surface (Figure 1). Among the six known principles of heat removal or absorption from the outer surface of a body, the widest range of practical applications is provided by those based on the use of blowing effects and physical and chemical transformations.

The mass transfer rate is the main characteristic of the process of destruction of heat-protective coatings in a high-temperature gas flow, equal to the product of the density of the coating material and the speed of linear movement of its outer surface.

The ratio of the mass transfer rate to the heat transfer coefficient on an impermeable surface, called the dimensionless mass transfer (destruction) rate, is a convenient parameter for presenting results for chemically active heat shielding materials.

Ablation is the process of material destruction when exposed to an external heating source.

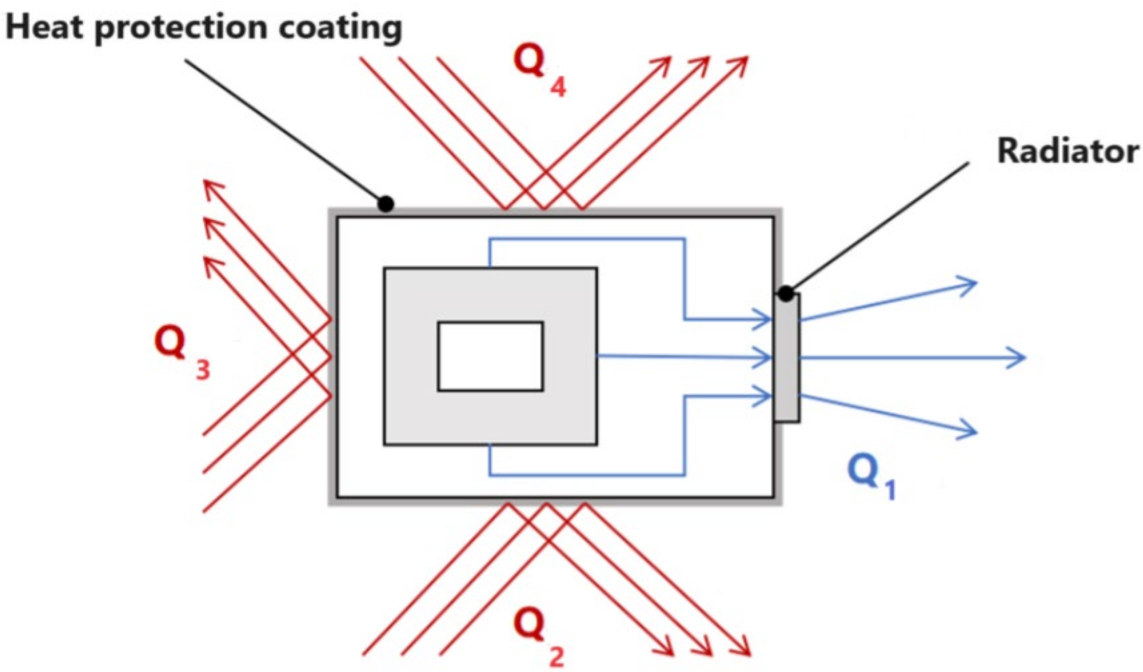

Figure 1 – Model of heat flows and thermal protection systems

Kinetic mode of destruction is a mode of surface destruction of heat-protective coatings exposed to convective or radiation heat, the rate of which is mainly determined by the kinetics of the reaction between the coating substance and chemically active components of the gas stream. A characteristic feature of this mode of destruction is a strong (exponential) dependence of the mass transfer rate on temperature. In contrast to the sublimation mode, the destruction rate here depends significantly on the content of chemically active components in the flow.

Fracture temperature is the temperature of the onset of surface destruction of a given heat-shielding coating in a certain range of external environmental parameters (not necessarily accompanied by mass removal, for example, surface melting). In a broad sense, this is any value of the surface temperature of the destructive heat shielding coating.

3.2. Methods of protecting technical systems

There are six main methods of heat removal (absorption): thermal conductivity using the heat capacity of condensed substances, convection, mass transfer, radiation, electromagnetic fields, and physical and chemical transformations. In practice, two or more of these methods are often used simultaneously. Each of these methods or a combination of them can be implemented in the form of different methods of thermal protection, depending on the specific design.

1) Absorption and accumulation of heat by condensed matter. Heat-saving systems are low-temperature systems, as they operate at temperatures below the melting point of the heat-absorbing material. Heat is removed from the surface by thermal conductivity in accordance with Fourier's law. The maximum amount of heat that can be absorbed by such a system is released

$$q_0 = -\lambda \frac{dT}{dn} \quad Q = \int_{T_0}^{T_p} c \cdot dT$$

2) Convective cooling. Heat is transferred from the wall heated by a hot gas flow to the coolant or gas. The temperature difference of the wall at a given thickness δ is given by the formula

$$T_{W1} - T_{W2} = q \cdot \frac{\delta}{\lambda}.$$

The heat flux density q under steady-state conditions is determined by the coolant flow rate m, its heat capacity c, and the temperature difference $T_{W2} - T_0$:

$$q \cdot S = cm(T_{W2} - T_0),$$

where S is the heat transfer surface area.

Depending on the method of heat dissipation into the surrounding space, convective cooling systems are divided into closed and open systems. A mandatory element of a closed cooling system is a heat exchanger, in which the cooler that has received heat from the hot wall dissipates it into the environment or transfers it to another coolant.

3) Mass transfer cooling principle. This cooling principle can be implemented in the form of *porous (Figure 2), film, or barrier* cooling. When cold gas or liquid is introduced directly into the wall layer of the counterflow, the thickness of this layer increases, the hot gas is repelled from the protected surface, resulting in a decrease in the intensity of heat transfer on the surface.

The advantages of this method of protection over others are, firstly, the preservation of the external shape of the protected surface, and secondly, the ability to maintain the surface temperature at the desired level by adjusting the cooler flow accordingly.

Consider **film cooling**. Hot gas moves along a wall that is covered with a film of coolant that enters through one or more slots or holes located at a certain distance from each other along the surface. The surface temperature of the body will not exceed the boiling point of the liquid as long as there is a film on the surface.

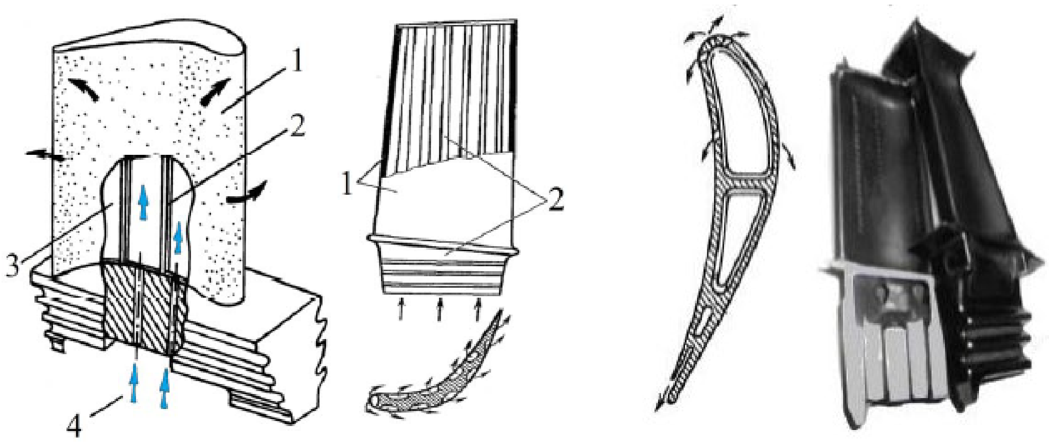

Figure 2 – Gas turbine blades with porous (left) and convective film (right) cooling *(1 - porous shell; 2 - bearing rods; 3 - air cavities; 4 - air supply channels)*

In barrier cooling, the protected wall is insulated from the hot gas flow by a layer of cold gas that is fed to the surface through slots or holes.

Porous cooling is a very effective method of thermal protection. One of its advantages is that the coolant is delivered through the surface. Passing through the pores, the coolant takes heat from the wall, and when it reaches the surface, it reduces the intensity of heat transfer between the hot gas and the wall, affecting the boundary layer. The cooler can be gas or liquid. Gases are generally preferred due to their higher operating temperatures and lower pressure drop as they flow through the pores. In terms of coolant consumption per unit of protected surface, porous cooling is more efficient than the other methods already discussed. However, the use of porous cooling requires the manufacture of porous walls using a rather complex technology. In addition, when operating such a system, it is necessary to take measures to clean the cooler to avoid clogging of the pores.

4) Radiation cooling. The heated surface of a body becomes a source of thermal radiation, dissipating the thermal energy that comes to it into the surrounding space. The radiation flux density q of a surface with temperature T and blackness ε is characterized by the Stefan-Boltzmann law:

$$q = \varepsilon \sigma T^4,$$

where σ — is Stefan-Boltzmann constant, which is approximately equal to $5{,}67 \cdot 10^{-8} \frac{wt}{m^2 K}$.

The capabilities of a radiation cooling system are limited by the level of permissible surface temperatures. The radiation cooling method is based on the idea of equality of the heat flux supplied to the surface from the outside and the heat flux dissipated by this surface through radiation. The surface temperature T, assuming that the heat transfer inside the coating is equal to zero K, is determined by the equation:

$$T_W = \sqrt[4]{q / \varepsilon\sigma} .$$

Obviously, with this method of cooling $q \leq \varepsilon\sigma T_p^4$. Refractory metals, such as molybdenum, tungsten, etc., are used as structural materials for the radiation cooling system.

5) Electromagnetic heat transfer control. To regulate the temperature of the external surface, methods of electrical or magnetic influence on the plasma flowing around the surface to be protected can be used. The magnetohydrodynamic method requires the creation of a force field in the ionized plasma flowing around the body. The magnetic field, acting on a layer of compressed gas, which includes, in addition to neutral molecules and atoms, electrically charged ions and electrons, increases the distance between the shock wave and the body surface, which leads to a thickening of the boundary layer and, consequently, to a decrease in velocity and temperature gradients.

The thermoelectric method of absorbing heat by converting it into electrical energy can also be used.

6) Cooling of bodies due to physical and chemical transformations on their surface. It is well known that any phase transformation is accompanied by a significant thermal effect. In metals, melting results in a partial weakening of interatomic bonds, and during evaporation, all the bonds of the crystal lattice are broken and the atoms become almost independent of each other, so the thermal effect of evaporation is much higher (10-20 times) than the thermal effect of melting. If a film with a very low melt viscosity is formed during melting, it can be blown off the surface almost instantly by an oncoming gas flow. Therefore, it is important not only to select a substance with a high thermal evaporation effect, but also to ensure that this effect is always realized when the surface is destroyed. Therefore, ablative thermal protection systems are designed as combined systems that meet the following conditions:

1) absorb a large amount of heat during physical and chemical transformations;

2) have a high value of volumetric heat capacity c_V;

3) if possible, have high erosion resistance to ensure a small mechanical mass

loss;

4) if possible, have a high temperature of the destroyed surface and a high value of its degree of blackness (ε);

5) form gaseous products with a low molecular weight during destruction to effectively reduce convective heat flow;

6) the melt film, if formed, must be sufficiently viscous.

To conclude the review of thermal protection methods, we can make some qualitative generalizations:

– heat storage systems have limitations both in terms of the total amount of heat released and the maximum specific heat flux due to the limited thermal conductivity of materials.

– radiation cooling systems are limited in terms of maximum specific heat flux, but in practice can operate at any total heat supply.

– for aerospace systems with a descent time of less than 10 minutes, *ablative heat shielding materials have an absolute advantage* over other possible methods in terms of weight efficiency.

– for very long, and therefore less strenuous, thermal descents in the atmosphere, mass transfer comes first, followed by a radiation thermal protection system. This is because an increase in the time of descent in the atmosphere, without reducing the total amount of heat, proportionally reduces the density of the heat flux supplied. The equilibrium temperature is reduced to such an extent that the radiation cooling system can fully cope with the task of dissipating the energy supplied to the surface of the descent object without complex additional measures.

3.3. Separate means of ensuring thermal conditions

Let us consider in more detail examples of elements of thermal management systems for complex technical facilities: screen-vacuum thermal insulation, heat pipes and radiation-optical coatings, which, however, are subject to changes in their characteristics under the influence of environmental factors.

3.3.1. Screen and vacuum thermal insulation

The impact of external heat exchange on the internal thermal conditions of technical facilities can be significantly reduced, and in some cases reduced to an insignificant level, if special thermal insulation is used (Figure 3).

The element of such thermal insulation is a package assembled from opaque screens and cushioning material, which largely prevents the screens from contacting and thereby reduces conductive heat transfer. Depending on the operating conditions, the screens are made of polymer film materials or metal foil. Shields made of polymeric materials are used when their temperature does not exceed 150°C.

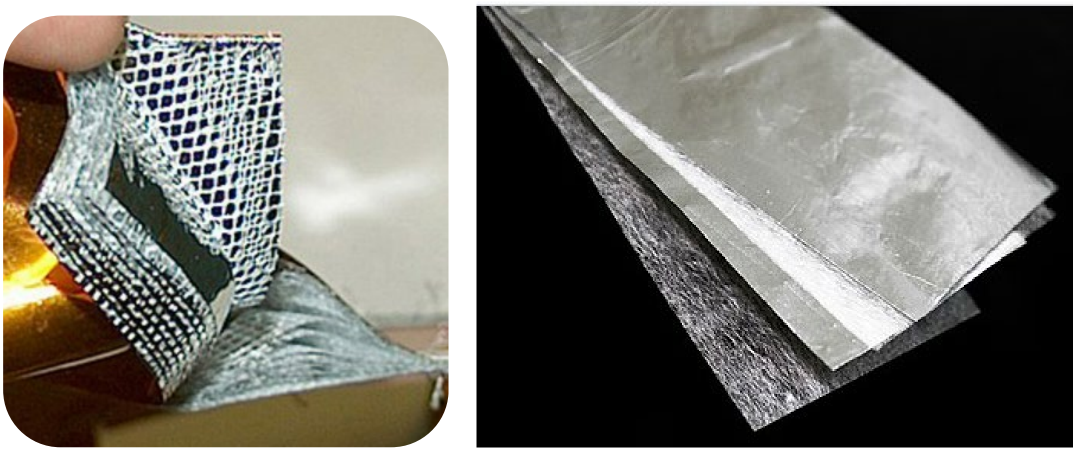

Figure 3 – Layers of screen-vacuum thermal insulation in a section

At higher temperatures, the screens are made of metal foil: aluminum foil if the temperature does not exceed 500°C, and nickel foil if the temperature does not exceed 1000°C. The thickness of the screens is sometimes 5 microns and sometimes 10 microns. In an uncompressed, pumped package, heat transfer through the insulation is mainly due to radiation heat transfer between the screens. To evaluate the thermal insulation properties of the screen-vacuum insulation, we assume that the thermal conductivity of the residual gas and the heat transfer by conduction through the contact points of the screens are negligible compared to the heat transfer due to radiation heat exchange between the screens. In addition, let's assume that the **degree of blackness of the screens** ε is the same on both sides and does not depend on temperature. In this case, in the steady-state mode, the density of the resulting **heat flux** q_0 through the n package of screen-vacuum insulation is determined by the following expression:

$$q_0 = \frac{q_W - \varepsilon_W \sigma T_0^4}{\frac{\varepsilon_W}{\varepsilon_N}(n-1)+1},$$

where q_W – is the density of heat flux absorbed by the outer surface of the screen-vacuum insulation package;

$\boldsymbol{\varepsilon}_W$ and $\boldsymbol{\varepsilon}_N$ – are, respectively, the degree of blackness of the outer surface and the

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reduced degree of blackness, with $\varepsilon_N = \frac{1}{\frac{2}{\varepsilon}-1}$;

T_0 – is the temperature of the last internal shield - a fixed temperature equal to, for example, the internal temperature of the compartment (object of protection).

In engineering practice, the thermal insulation properties of insulation are evaluated by the value of the **resistivity** R.

It is the value of R that is used in the study of the thermal regime of an object whose thermal regime is ensured by insulation. In this case, the value of the heat flux q_0 is determined by equation:

$$q_0 = \frac{T_W - T_0}{R}.$$

Since $T_W^4 = \frac{q_W - q_0}{\varepsilon_W \sigma}$, using the first expression above for q_0, we obtain the following expression for estimating the value of R:

$$R = \frac{n-1}{\varepsilon_N \sigma (T_W^2 + T_0^2)\cdot(T_W + T_0)}.$$

Of interest are the results of comparing the thermal insulation properties of insulation with those of conventional thermal insulation materials, the thermal conductivity of which is usually characterized by the thermal conductivity coefficient λ.

The relationship between λ and R can be established using the thickness of the insulation δ. After all, on the one hand $q_0 = \frac{\lambda}{\delta}(T_W - T_0)$, and on the other $q_0 = \frac{T_W - T_0}{R}$.

$\lambda = \delta / R$ By isolating parts of the object of protection with screen-vacuum insulation, it is possible to reduce the impact of external heat transfer on the internal thermal state of these compartments and elements to a small, and in many cases negligible, value.

3.3.2. Heat pipes

Another important element of the thermal management system for technical facilities is heat pipes (Figure 4), which are devices with very high thermal conductivity. The heat flow from the device (3) is transferred through the structural element (4) to one of the ends of the heat pipe (1). The refrigerant in the closed space of the heat pipe heats up and turns into a gaseous state, taking away the heat necessary for vaporization. The vaporized refrigerant flows to the other end of the heat pipe (this flow is shown by the light wide arrows).

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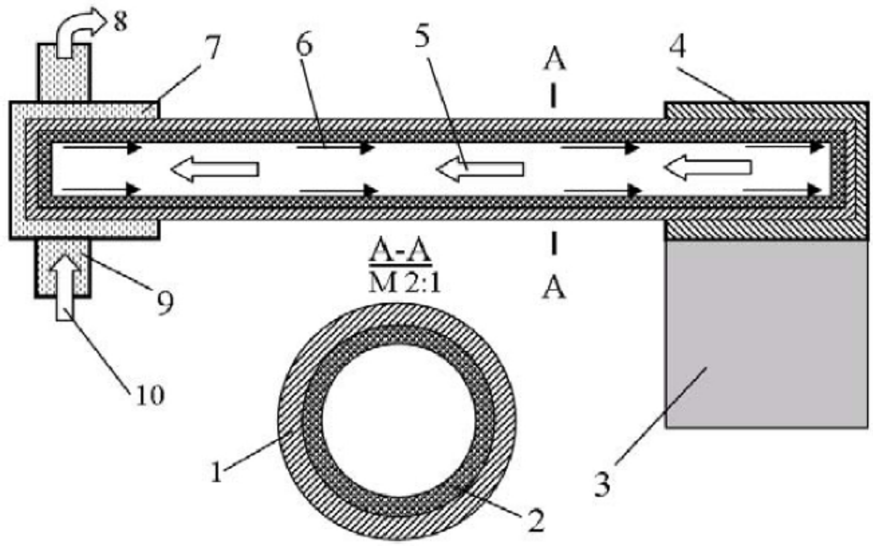

Figure 4 – Diagram of the heat pipe

The temperature of the second end of the heat pipe is lower, so the vaporized refrigerant condenses, releasing the latent heat of vaporization to the structural elements of the second end of the pipe. The refrigerant returns in a liquid state through the capillaries or porous walls of the heat pipe (2). The heat flux is removed from the structural elements of the second end of the heat pipe by a heat sink or cooling liquid (element 7). The heat is then discharged into the surrounding space either directly from the heat sink element (7), if it is located on the outer surface of the object, or by means of a liquid cooling circuit (if it is in the thermal management system) and a radiator-cooler.

In addition to high effective thermal conductivity, the heat pipe is characterized by an isothermal surface with low thermal resistance. In this case, the condensing surface of the heat pipe operates at an almost constant temperature. If localized heat runoff occurs in a certain territory/area, the amount of steam condensation in this place increases and thus the temperature is maintained at the same level. Improved pipe performance is achieved through the use of a feedback loop. The gas pressure in the tank is changed by an electric heater, which is regulated by a signal from a sensor installed at the heat source.

3.3.3. Radiation-optical coatings

The use of heat-insulating materials, coatings, and surface treatments to obtain certain radiation-optical characteristics allows, first of all, to reduce and limit the limits

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of changes in loads on the system, which, of course, makes it possible to simplify the system and improve its mass and energy performance. The use of materials and coatings as passive regulators of the intensity of external heat transfer is associated with one unfavorable circumstance: many materials, when exposed to short-wave electromagnetic and particle radiation from the Sun, change their radiation-optical characteristics over time, i.e., *absorption, reflectivity, transmission, and emissivity.* Changes in these characteristics are the result of so-called **radiation damage** to materials, which occurs mainly due to ionization, electronic excitations, displacement of substance atoms, dissociation of chemical bonds in molecules during absorption of high-energy photons and interaction with high-energy charged particles.

Materials degradation creates difficulties in solving the problem of ensuring the thermal regime of aerospace systems, especially in connection with the increase in the A_S coefficient of white coatings applied to surfaces exposed to solar radiation to reduce their temperature level.

The degradation of coating properties worsens the performance of radiant refrigerators used in active temperature control systems and increases the overall temperature level when using passive thermal management systems. Some idea of the nature of A_S change in time for several known thermostatic coatings and materials in operation can be obtained from the consideration of Figure 5. Figure 5 shows the dependence of the ratio $A_S(\tau) / A_S(0)$ on the time τ (months) of exposure to solar radiation of the experimental samples of coatings.

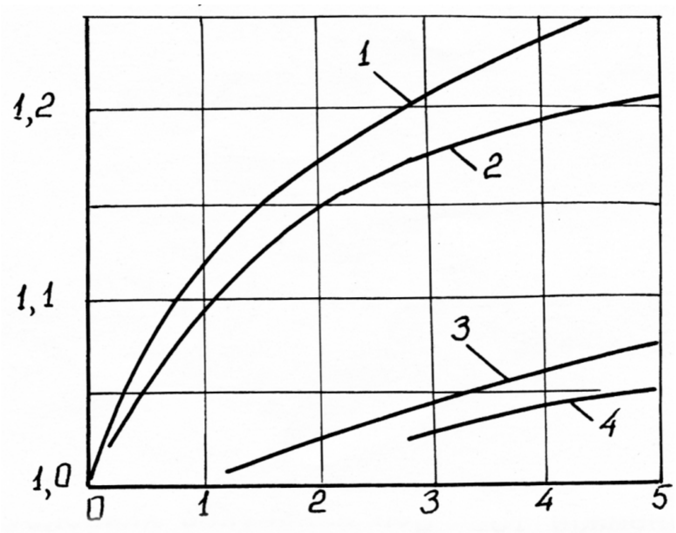

Figure 5 – Changes in space over time of the absorption capacity of some coatings in relation to solar radiation

1 - white enamel, 2 - polished aluminum, 3 - paint based on aluminum powder (pigment) and silicone binder, 4 - black paint.

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3.4. Investigation of fracture mechanisms

3.4.1. Mechanisms of destruction of thermal protection materials

The principle of operation of ablative thermal protection systems is characterized by the loss of the surface layer or decomposition of one of the material components in order to maintain a favorable thermal regime of the internal layers and the protected structure itself. The destruction of the surface layer occurs as a result of various physical and chemical transformations under the influence of convective and radiation heat flows coming to the surface, diffusion flows of chemically active components, as well as under the influence of pressure and friction forces.

Chemical reactions can occur both with the participation of counterflow components and independently of them. In addition, erosion can occur on the surface of the heat shielding coating under the influence of internal pressure or external forces, as well as as a result of thermal stresses - mechanical removal in the form of individual particles.

Figure 6 – Thermal ablation protection of the Apollo command module capsule after return

The use of ablative thermal protection systems has significant advantages over other methods of thermal protection. The main one is the self-regulation of the process, i.e., a change in the mass flow rate of the coating material when the thermal load changes. Fracture processes are accompanied by phase and chemical transformations, as well as injection of fracture products into the oncoming flow, which leads to a decrease in the temperature gradient across the boundary layer and, consequently, to a decrease in the heat flow to the wall. The most common ablative heat shielding materials are usually composite compounds, and their individual components have different thermochemical resistance under given external flow conditions.

However, in the process of destruction of the composite material, not individual failure rates for each component are realized, but a **certain total indicator**, determined mainly by some one component, the mass content of which in the material is large enough or it is able to form a mechanically strong frame that has the best ability among other components to withstand the aerodynamic effects of high-temperature gas flow. The role of other components of the composite material is not limited to that of a thermal ballast, but through chemical and physical interaction with the defining component, they affect the weight transfer of the latter. Gasified substances formed during the destruction of the thermal protection coating, getting into the boundary layer, have a chemical and physical effect on it. In many cases, chemical reactions occur with the release of heat, which worsens the heat balance in the surface layer. However, the formation of large masses of gaseous products as a result of these reactions ultimately neutralizes this undesirable effect, as it leads to an increased blowing effect. Graphite is very popular as a heat shielding material. Its fracture mechanism differs from the discussed fracture mechanism of composite materials. The difference is primarily due to the fact that graphite does not form a melt under moderate pressure. On the surface of graphite, not only sublimation can occur, but also a number of chemical reactions, the thermal effect of which differs from the heat of sublimation. The destruction of graphite begins long before the sublimation temperature is reached. This is due to the high reactivity of graphite in many gaseous media, especially in oxygen and air. At surface temperatures of up to 1100 K in air, graphite fracture is usually entirely determined by reaction kinetics, i.e., the fracture rate varies exponentially with surface temperature. After a small transitional section, a region begins where the destruction process is limited by the rate of counter-diffusion of the oxidizer and destruction products in the multicomponent boundary layer. At the same time, the rate of destruction is weakly dependent on the surface temperature, which can vary from 1200-1600 to 2400-3800 K, depending on the pressure. It is only at higher temperatures that the actual sublimation process, which depends on the pressure in the boundary layer, begins to play an increasingly important role in the removal of the graphite mass. The mass entrainment rate increases exponentially with increasing wall temperature. As for the thermal effect of fracture, at low surface temperatures it is not only very different from the heat of sublimation (in the case of oxidation, it can even become negative), but also significantly depends on the composition of the gas in the boundary layer.

3.4.2. Effective enthalpy of destruction

Due to the complexity and diversity of the destruction mechanisms of thermal protection materials, the question of criteria for comparing thermal protection materials is becoming very relevant. A clear characteristic for comparing different thermal protection materials is the so-called **effective enthalpy of destruction**:

$$I_{EFF} = \frac{q - \varepsilon\sigma T_W^4}{G_\Sigma},$$

where $q = (\frac{\alpha}{c_P}) \cdot (I_\delta - I_W)$;

G_Σ – is the mass flow rate per unit surface area.

The effective enthalpy I_{EFF} determines the amount of heat that can be "blocked" by the destruction of a unit mass of a coating whose surface has a temperature of T_W as a result of all physical and chemical processes accompanying this destruction. In other words, this is a characteristic of the energy intensity of mass removal from the surface of ablative heat-protective coatings, which includes not only the amount of heat absorbed during heating, thermal and phase transformations of a unit mass of material, but also the thermal effect of blocking the convective heat flow supplied when gaseous destruction products are injected into the boundary layer. The effective enthalpy I_{EFF} is an indicative characteristic for comparing different heat shielding materials. The higher the effective enthalpy of a material, the better it is. Attention should be paid to the known independence from geometric dimensions. After all, unlike the heat flux, the value of which, given the parameters of the incident gas flow (p_δ i I_δ) is inversely proportional to $\sqrt{R}$, where R — is the size of the body, the effective enthalpy clearly does not depend on either the shape or size of the body. This makes it possible to use it as a parameter to comply with the conditions of bench-scale experimental studies of a full-scale destruction situation. If we denote by γ the parameter characterizing the ability of the coolant to reduce the heat flux, which is commonly called the injection coefficient, and by G_W the mass of gaseous decomposition products with a thermal effect of ΔQ_W, then the expression for the effective enthalpy can be written as

$$I_{EFF} = \bar{c}(T_W - T_0) + \Gamma(\Delta Q_W + \gamma(I_\delta - I_W)),$$

where $\Gamma = \frac{G_W}{G_\Sigma}$.

It should be noted that the coefficient γ depends on the ratio of the molecular weights of the injected products and the incident gas flow, but it is primarily a function of the flow regime in the boundary layer. In engineering practice, it is assumed to be approximately 0.6 for laminar and 0.2 for turbulent boundary layers. From the definition of the effective enthalpy and the above expression for it, it follows that in all cases when $\Gamma \neq 0$, it should increase significantly with the growth of the enthalpy of the retarded flow. The parameters of the counterflow can also be influenced by changes in the temperature T_W of the fractured surface, the fraction of removal in the gaseous form (parameter Γ) and the total thermal effect of surface processes (ΔQ_W).

3.4.3. Failure mechanisms of heat engine components

The working conditions of structural materials of heat engines are characterized by a variety of operational factors, which primarily include high levels of stresses and temperatures, their cyclicity and duration, and the presence of a chemically active working environment. In the course of the study of heat engines after operational operation, the presence of damage of various nature, *namely cracks of mechanical and thermal fatigue, irreversible ultimate deformation of parts, burnouts, peeling of coatings, and wear of friction pairs, was established.*

Combustion chamber. The operating conditions of engine combustion chamber elements are characterized by significant values of cyclic mechanical and thermal stresses (Figure 7). This led to the appearance of mechanical and thermal fatigue damage (cracks), irreversible deformation of structural elements. The depressurization of brazed seams and other areas of the fuel collectors was detected. One of the reasons for these defects was thermal stresses arising from the limited deformation and the difference in the coefficients of linear expansion of the materials of the protective coating, weld, inlet tube, and injector body.

This resulted in the formation of cracks in the coating and the wall of the inlet tube, which caused further depressurization of the fuel channel and burnout of the combustion chamber housing parts. Cracking along the collector's welds occurred at the weld boundary (fillet).

No metallurgical defects or obvious brazing defects were found in the fracture zone. Metallographic analysis of the fuel circuit pipeline fracture showed no changes in the structure and composition of the metal. The cracks originated from linear concentrators located near the outer surface of the pipeline. Cracks were also observed on the vessel diffuser struts (Figure 7). The average length of the cracks varied in the range of 3...6 mm.

Figure 7 – Cracks in the body of the main combustion chamber

1. **Gas turbine.** The most stressed structural elements of a gas turbine are its disks, impellers, and nozzle blades. The blades are produced by the directed crystallization method and have gas-plasma high-temperature protective coatings. Despite the material's safety margins, the parts are characterized by thermal fatigue fractures in the low-cycle fatigue region. The most common defects of the blades were: thinning of the inlet edge, appearance of thermal fatigue cracks, and gaps. For these reasons, up to 50% of the blades were rejected. There are also cases of blade breakage (Figure 8). In this case, the surface of the blade was brown and dark gray in the fracture zone. At the fracture site, the surface of the trough and the inlet edge was burned. In addition, thermal fatigue cracks were detected on the inlet edge and on the trough side, as well as peeling of the coating. The fracture was oxidized and had a gray color of various shades. At the inlet edge at the site of the longitudinal crack formation, wall thinning to 0.1 mm or less was recorded.

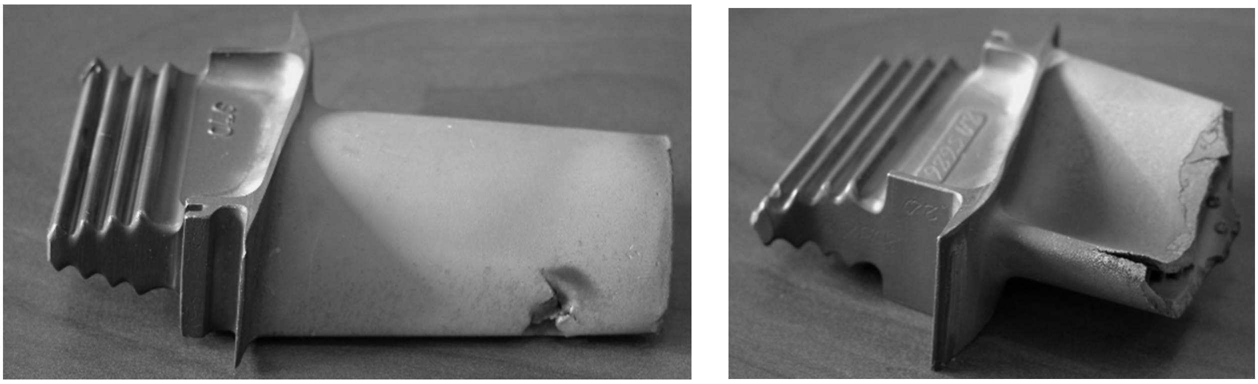

Figure 8 – Destruction of high-pressure turbine blades

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There was a "different thickness" of the walls, especially in the area of the inlet edge on the side of the trough and back. Metallographic analysis of the material showed the formation of interdendritic porosity, which contributed to the degradation of its mechanical properties and the active accumulation of thermal fatigue damage until the appearance of a main crack and its further growth. Changes in the material structure also caused unidirectional irreversible deformation of the blade.

Despite the relatively low stress values, a significant number of defects were found in the nozzle blades (Figure 9) in the form of thermal fatigue cracks in the stress concentration zones and in the area of the cooling system channels.

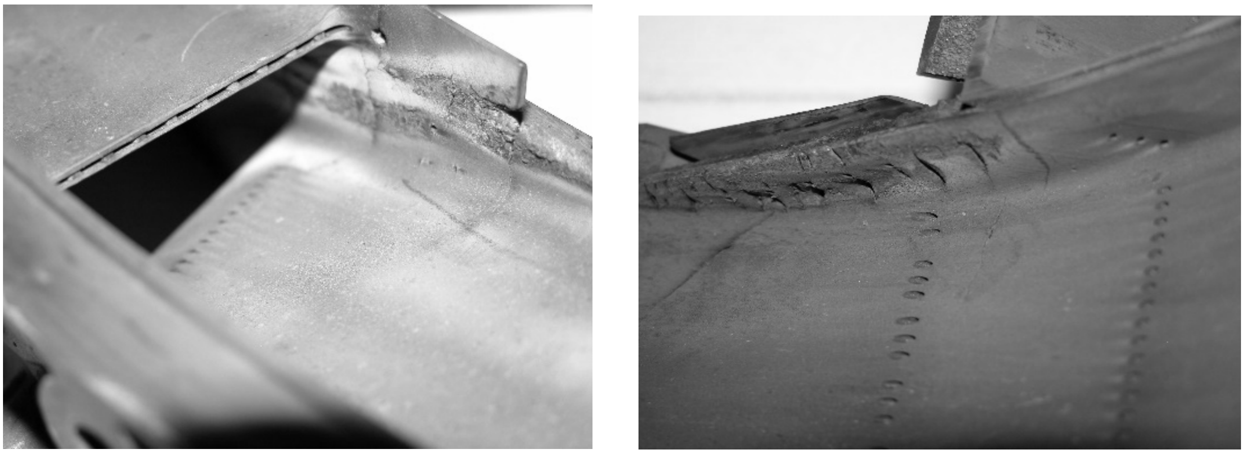

Figure 9 – Thermal fatigue cracks in the nozzle blades

The rejection statistics show that the most intensive material hardening occurs during the overhaul life, which is associated with both the accumulation of microdefects and the quality of the previously performed repairs. In addition, high-temperature wear occurred in gas turbine parts. This is observed on the surfaces of the sealing inserts that provide the required radial gap between the casing.

Other components. The structural elements of these units are particularly characterized by thermal extremes. For example, the temperature difference between different parts of the mixer can reach 200...250^{0}C. The heterogeneity of the thermal state of the part caused thermal stress and, as a result, the appearance of thermal stress cracks. Their length in the area of the holes in the base material ranged from 3 to 15 mm. Wear marks appear on the rubbing surfaces and in the hinges, thermal fatigue cracks appear in the body of the sashes, and the sashes themselves are permanently deformed.

Analyzing the results of the study of heat engine parts, it should be noted that mechanical and thermal defects (cracks, wear) are the main type of damage to parts that limit the service life.

Conclusions

The research summarizes theoretical and practical materials on the mechanisms of destruction and protection of heat-stressed reusable technical systems. It has been established that the functionality of the material decreases with service life. It is advisable to use the research results in the development and implementation of technological measures in the processes of manufacturing, repair and operation of reusable technical objects. The statistical analysis of the defecting results shows the importance of timely and high-quality diagnostic and repair work, confirms the relevance of improving the scientific basis for predicting the current and limit state (properties) of materials before and after restoration measures, as well as the introduction of effective technologies for diagnosing and restoring structural elements.

The rapid development of scientific and technological progress and the need to ensure the operability of structural elements of technical facilities in modern conditions stimulates the development of manufacturing and repair technologies, namely creation of high-quality structural materials, coatings and product material systems [9, 10, 11, 12, 13, 14, 15, 16, 17]; improvement of technologies for restoring the properties of structural elements and ensuring further safe operation; improvement of technologies for non-destructive testing of the technical condition of structural elements in the process of manufacturing, repair, and operation. Further development of technologies for diagnosing and restoring structural elements of aerospace systems, through the introduction of modern means and methods of their use, will allow to meet the growing demands of operators to increase resource indicators and reduce operating costs.