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# Application of Graph-Analytical Method of Risk Analysis "The Tree Structures" For the Study of Complex Systems Survivability by the Example of Liquid Rocket Thrusters

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**Abstract**

The article is devoted to an important topic - the assessment of survivability of complex technical systems, discusses the need to develop a methodology of forecasting reliability of complex systems on the example of liquid rocket thrusters with running a part of composite materials under actual operating conditions for their successful practical use in the propulsion systems. It is proposed to use graph-analytical method of risk analysis "tree structures" (a method of prof. Romanovsky) to predict the behavior of such systems.

**Keywords:** Complex technical systems, Graphic-analytical method for the analysis of risk, Composite materials, Liquid rocket thrusters, Risk analysis, Assessment of survivability.



**Contents**



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## 1. Introduction

The problem of determining the survivability of complex systems occurs every time a new technology emerges or an existing one being upgraded. The more complicated the system, the more difficult to get an adequate assessment of the survivability of the system using the classical probabilistic assessment. Survivability is closely associated with the risk of one of the approaches to the analysis which was proposed in [1]. In this paper, to evaluate the survivability systems is proposed to apply the graphic-analytical method for the analysis of risk "tree structures", given in Romanovsky [2], Romanovsky [3], based on operating with events. As the system under study is considered small thrust jet engine with running a part of composite materials (CM).

The first attempts to introduce composite materials as a material for small thrust jet engine combustion chamber has been made in the nineties of the last century. Some foreign developers have already implemented small thrust jet engine combustion chamber of the CM in the composition of its propulsion systems [4].

Practical implementation of the application of CM in small thrust jet engine is based on achieving the goals of survivability of such engines are not below the level of survivability of small thrust jet engine from traditional materials. In the available sources of information search works, to some extent, addressing issues of reliability with small thrust jet engine running part of the CM in actual use, not a success. A methodology of forecasting the behavior of such small thrust jet engine for their successful practical use in the propulsion systems is needed.

## 2. Materials and Methods

Small thrust jet engine (STJE) are used as the executive bodies of the control system for the orientation, stabilization and correction of spacecraft. Based on the destination for a small thrust jet engine is continuously increasing. I.e. active lifetime (15 years or more); big resources both in total operation time (up to 50 000 s or more), and in the total number of inclusions (more than 106); multimode, work in both continuous and pulsed modes of a large set with the assumption of any combination of switching times and pauses; high reliability with acceptable thermal state as when it is in continuous and pulsed modes, and during the long shutdowns. [5]

According to Standard 17655- 89 Rocket Engines for Liquids [6] reliability of liquid rocket engine (STJE) is the feature STJE maintain a healthy state under specified conditions. Usable state STJE is the state in which STJE is able to create a draft set of values and direction, fulfilling the established requirements for the values of specific impulse, the ratio of fuel components and operating conditions of the components of the roaming device. Under survivability small thrust jet engine we will understand (as there is no such term in the document) its reliability in actual use.

The main difference of the STJE from the full-size small thrust jet engine is not in the difference between the size or other characteristics, and that it is near-wall processes play a decisive role in the intra-chamber processes. You can embed the newest materials, increase the allowable temperature of the wall of the flow and thus, ultimately, to increase the specific impulse, but most likely, the most important challenges remain complex and specific problems of internal thermophysics of such engines.

Internal cooling is the main method of thermal protection of the control liquid fuel engine and is implemented through the creation of a parietal low-temperature gas curtain. The most popular among the various schemes of the curtain forming is the scheme with surface irrigation of the cylindrical portion of the combustion chamber with the liquid fuel component. Gas curtain is formed with the formation of the products of decomposition and evaporation of the fuel film liquid component (Figure 1).

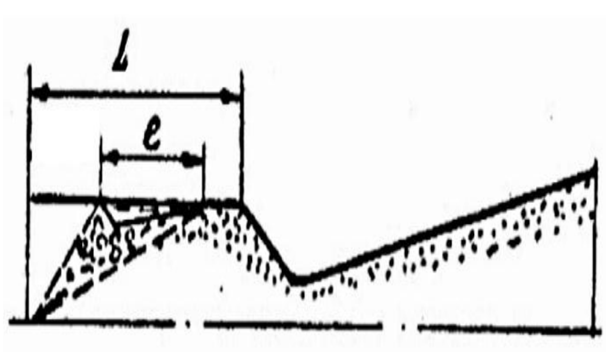

**Figure-1.** Scheme of internal cooling.

The main parameters determining the efficiency of the cooling system for the chosen fuel, flow profile of the circuit and thermal protection, can be attributed excess oxidant factor $\alpha_{ок}$, length or time of stay of the fuel in the combustion chamber, the combustion chamber pressure p*, fuel consumption, used for creation a parietal layer of low-temperature, or area chamber length ℓ irrigated with liquid fuel component. The efficiency of the cooling system is its ability to ensure the maintenance of the structure temperature within the prescribed limits at the lowest possible loss of specific impulse. [7].

Criterion for the choice of fuel consumption for the gas curtain creation is the maintainance the temperature of the wall within its operating condition. Specific impulse must correspond to the maximum value for the specific operating conditions of the engine [8].

As an example, we present the results of numerical analysis of the influence of various parameters on the thermal state and the specific impulse of the control engine fueled with unsymmetrical dimethylhydrazine and nitrogen tetroxide. Main dimensions of the turbine setting are diameter of the cylindrical portion camera - 26 mm; the length of the cylindrical portion of the chamber L = 36 mm; the length of the chamber irrigated with fluid fuel component, ℓ = 13 mm; the combustion chamber pressure p* = 0.5 MPa; the diameter of the critical section - 12 mm; diameter of the nozzle section - 176 mm; length of the supersonic part of the nozzle - 100 mm.

The analysis is performed using mathematical simulations [9] of the continuous operation of the engine.

Fig. 2 shows the effect of the coefficient of excess oxidant αок at maximum flow along the length of the temperature thermally insulated chamber wall surface T and a specific impulse of the engine J.

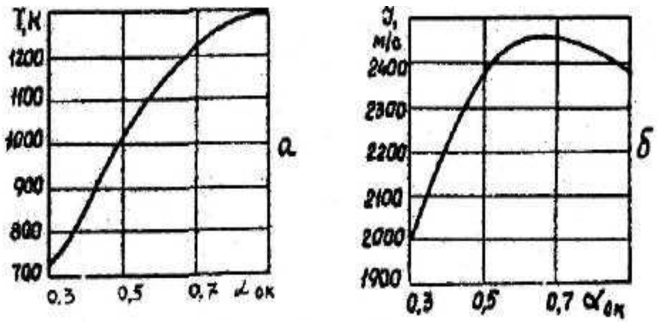


**Figure-2.** Oxidizer excess factor effect for temperature insulated chamber surface (a) and the specific impulse of the engine (b)

As can be seen, with increasing αок temperature structures also monotonically increases. At the same time, the specific impulse varies depending on the ratio of excess oxidant by a curve with maximum reaching maximum values at αок = 0.65. This is due to the fact that when there is a monotonic increase αок temperature of the combustion products also increases, and determines the increase of the wall temperature. Simultaneously, the αок change is also the change of composition and properties of the combustion products. The cumulative effect of these factors can lead to a nonmonotonic variation of the specific impulse, with its extreme value corresponds αок significantly less than that which is typical for large engines.

It should be noted that since the gradual warming up of the gas curtain and its mixing with the main stream within the flow chamber, the fuel used for the organization of the internal cooling involved in creating thrust and the specific impulse losses are comparatively small.

The main mode is the control engine pulse mode. At engine design one should take into account that while pulse mode is on, conditions for the wall overheat at the site of formation of the gas curtain to a higher temperature emerge. This overheating occurs, firstly, due to longitudinal heat flows in the chamber wall during the period of time (τр) between the engine switches (τк), where they can not be transferred in the liquid film due to her absence, and, secondly, for account of the impact of high-temperature combustion products on wall unprotected with the liquid film for a certain length of time. The latter happens due non-simultaneous termination of combustion in the chamber and the closure of the surface irrigation with fluid.

At loss of propellant occurs on the overheated wall  it is cooling and the liquid film is heated to the boiling point and evaporates.

The density of the mass flow of steam from the wall surface on the forming site the air curtain depends on the excess wall enthalpy for a certain period of time and can be greater than its critical value at which the squeezing from the gas curtain wall and its mixing with the high temperature core. Thus, for some time the existence of an organized low-temperature near-wall gas curtain is impossible. In this case only the air curtain (parietal region with a temperature below the temperature of gas in the core of the flow) works. The effectiveness of the air curtain is lower than the gas curtain effectiveness, so the values of the adiabatic wall temperature under pulsed operation of the engine will be higher than their values in continuous operation.

As an example, Figure 3 shows the distribution along the length of the flow chamber adiabatic wall temperature Tr and heat transfer coefficients α for pulsed and continuous modes of operation of the engine [10, 11]. As seen, the pulse mode is thermally heavier than continuous operation mode.

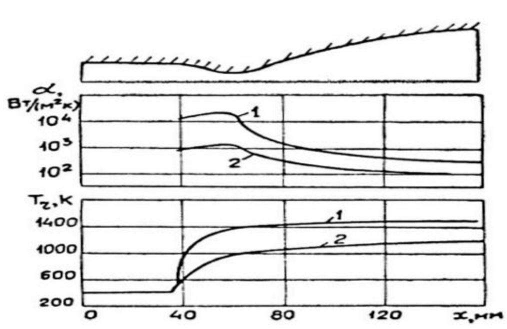


**Figure-3.** Distribution of the heat transfer coefficients and adiabatic wall temperature along the highway the engine chamber: 1 - pulse mode (τр = 0.06 s; τк = 0.04 s); 2 is a continuous mode.

To solve the problems of the organization of the chamber walls protection from overheating due to their design features, the pulsed mode of operation and the availability of powerful total convective and radiative heat fluxes to the wall are applicable: curtain internal cooling, the use of heat-resistant coatings or composite materials (CM) [12].

Materials for small thrust jet engine must work reliably in a complex combination of power and temperature fields, when exposed to aggressive environments, radiation, high vacuum and high pressures. Often the requirements for materials, can be controversial. This task can be accomplished through the use of composite materials. CM allow for a given combination of dissimilar properties: high specific strength and stiffness, heat resistance, wear resistance, thermal properties, and others. Spectrum properties of the CM can not be obtained using conventional materials. The use of CM allows you to create previously unavailable new designs [13].

MAI researchers conduct research in the field of small thrust jet engine. The possibility of using carbon-ceramic composite materials (CCCM) as the material of the combustion chamber is regarded as one of the most promising ways to improve STJE [14].

The desire to apply the composite material to create a small thrust jet engine combustion chamber is due to ensure increase of specific impulse of the engine by increasing the temperature of the combustion products and the operating temperature of the wall by changing the mixing and reduce fuel component usage on the curtain.

On the basis of fire experiments on the engine MAI-202-200 (AT+UDMH) analysis was carried out to increase the specific impulse in the case of the combustion chamber made of the CM. As a result of calculations on the experimental and theoretical model of the thermal state of the small thrust jet engine "MAI-202-200" (AT + UDMH), it was shown that the application of the new material will significantly increase the specific impulse (Figure 4).

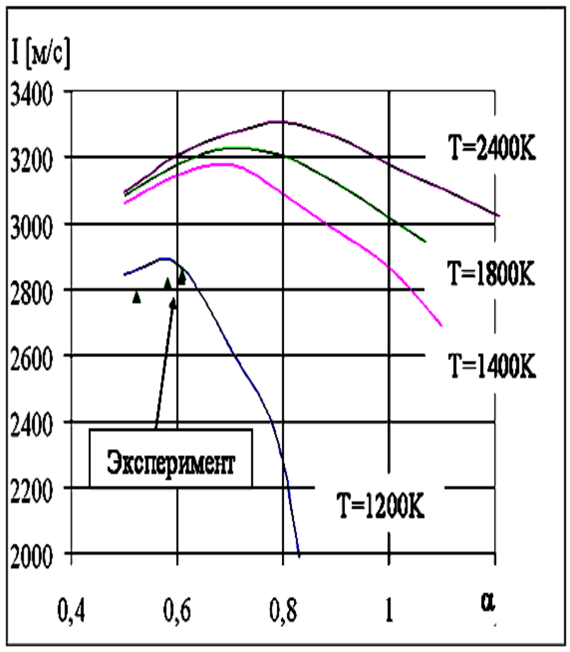


**Figure-4.** Calculated dependence of the pulse of the MAI-202-200 engine depending on the oxidizer excess coefficient for different maximum temperature of the combustion chamber wall.

Comparison of specific impulse represented by 2b and Figure 4 shows the favor of the new materials for small thrust jet engine.

## 3. Results

We now turn to the methodology of predicting the behavior of small thrust jet engine in terms of survivability using the graph-analytical method of risk analysis "tree structures" [2, 3]. To do this, we should perform an analysis of the impact of various factors on the survivability of small thrust jet engine with a flowing part of the CM on the basis of operating events.

Running state of the engine is determined by a summary state of the composite material of construction of the running part, and the response of the turbine setting for thermophysical stress (Figure 5). Under the stress of running thermophysical part we mean the total response to temperature, pressure, velocity, chemical composition of the working turbine setting of the engine.

Such problems are quite serious:

- Requirements for the connection of the "composite-metal" are high strength at high temperatures and in corrosive environments, high oxidation resistance, strength of connection issues (taking into account the heat load) [14];

- Materials based on compounds with near zero coefficient of thermal expansion (CTE) are used in devices subjected to thermal stress. In composites with the participation of such compounds can be obtained by a given CTE that allows you to create products that are not subject to destruction at the contact points of structural elements [15].

CM condition, in turn, will be determined by a set of age-related changes of CM (characteristics of the material at the specific moment of time), the reaction of CM on the impact of the environment of the engine (apologize for a certain mysticism in his address to the engine as a living creature) and the reaction of CM on thermophysical stress. About the response of a material impact on the environment: ordinary carbon in the solid state can be graphite or diamond. There is no guarantee that the composite material will not be modified in real-world conditions.

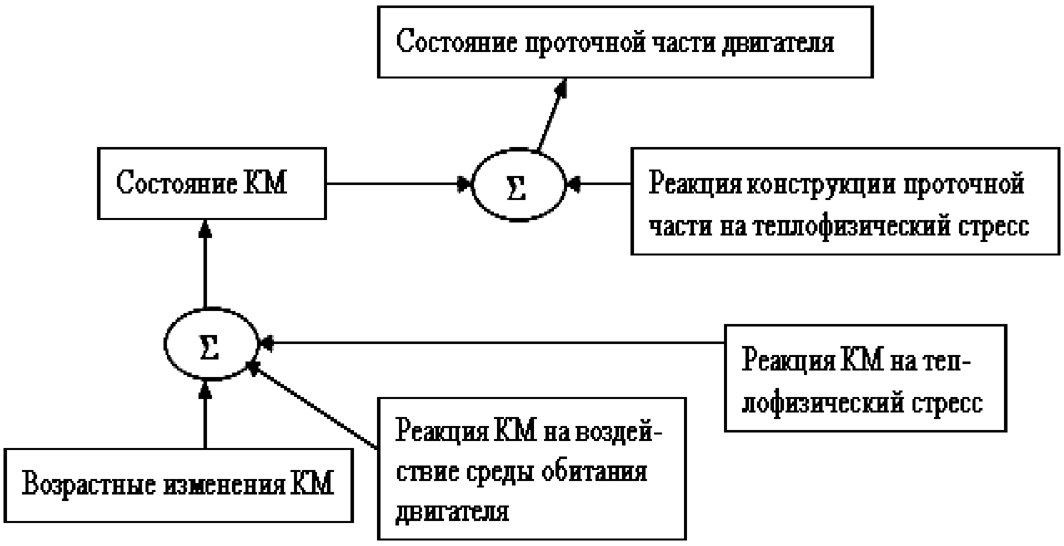


**Figure-5.** Factors affecting the conditions of the turbine setting of the engine.

Operator "set of events» (Σ) is a formal neuron [3] and has a group of synapses - unidirectional input connections and axon - the output connection. Each synapse is characterized by synaptic connection or her weight Wi, characterizing the channel capacity and evaluating the influence of the input signal to the output signal. Current state of the neuron is defined as the weighted sum of its inputs (Figure 6).

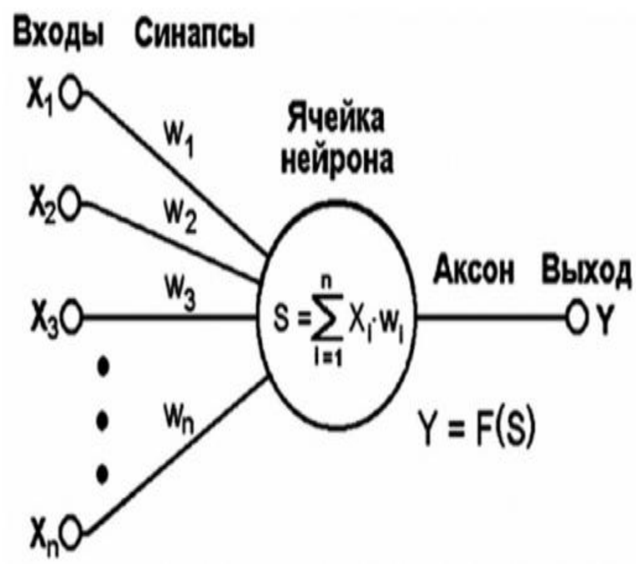


**Figure-6.** Formal neuron scheme.

In this case, the weights Wi will determine the extent to which a particular input factor, ultimately, on the characterization of the state the engine turbine setting. To quantify this state we need full information on all components - "the participants of the analysis."

Let’s consider the possible course of events in the operation of small thrust jet engine with a flowing part of the CM (Figure 7).

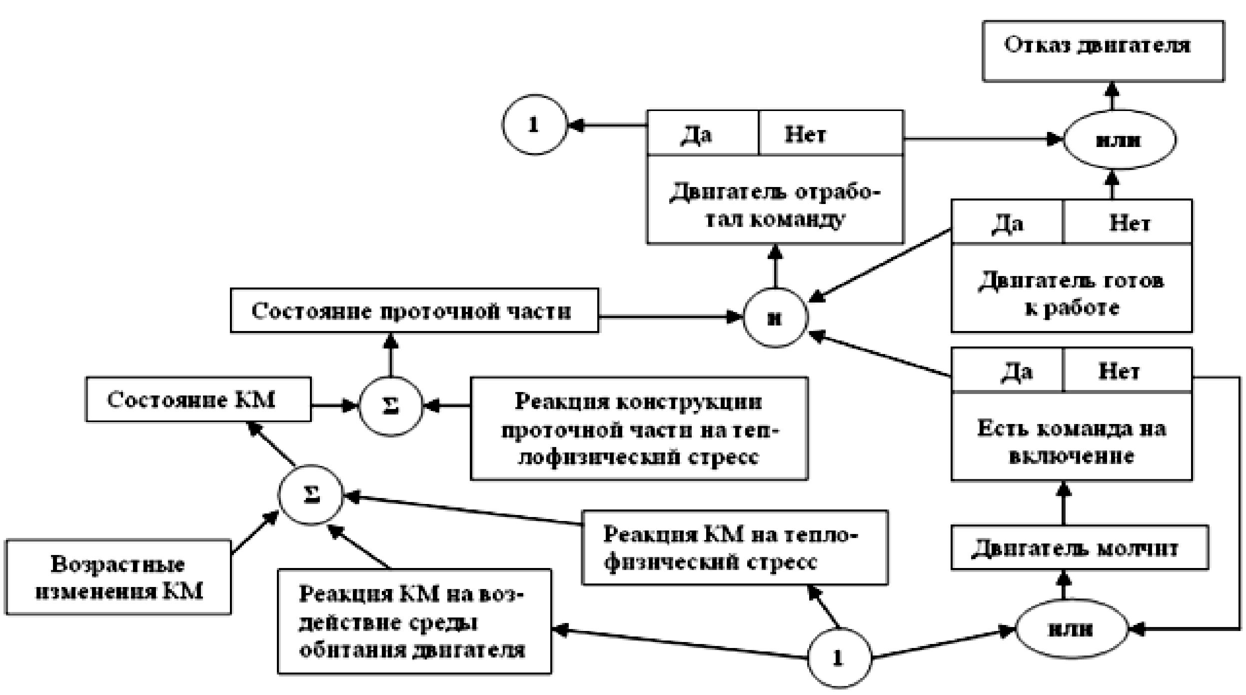


**Figure-7.** Possible course of events in the operation of small thrust jet engine with a flowing part made of the CM.

The engine is in the idle state ("silent") and if there is no activation command this mode continues. When activation command is given (work in any of the available modes), readiness of the engine to work in this mode and acceptable condition of the turbine setting motor can work out the command and return to the standby mode. In this case, the reaction of CM and the turbine setting on the overall stress on the thermophysical will follow. Further changes may occur in the turbine setting beforethe next engine activation.

If the engine is not ready or the engine did not work out the command, depending on the circumstances, it can be interpreted as a random failure or total failure of the engine.

## 4. Conclusion

Conducting probabilistic forecasting reliability of liquid rocket thrusters with running a part of composite materials under real conditions of their operation is possible with details of events [16] and the availability of information from different disciplines on the reaction of CM of the structure itself running on the internal and external influences.

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