Research into the physical and chemical properties of fire-retardant materials of structural elements of trucks running on gas engine fuel with the aim of increasing their fire-retardant efficiency

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Abstract. The fire load is an integral part of the fire hazard definition. Reducing this load is one of directions to fight fires in transport. To study the physicochemical processes and thermal effects occurring as a result of thermal decomposition of wood fire-proofed by retardants like BAN, OK-GF, OK-DS (OK-GFM), SPAD-0 and their chemical compositions, we used the methods of differential thermal analysis, thermogravimetry, and derivative thermogravimetry. In addition, to study the intensity of physicochemical combustion processes, tests to control changes in woodwork masses and temperature at the top of pipe depending on the duration of combustion of the samples and the consumption of fire retardants were conducted. Fire retardant compositions like OK-GF, OK-DS, Pirilax biopyrene at the consumption of 0.1 kg / m2 ensure flame and combustion resistance of the wood. The analysis of the research results confirmed the possibility of assigning to wood structures of a lorry's body of the group 1 of flame and combustion resistance. Using the above fire retardants and their compositions in the treatment of lodgment elements and runners significantly affects the possibility and duration of the combustion process of a lorry. This was tested by means of an artificial fire source method (without chemical treatment, the burning time does not exceed 50 minutes). This significantly improves post-collision safety of vehicles with an increased fire load in terms of fire resistance because of using the natural gas as a motor fuel.

1. Introduction
The innovative variant of the Russian Federation transport system development [1] provides for a significant improvement in the environmental friendliness, energy efficiency and safety of transport by means of changing the structure of the fuel and energy resources used. The most common type of road accidents is vehicle collisions (42.3%) [2]. In the course of commercial vehicles (CV) collision with a gross weight of more or equal to 10.5 tons (category N2), the peak (maximum) deceleration values can
reach up to 130 g on the second frame cross-member, 98 g on the cab floor, and 26.5 g on the first gas
cylinder located behind the cab [3]. And in the case of subsequent overturning of the lorry, the
maximum value of acceleration can be: 5g on the cab floor, and 6 g on the bed. In addition, today a
characteristic feature of Russian cargo fleet is a significant proportion of outdated CV models with
long service lives. With a total CV fleet of 6.48 million units [4], 78.8% of them are older than 5-10
years. In modern production and motor transport processes, new technologies are usually more fire-
hazardous [5] due to the widespread use of fire-hazardous technologies filled with fire-hazardous
substances, materials, and products [6]. These facts aggravate the accident rates of highway transport,
which accounts for 97% of all deaths in transport [7] worldwide. Road traffic accidents at the global
level [8] are one of the leading causes of death in the world and annually claim more than 1.35 million
lives, lead to injuries to up to 50 million people and are the eighth leading cause of death for all age
groups of the population.

Currently, the system for ensuring operational safety of the complex "man-car-road-environment"
includes external and internal passive safety of the vehicle [9, 10] and is regulated by a set of
normative documents GOST R, UNECE Regulations No. 29, 58, 61, 73 (Fig.1).

The fire load is an integral part of the fire hazard definition. Reducing this load is one of directions
to fight fires in transport. CV fire load determines the main indicators of a fire: the time of
development and combustion, the size of dangerous fire factors. The fire load is divided into
permanent and temporary. Permanent fire load \( P_s \) is determined by the masses of combustible and
combustion-resistant substances and materials of structures (the floor and sides of the load bed,
usually made of wood materials), aggregates and equipment of CV; temporary fire load is determined
by the masses of fuel, and cargo being transported. The temporary fire load of a gas-cylinder CV
modification will be 12.3% higher than that of a similar one with liquid petroleum fuel.[3]

Thus, based on the above, in order to formulate measures to ensure the safety of CV running on gas
motor fuel, it is necessary to conduct theoretical studies in order to assess the situation and develop
recommendations for improving fire safety by virtue of the fire resistance of GMF CV structural
elements.

2. Theoretical study
Lorry structures under heat exposure are characterized by the property of maintaining their functional
purpose (non- and load-bearing capacities) for a certain time, and the degree of participation of the
structure in the fire propagation process.

The results of tests of category N2 CV with a gross weight of 12.0 tons running on gas motor fuels
[13] by creating an artificial fire source showed that:
- complete ignition of lorries occurs not later than in 3 minutes 30 seconds - 10 minutes 30
seconds;
- safety valve of the cylinder with propane-butane mixture is triggered at a pressure of 34 kgf / cm\(^2\),
followed by gas discharge from the cylinder during 31 minutes;
- tear of the charging valve of a 50-liter cylinder in 5 minutes 25 seconds at a pressure of 260 kgf /
cm\(^2\), followed by a pressure release and natural gas discharge within 11 minutes.
- combustion process of lorries lasted up to 50 minutes.

The dynamics of ignition and combustion of CV with storage systems for liquefied petroleum
(propane + butane) and natural gases under pressure in 50-liter steel cylinders is described by the
developed phenomenological mathematical models (Table 1). They provide, with a sufficient degree
of accuracy (multiple correlation coefficient \( R = 0.95 \)), simulation of the combustion process of
dynamics of CV on liquefied petroleum or compressed natural gas over time with changing the
pressure in the cylinder and the temperature of the cylinder wall and valves, and the temperature in the
engine room.

The difference in these characteristics is manifested depending on the location and parameters of
the ignition sources. The capacity of the structure to maintain its functional purpose is characterized by
the term fire resistance, and the degree of its participation in the process of fire propagation is
characterized by the term fire hazard (fire load [11]).

Loss of non-load-bearing capacity is the heating of the structure to temperatures over those, which can cause destruction or ignition of materials on the heated surface, formation of cracks and burnouts, through which combustion products can penetrate.

Now we meet the difference between the actual $\Pi_0$ and the required $\Pi_T$ degrees of fire resistance of the structure. The actual degree is determined by the lowest actual limit of fire resistance of the structural element; the required one is the minimum degree of fire resistance that the lorry should have in accordance with the safety requirements. The safety requirements are met when $\Pi_0 > \Pi_T$.

The density is taken according to GOST 2.1.044-84 when determining the fire hazard indicators of materials in the flame $q_0 = 50 \text{ kW/m}^2$; when determining the intensity of smoke generation $q_0 = 25$ and $33 \text{ kW/m}^2$. With known values of $q_0$ and $t_{\text{пр}}$, firebreaks are determined in the event of a fire in buildings or CV. When $K<1$, the heat flux perceived by the material exceeds the limit value, and thermal destruction and ignition of combustible materials occur, as well as deformation of the skin, cabin doors and compartment covers.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Block diagram of the passive safety system: PSS - passive safety system; PSV - passive safety of the vehicle; PRS - passive road safety (road fences, injury-proof poles, etc.); PHS - passive human safety (riding hats, restraint systems, child restraint systems); C-P - car-pedestrian; C-OI - car-object of impact; C-H-RSh - car-human-restraint system for humans; C-Cargo-RScargo-H - car-cargo-restraint system for cargo-human; C-C - car-car; SO-C - stationary obstacle-car; SSSS_{GMF} - gas motor fuel storage and supply safety system.}
\end{figure}

The intumescent coating is used to increase the fire resistance limit of firewall partitions. The limits of their fire resistance are the time to reach temperatures of 413 K and 353 K under the protective intumescent coating for non-combustible and combustible materials.

The limit of fire resistance of wooden structures:

\[ \Pi = \tau_v + \tau_p, \]

where $\tau_v$ is the time elapsed from the beginning of the heat exposure to
the moment of ignition of wood;  
τп - time elapsed from the moment of ignition of the wood up to the moment the structure loses its load-bearing capacity.

Time:  
τп = δпр / ν,  
where δпр is the ultimate depth of wood charring;  
ν - the rate of wood charring.

Table 1. Mathematical model for fire simulation of cargo vehicles running on natural and liquefied petroleum gases [13]

| Subitem No. | Design features of the GMF storage system | Name of the functional dependency | Functional dependency | Note (scope of application) |
|-------------|-----------------------------------------|----------------------------------|------------------------|-----------------------------|
| 1           | Gas fuel storage system (propane+butane mixture) on a category N2 cargo vehicle | Change in the pressure of the liquefied gas (propane+butane mixture) in a cylinder, kg / cm² | \( P_{\text{press}} = (0.11t+9) \) \( P_{\text{press}} = 32e - \frac{(t-12.5)^2}{13.8} \) \( P_{\text{press}} = 9.07(t-16.5) \) | 0 ≤ t ≤ 10 10 ≤ t ≤ 12 16.5 ≤ t ≤ 30 |
| 2           | Change in the temperature of the cylinder wall | \( T_{cw} = 25.5t + 115 - \frac{(t-3.5)^2}{1} \) | | 0 ≤ t ≤ 11 11 ≤ t ≤ 36 |
| 3           | Change in the temperature of the safety valve | \( T_w = 13.4(t-2) \) | | 2 ≤ t ≤ 10 |
| 4           | Change in the temperature in the engine room | \( T_{\text{engr}} = -3.34t^2 + 160.35t - 1358.2 \) | | 11 ≤ t ≤ 37 |
| 5           | Natural gas storage system under pressure of 19.6 MPa on a cargo vehicle of category N2 | Change in the pressure in the cylinders when simulating a fire | \( P = 10t + 160 \) | |
| 6           | Change in the temperature in the engine room | \( T_{\text{engr}} = 0 \) \( T_{\text{engr}} = 80 + 190e \) | | 0 ≤ t ≤ 3 3 ≤ t ≤ 15 |
| 7           | Change in the wall temperature 1st cylinder | \( T_{\text{wall1}} = 80 + 220e - \frac{(x-9)^2}{3.66} \) | | 15 ≤ t ≤ 9 |
| 8           | Change in the wall temperature 3rd cylinder | \( T_{\text{wall3}} = 80 \) | | 15 ≤ t ≤ 9 |
| 9           | Change in the wall temperature 5th cylinder | \( T_{\text{wall5}} = 50 \) | | 5 ≤ t ≤ 9 |
| 10          | Change in the wall temperature 7th cylinder | \( T_{\text{wall7}} = 45 \) | | 6 ≤ t ≤ 9 |
The direction for solving this problem can be fire retardants that have the ability to form a foamed heat-insulating layer on the surface and release inert gases during decomposition in quantities sufficient for the outflow of air oxygen from the combustion zone. Altogether, they allow decreasing the temperature of waste gases to 140 °C to 180 °C, which provides the maximum fire-retardant effect.

Methods of differential thermal analysis, thermogravimetry, and derivative thermogravimetry were used to study the processes occurring as a result of the thermal decomposition of wood protected with BAN, OK-GF, OK-DS, (OK-GFM) and SPAD-0 fire retardants, as well as the thermal effects accompanying these processes (Fig. 2 and 3). Also, to study the intensity of combustion processes, tests to control changes in wood work masses and temperature at the top of pipe depending on the duration of combustion of the samples and the consumption of fire retardants were conducted (Fig. 2, 3, 4, 5) [12, 13].

3. Calculation part

The conducted studies of fire resistance of pine wood samples treated with fire retardants of different quality: BAN with heat treatment; wood treated with OK-GF; wood treated with OK-DS (OK-GFM); wood treated with SPAD-0 fire retardant, with recording of thermograms of thermal effects occurring in wood samples [12] showed pronounced distinctive features of the development of decomposition processes of wood treated with fire retardants, proving a different degree of its fire resistance and, accordingly, a different level of combustibility of materials, speed and depth of processes occurring in samples treated with fire retardants of different quality. The process of intensifying the thermal decomposition of wood without fire retardant treatment goes without inhibition, i.e. endothermic effects are absent; it is intensifying until the complete decomposition of the wood complex. Inhibition of wood decomposition processes by BAN fire retardant showed a shift in the processes towards a decrease in the rate of thermal decomposition, a decrease in the depth of the exothermic effect of wood decomposition compared to untreated wood. The processes of decomposition and intensification of mass loss of wood samples treated with fire retardants OK-GF, OK-DS (OK-GFM) and SPAD-0 do not have deep peak maxima, and proceed smoothly over time, which indicates the absence of large thermal effects. The approval of the results of thermal analysis methods, as well as determination of the minimum consumption of fire retardants that provide the first group of fire resistance efficiency were obtained during tests on computer tomograph according to the GOST 16363-98 method (Fig. 2, Table 2). The level of fire resistance efficiency (the group of combustibility of fire-resistant wood) was determined by the mass loss of samples after fire exposure.

During the tests, the maximum temperature of the flue gases was recorded, as well as the after-flame and smoldering time of the samples. Almost all the curves shown in Figure 4 have inflection points. These inflection points indicate the end of the effective impact of the weight gain of fire retardants on the level of fire resistance performance for each specific one. For fire retardants that are not able to solve the problem of group I of fire resistance efficiency by surface penetration treatment of wood, the inflection point (Fig. 2), dependence 1, is located in the zone of group II of fire resistance efficiency (flame-resistant wood, combustibility group B2). This shows that a significant increase in the weight gain of BAN fire retardant with surface treatment of wood, an increase in consumption of more than 0.32 kg/m² [13], does not solve the practical problem of further reducing the flammability of wood. At the same time, the inflection point for the fire retardant OK-GFM is located in the area that provides the wood with the fire-resistance effectiveness of group I, which is achieved by capillary intake of sawn wood.

Thus, the inflection points on the curves of the dependence of the wood fire resistance value on the consumption of fire retardants (FR) show that the upper part, the line up to the inflection point, is a characteristic of the effective consumption of FR, and the lower line after the inflection point characterizes the ineffective consumption of FR. As practical experience shows, for the fire retardant OK-GFM at the inflection point, the stable results are an average mass loss of 7% (5-8%), the maximum flue gas temperature of 190°C (170°÷220°C) and the after-flame and smoldering time of samples is up to 30 s.
The analysis of experimental theoretical studies of the main directions of using fire-resistant wood structures with different levels of fire-resistant efficiency in accordance with the functional features of the objects showed (Table 1):
- the proposed fire retardants are capable of providing the first fire resistance group, adequate to combustibility group B1, at low consumption and impregnation of wood material to a depth of 1-3 mm, which was previously achieved only with a high consumption of agents when full-cell pressure impregnation;
- on the basis of the ability of water-soluble fire-retardants, it is possible to create on the surface of wood impregnated with such agents, in the conditions of its ignition, a plentiful foamed carbon coat, which additively enhances the overall fire-resistance effect;
- for the formation of a foamed coal layer, it is advisable to impregnate wood with starch hydrolysates (di- and monosaccharides) obtained in the presence of phosphoric acid, followed by the use of phosphorus-nitrogen-containing antipyrins (ammonium phosphates, dicyandiamide, carbamide, hydroxylamine sulfate, etc.);
- in the considered works [12, 13], the features of the foaming of antipyrins under the influence of a heat flow of a constant density of 35 kW/m² on wood were studied;

![Figure 2](image-url) **Figure 2.** Curves of changes in the mass of fire-resistant wood during tests according to GOST 16363-98 depending on the quality and quantity of antipyrins [13]: 1-wood, fire-protected by the BAN composition; 2-wood, fire-protected by OK-GF; 3-wood, fire-protected by OK-DS; 4-wood, fire-protected by OK-GFM.

The proposed fire retardants OK-GF and OK-DS and their modified compositions A and B already at consumption of 0.1 kg / m² can provide flame resistance, and the modified composition B based on (Pirilax) can provide combustion resistance of wood. The proposed modified compositions (A) and
(B) are close to the fire retardants OK-GF, OK-DS, and (C) – is close to the action of the biopyrene Pirilax. But here, in contrast to the Pirilax composition, not a thermally insulating film is formed, but a thermally insulating intumescent coating, the thickness of which increases with increasing temperature. Also, unlike Pirilax, in the samples treated with modified composition B, the loss of mass is much smaller (Fig. 3).

Tests on the Fire Tube stand show the behavior of control samples made of unprotected wood and samples modified with the obtained compositions in the flame of a gas burner (Fig. 4 and 5).

Tests for combustibility showed that the compositions (OK-GF) and (OK-DS) at consumption of 0.3-0.4 kg/m², (Pirilax) at 0.1-0.3 kg/m² transfer wood to the group of low-flammable materials.

Based on the multifunctionality of the use of fire-protected wood materials and wood structures, high-performance fire retardants; they contain, in alia [13]:

- orthophosphorous acid, starch hydrolysates, hydrogen phosphates, ammonium and hydroxylamine sulfate;
- orthophosphorous acid, starch hydrolysates, dicyandiamide and ammonium sulfate;
- orthophosphorous acid, starch hydrolysates, dicyandiamide and urea;
- orthophosphorous acid, starch, formaldehyde, dicyandiamide and urea.
### Methods of experimental research of fire-protected wood materials

| Methods of experimental research of fire-protected wood materials | Marking of fire retardants used to treat wood materials |
|---------------------------------------------------------------|------------------------------------------------------|
| Wood BAN OK-GF OK-DS OK-GFM SPAD | 2 | 3 | 4 | 5 | 6 | 7 |
| GOST 16363-98: weight loss, % | 90-95 | 15.9 | 9 | 9.7 | 9.7 | 9.75 | 9.75 |
| GOST 30244-94, combustibility group for surface treatment of wood | B3-B4 | B2 | B1 | B1 |
| GOST 12.1.044-98, GOST 30219-95, combustibility group | G | TV, TG | TG-1C | TG-1C, 1B | TG-1C, 1B, TG-1C, 1B, 1A |
| Methods of thermal analysis: differential thermal analysis, exo and endo effects, °C; | 338 | 250 | 255 | 255 | 245 | 245 |
| Method of thermogravimetry, weight change, %; Method of derivative thermogravimetry, endo-effects, °C | 68 | 53-55 | 43 | 41 | 41 | 41 |
| Original method for determining the electrical resistance of coal, $\text{Ohm}$ | 10$^{6}$-10$^{7}$ | TV-3-10$^2$-4-10$^3$ | TG-5-10$^3$ | 9-10$^4$ | 5-10$^3$ | 3-7-10$^3$ |
| GOST 12.1.044-89: Flame Propagation Index | More than 70 | More than 20 | Less than 70 | 10-0 | 10-0 | 10-0 |
| GOST 12.1.044-89: Smoke generation, m$^2$ / kg (moderate at 50-500 m$^3$ / kg); | 717 | Less than 2 | Less than 500 | Less than 500 | 205 | 273 |
| Toxicity of the products of combustion, hazard class | 2 | 3 | 3 | 3 | 3 | 3 |
| Sanitary and hygienic properties, hazard class | 3 | 3 | 3 | 3 | 3 | 3 |
| Biosecurity, threshold absorption, no more than 10% | More than 60 | Less than 10 | Less than 10 | 5.3 | Less than 10 |
| Corrosive aggressiveness: g/m2 days, less or equal to 4; mm / year, less or equal to 0.099 | 26 | 21 | 1.41 | More than 2 | 0.066 |
Figure 4. Dependence of the weight loss of control samples, as well as modified with compositions (A), (B), (C) on the combustion time: 1-curve that characterizes the properties of non-treated pine wood; 2, 3, 4-curves that characterize the properties of pine wood modified with compositions (A), (B), (C) at consumption of 0.4, 0.4 and 0.3 kg / m$^2$

4. Conclusions

The considered results of differential thermal analysis, thermogravimetry, derivative thermogravimetry, change of wood work weight and combustion temperature at the top of pipe depending on the duration of combustion of the samples and the consumption of fire retardants BAN, OK-GF, OK-DS (OK-GFM), SPAD-0 ensure flame and combustion resistance, which confirmed it possible to assign wood structures of a cargo vehicle body with the 1st fire-resistant efficiency material group.

The proposed highly effective fire retardants BAN, OK-GF, OK-DS (OK-GFM), SPAD-0 are characterized by the technological capacity of treating wood materials and allow processing fire protection on the site of an auto-transport enterprise right aboard CV when it is reequipped to work on GMF, with minimum equipment, with high speed and good quality. The use of complex and energy-saturated technological processes of full-cell pressure impregnation, for example, in autoclaves according to the "vacuum-pressure-vacuum" method is excluded.

Using the fire retardants above in the treatment of the elements of the flat body and runners have a significant impact on the occurrence and duration of the combustion process of a lorry during testing of creating artificial fire source (without treatment the combustion duration is not more than 50 minutes [14]). This will significantly improve post-collision safety and fire resistance of vehicles using the natural gas as a motor fuel and will require testing to adjust phenomenological mathematical
models.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{temperature_graph.png}
\caption{Dependence of the temperature at the top of the pipe on the combustion time of the samples: 1-curve that characterizes the properties of non-treated pine wood; 2, 3, 4-curves that characterize the properties of pine wood treated with modified compositions A, B, C at consumption of 0.4, 0.4 and 0.3 kg / m².}
\end{figure}

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