Experimental studies of the process of initiation and spread of the dangerous fire factors while burning of the tube stock in the tunnel

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Abstract. The present article is concerned with the analysis of the experimental results performed with full-size large-scale prototypes of tube stock in subways in case of the fire in the tunnel. The process of the fire spread in the passenger compartment and along the tube stock is investigated.

1. Introduction
The experience of subways operation provides evidence that the fires in them occur rather regularly, while in case of the operational imperfections and the absence of required level of the fire protection the fires can result in catastrophic consequences, accompanied by mass mortality of the people and large material loses.

Dangerous factors of the fire (DFF) affecting the people and assets include [1]:
1) Flame and sparks;
2) Heat flow;
3) increased temperature of the environment;
4) increased concentration of the toxic combustion products and thermal decomposition;
5) Reduced concentration of oxygen;
6) Decrease of visibility in the smoke.

Dangerous factors of the fire, according to [2] include:
- increased temperature;
- smoke;
- reduced concentration of oxygen;
- toxic combustion products and products of thermal decomposition.

Critical duration of the fire is determined as achievement by one of the DFF its ultimate value.

From the obtained results of the calculations or the experimental investigations of the values concerned with the critical duration of the fire the minimal one is chosen.

The data known from the literature [3] mean that the main reason of combustion of the tube stock in the subway is malfunction of the electrical equipment.

Therefore, as the possible points of the fire appearance the following ones were adopted:
- operator’s cab of the tube stock;
undercar equipment.

The most characteristic transit vehicles in Russia are those ones finished with plastic. Therefore, below we consider experiments performed only with this material.

The object of investigations is the process of the fire spread along the tube stock in the single-track in the interstation tunnel of subway and conditions of DFF formation at the escape routes. By the implementation of the full-scale experiments in the experimental tunnel and using methods of physical modeling it was investigated the process of the fire spread into the cabin of the transit vehicle as well as along the tube stock [4, 5]. In addition, temperature measurements were performed as well as gas analysis of the combustion products.

In order to study possible ways of the fire spread into the transit vehicle and its affect on the partition the flame experiment was performed inside the operator’s cabin of the transit vehicle of «E» serial number. For combustion of the cabin 0.5 kg of cotton waste and 1 liter of kerosene were applied.

Development of the fire occurred in the following way:
- 1-2 min – emission of smoke into the passenger cabin over set-in of the door;
- 7 min – increase of the smoke emission into the passenger cabin;
- 17 min – intensive smoke emission into the passenger cabin;
- 26 min – flame yield into the passenger cabinet (under the ceiling);
- 28 min – destruction of the windshield in the operator’s cab;
- 31 min – falling down of the burning of ceiling lining in the passenger cabin.

According to the description of the experiment one can assume that in the period from 7-17 minutes both as in the passenger cabin as in the tunnel attaining of the critical DFF values happened: loss of visibility, reduced concentration of oxygen and formation of the toxic combustion and thermal decomposition products.

In other experiments [6-9] 1 kg of cotton waste wetted in 0.5 liter of kerosene was applied as a combustion source. Air flow rate of 1.5 m·s⁻¹ was provided with the help of ventilation installation mounted in the butt of the tunnel. Four fire experiments were performed in the tunnel full-sized mockup; in each of them operators cabin was stuffed with different fire load.

### 2. Results of experiments

A distinctive feature of these experiments from the previous ones was the fact that fire-resistant partition was placed between the operator’s cabin and passenger cabin, that prevented DFF spread to the passenger compartment of the transit vehicle. However, destruction of the wind-shield in the operator’s cabin resulted in formation of the DFF in the tunnel and in the transit vehicle.

Insignificant excess of temperature about 60 °C during 5 minutes in the tunnel was registered in the experiment at the level of operating zone opposite the first door of the injured transit vehicle relative to the seat of fire. However, no crucial value of temperature was attained in this experiment. The value of 70 °C was taken as a crucial one in accordance with [2, 10].

Moreover, while performing the experiments a dynamics of spread of the toxic substances by escape routes was studied. The following toxic substances were analyzed: CO, HCN, HCl. In the experiment the values of CO concentration were determined exceeding that one maximum permissible concentration (MPC) in the case of accident. It was implied that MPC for CO in this case was adopted as that one if a man can escape from the dangerous area and take part in the accident elimination [11 - 13]. For example, inside the injured transit vehicle the crucial MPC level for CO was attained at 16.5 minute, while in the tunnel at the juncture of the injured and adjacent transit vehicles it was attained at 25-th minute. At the same time no MPC level of CO was attained at the escape routes.

The values of HCN and HCl concentrations inside the cabin of injured transit vehicle (33.0 mg·m⁻³ and 33.0 mg·m⁻³, respectively) and in the tunnel (28.0 mg·m⁻³ and 35.0 mg·m⁻³, respectively) already in the first ten minutes indicate at the possibility of dangerous effect of these substances on the people during the fire. For example, at the concentration of HCN 24.0 – 48.0 mg·m⁻³ there appear symptoms of slight intoxication (dizziness, head-ache, nausea, vomiting) in case of the inhale for several minutes, while for concentration of HCl of 7.5-15.0 mg·m⁻³ – insignificant irritation of the eye mucous tunic...
and respiratory tracts occurs, while at HCl concentration of 52.5 mg·m⁻³ – an irritation of upper airways happens [31]. At the same time content of HCl is regulated [2] and its values in the experiment exceed maximum permissible content (MPC).

While combustion of the under-carriage equipment inside full-size tunnel mockup accumulator box was taken as a combustion source representing the largest fire load in the under-carriage equipment (92.4 kg·m⁻²).

Just as in the first variant temperature, fields and composition of the gas environment in the injured, adjacent transit vehicles and in the tunnel studied for the fire-resistant design of the field.

Results of the experiment demonstrated that the maximal temperature at the distance of 1.5 m from the floor of transit vehicle (thermocouple was placed just above the fire set area) was attained for 24 minutes and its maximum value (60 °C) was below the crucial one, as determined in [2]. In the other points of measurements, the temperature did not exceed 40 °C.

From the viewpoint of support of the safe evacuation in this experiment a special interest is connected with formation of the toxic gases concentration.

Figure 1 represents data on CO concentration at the escape routes. As it is seen from the represented data concentration of the toxic gas is not especially dangerous while the passenger’s evacuation. Analysis of results concerned with the changes of HCN and HCl concentrations at the certain parts, showed that:

- HCN concentration for the first ten minutes inside tunnel is much smaller the accident MPC, that is of 16 mg·m⁻³ [11] under isolated effect on a human for 15 minutes;
- the changes of HCl concentration within the first ten minutes near the injured transit vehicle did not go beyond the permissible limit [31]. Near adjacent transit vehicle HCl concentration at the 15-th minute of a stable combustion of the accumulator box and wire insulation increased up to 55 mg·m⁻³, that is as more than twice bigger than the value set in [2].

![Figure 1](image)

**Figure 1.** Change of CO concentration at the escape routes during the fire in the under-carriage equipment: 1 - CO concentration in the cabin of the injured transit vehicle; 2 – CO concentration inside a tunnel at the juncture of the injured and adjacent transit vehicles; 3 – crucial value of CO concentration, equal to 1,16·10⁻³ kg·m⁻³ [2]; 4 – value of the accident MPC for CO, equal to 0,6·10⁻³ kg·m⁻³ [14].
Results of experiments on the content of HCN and HCl in the gas-air environment of the transit vehicle cabin and tunnel are limited and they do not give ideas on the concentration fields and spread rate of the gas. Nevertheless, the largest values of HCl concentration of 55 mg·m⁻³ from a number of those ones measured in the experiments make evidences concerning possibility of its harmful effect on the people in case of appearance of the real fire.

In the study of the floor fire-resistance for the transit vehicle «E» the wooden accumulator box was used as a fire load of the simulated fire seat.

The firing was performed with the use of 1 kg of the cotton waste wetted with 1,5 litres of kerosene and placed on the boxes of the storage batteries. Combustion was developed in the following way:

1 min – smoke emission from combustion of the cotton waste;
6 min – smoke emission from under the settee;
7 min – smoke penetration from under the transit vehicle into the cabin through the passing unit of conduit;
13 min – combustion of the wooden details of the box;
19 min – formation of the cross crack in the floor cover just above the fire seat and smoke emission from the crack;
20 min – release of the flame out of the transverse sizes of the transit vehicle;
21,5 min – combustion of the paint on the transit vehicle;
23 min – деформация floor deformation above the fire seat;
30 min – visibility inside the cabin towards partition is about 10 m and so on.

Results of experiments demonstrated that at the time of attaining maximum temperature values coating of the floor from the cabin side was heated up to 250-270 °C in several points. An intensive thermal decomposition of the plywood takes place in this moment of time with a considerable smoke emission. Decrease of the oxygen content in the cabin was of 2%, while content of carbon oxide was of 1 %, that is quite permissible for the safe escape of passengers. Combustion went beyond the sizes of the transit vehicle, next, the paint caught fire on the side surface, the temperature at 100 mm from the surface of the door attained 400-500 °C, that makes it impossible to pass this part of the route in the tunnel by passengers along the injured transit vehicle. Change of temperature at 100 mm from the surface of the door in the lower area is presented in figure 2. As it is seen from the data presented in the figure, the crucial value of temperature was attained to the 15-th minute after beginning of combustion.
Next object of the study was the process of fire development in the tunnel. Temperature conditions were investigated by the results of fire experiments with transit vehicles in the mockup of the part of tunnel of М1:1 size. Thermocouples were arranged in the tunnel mockup at the height of 1.5 m above the level of track concrete that corresponds to the level of the operation zone. The doors of injured transit vehicle were opened from the side where thermocouples were arranged. Patch array of thermocouples at the escape routes inside the tunnel is presented in figure 3.

Figure 2. Change of temperature at 100 mm from the surface of the door in the lower zone: 1- temperature at 100 mm from the door surface in the lower zone; 2- crucial value of the temperature.

Figure 3. Patch array for thermocouples at the escape routes in the tunnel: – ventilation installation; 2 – tunnel mockup; 3 – fire seat; 4 – partition; 5 – cabin of the transit vehicle; 6 – thermocouple; 7 – number of thermocouple.
Air flow inside a mockup was provided by the ventilation installation with a dispenser of the flow. The mean air flow rate in the mockup of a tunnel was specified from the range of the mean air flow rate values in the tunnel for the case of subway train stop.

The change of temperature at the escape routes in the tunnel during the fire inside the operator’s cabin is presented in figure 4.

Consideration of these experiments demonstrates that dangerous temperature (70 °C and above) emerged beginning from 4,8 minute. To the 13-th minute an increase of temperature up to its crucial value occurs at the juncture of the injured and adjacent transit vehicles.

In what follows the objects of investigation were also the temperature conditions of the real fire in the tube stock. Experiments were performed at the full-size and full-scale mockups. Temperature and aerodynamics measurements were made. It should be noted that the phase of fire spread along the transit vehicle was eliminated in practice since the source of fire was cotton waste wetted with kerosene uniformly distributed over the floor of the transit vehicle. As a result of investigations a mathematical model of the tube stock in the railway track tunnel was developed [15]; this allowed performing of the calculations for a large number of the fire variants in a dependence of the point of its development, ventilation regime, the rate of the fire spread, fire load and so on. This model is in a rather good agreement with the results of experiments.

![Figure 4](image)

**Figure 4.** Change of temperature at the level of operator’s zone in tunnel during the fire inside the operator’s cabin: 1 - 9 - numbers of thermocouples; 10 – crucial value of temperature.

### 3. Conclusions

Analysis of the results for the performed studies does not allow revealing of the determining DFF and the time of attaining the crucial value. On the one hand, it is explained by different tasks assigned during the work execution, while on the other hand it is due to the conditions of the experiments. However, basing on the results of experiments it is possible to formulate the following conclusions:

- most dangerous from the viewpoint of providing safe escape of the passengers is the fire inside the operator’s cabin (hardware module);
- if the fire in the operator’s cabin occurs, DFF determining the crucial duration of the fire proves to be temperature;
- one should consider the fire inside the operator’s cabin as the fire development with the most rigid dynamics;
- under fire spread inside the cabin at the part of a tunnel (in the passage between the tunnel wall and transit vehicle) a higher temperature was observed in the areas of the open doors as compared with the other sections, as well as its increase in the tunnel with advancement of the flame front along the cabin of the transit vehicle. Therefore, the required time for escape of the passengers at the initial stage of the fire should involve the time of DFF blocking for the area including the cabin of the transit vehicle and the tunnel within the size of this vehicle.

References
[1] Technical regulations on fire safety requirements. Federal Law No. 123-FL Russian newspaper Federal issue 4720 of 01.08.2008
[2] Fire safety. General requirements 1996 GOST 12.1.004-91 (Moskow: Publishing House of standards)
[3] Ilyin V V, Fedorov A I and Grigorieva I N 1984 Fire load intensity and heat release of subway structures Fire protection of underground structures underground: Sat. scientific. Ti pp 11-20
[4] Krasnikov A V, Kulev D H, Fedorov A I and Getzevich A V 1986 The composition of combustion products of the basic materials of the subway cars Association. protection of underground. the facility has been established. of subways pp 5-8
[5] Belyatsky V P, Makhin V S and Baklanov I G 1990 Development of a fire in the rolling stock of the metro pp 26-9
[6] Makhin V S 1990 Fire hazard of all-metal passenger cars pp 43-52
[7] Efimov S G, Bakanov I G and Fedorov A I 1990 Fire tests of passenger cars pp 52-61
[8] Negodaev G D 1990 The formation of dangerous fire factors in the passenger car Fire podvig pp 61-8
[9] Makhin V S, Lickin V S, Krasnikov A V and Vakilov I G 1991 The formation of dangerous factors of fire during combustion of rolling stock in tunnel subway pp 111-8
[10] Merkushkina T G and Timoshenko V N 1988 Justification of the safety factor in determining the necessary time for evacuation of people A systematic study of fires and organizational problems of fire safety
[11] Stec A and Hull R 2010 Fire Toxicity Woodhead Publishing 728 p
[12] Popov V V 1995 Fire prevention measures for subway rolling stock by means of self-acting powder extinguishers Fire Safety Journal 25(2) p 183
[13] Dyakov VV 1996 Use of ventilation flows for delivery of fire extinguishing agents in fires in subway tunnels Fire Safety Journal 26(2) p 188
[14] Galea E R 1998 A general approach to validating evacuation models witch an application to EXODUS Jornal of Fire Sciences 16(6) pp 414-36
[15] Ageev P M 2012 Development of models and methods for studying the processes of fire development at metro stations // Dissertation for the degree of Candidate of Technical Sciences p 148