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Fire extinguishers for manned spacecraft

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ABSTRACT

Based on an analysis of fires in the oxygen-enriched atmosphere conditions in spacecraft and other sealed chambers of various purposes, the most dangerous groups of fires are identified. For this purpose, groups were compiled to analyze dependences that describe the increase of fire hazard to a critical value.

A criterion for determining timely and effective fire extinguishing was offered. Fire experiments in oxygen-enriched atmosphere conditions were conducted, and an array of experimental data on the mass burning rate of materials and their extinguishing by water mist was obtained.

Relationships colligating an array of experimental data were offered. Experimental and analytical studies were taken as a basis for hand fire extinguisher implementation for manned spacecraft.

1. Introduction

Manned spacecraft are objects of increased fire hazard due to the presence of an oxygen-enriched atmosphere, as well as a large number of potential ignition sources (e.g., electrical equipment, and electrical wires) and combustible, mainly polymeric materials (e.g., insulation and finish coatings, clothes, and bedclothes). The oxygen-enriched atmosphere reduces the activation energy for materials to ignite and significantly increases several fire hazard parameters, e.g., flame propagation velocity, and burnout velocity. Thus, more stringent requirements are needed for the effectiveness, speed and reliability of fire extinguishing.

The high speed with which fire spreads in such conditions usually leads to tragic consequences, including deaths [1–6].

This work [1,2] presents information about several fire accidents in medical altitude chambers and other sealed chambers. As a result of these fires, 29 men have perished, many people have received severe burns, and unique and expensive equipment has been out of order. In a number of cases, rescue activity was unsuccessful because of the high speed of the fire [2,4]. Three astronauts from the USA perished on the 27th of January 1967 during ground testing of the command module of the "Apollo" program as a result of fire in an oxygen-enriched atmosphere.

2. Substantiation of the most hazardous fire

Analyzing the data on the above mentioned fires shows that in spacecraft and other sealed chambers, fires can be divided into two groups: fires of flammable structural materials and fires of clothes on a person.

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The first group of fires (burning of materials) leads to progressive hazards, e.g., increase of medium volume temperature in a sealed chamber, increase of gas toxicity, and loss of visibility due to smoke. The progression of any of these hazards up to critical values creates conditions that are incompatible with human life.

A critical conditions access time can be calculated by solving the heat balance equation and mass balance equation. Specifically, the heat balance equation describing a medium volume atmosphere under temperature change T [7–9] has the form:

$$C_v \cdot \rho \cdot V \cdot dT/d\tau = W(\tau) - \alpha \cdot S \cdot (T - T_{н}) \qquad (1)$$

where C_v is the gas specific heat at constant volume inside the atmosphere of sealed chamber; ρ is the gaseous atmosphere density; V is the volume of a sealed chamber; S is the heat-absorbing area in sealed chamber; α is the effective heat-transfer coefficient; $T_{н}$ is the initial temperature of the environment and $W(\tau)$ is the functional relationship between heat generation in fire ignition and time τ.

The nondimensional temperature is $\theta = (T - T_{н})/(T_{кр} - T_{н})$, and Eq. (1) is transformed to the form:

$$d\theta/d\tau = W(\tau)/Q_{ад} - \theta \cdot \tau_{ад} \qquad (2)$$

where $Q_{ад} = C_v \cdot \rho \cdot V(T_{кр} - T_{н})$ is the quantity of heat required to create critical conditions in the absence of heat emission; $\tau_{ад} = \alpha \cdot S/C_v \cdot \rho \cdot V$ is the characteristic time of heat removal and $T_{кр}$ is the critical temperature of an environment.

The solution of Eq. (2) has the following form:

$$\theta = 1/Q_{ад} exp(-\tau/\tau_{ад}) \left[\int W(\tau) exp(-\tau/\tau_{ад}) d\tau + C_1 \right] \qquad (3)$$

The constant of integration C_1 can be defined from the initial condition: $\tau = 0$; $\theta = 0$. The critical conditions access time $\tau_{кр}$ is calculated from the solution of Eq. (3) when $\theta = 1$. If $Q_{ад}$ и $\tau_{ад}$ are equal for different sealed chambers, time values $\tau_{кр}$ are also equal in analogous fire conditions. This postulate may be used for fire testing on real models.

Changes in oxygen, toxic gases and smoke concentration are described similarly due to the similarity of heat and mass transfer in a sealed chamber atmosphere.

Fire hazard versus time relationship for a range of sealed chambers with volumes from 3 to 75 m^3 can be defined from the above mentioned equation solutions. The calculations show that while a fire burns in a sealed chamber, the toxic gases concentration limit is achieved first. Next, staff incapacitation occurs in consequence of overheating of the organism or inspired air inhalation burns. Loss of visibility because of smoke contamination and oxygen reduction occurs slightly later.

Because the known sealed chambers are equipped with individual respiratory protection, the impact of fire hazards to humans through the respiratory tract can be excluded from further analysis. Next, the most dangerous fire hazard within the sealed chamber is a medium volume temperature increase above the critical level, that is, above 70 °C (343 K).

The second group of fires (burning clothing on the body) leads to skin burns. When the skin burn surface area exceeds a critical value, it provides conditions for human death.

The limiting values of burn surface area and the calculation methodology of their formation time are described in studies [4,10]. Analysis of the data shows that the local action of flame on skin causes a dangerous burn much faster than general human body overheating. Under conditions of oxygen-enriched air, the time essentially depends on the pressure and oxygen content of air. In a number of cases, it can amount to several seconds.

3. Fire-extinguishing means efficient use criterion

The efficient use criterion for fire-extinguishing in a sealed chamber is saving people's lives. Adherence to the following inequality is necessary for the fulfillment of the condition:

$$K_1 \cdot \tau_{кр} > K_2 \cdot (\tau_{\Sigma} + \tau_{туш}) \qquad (4)$$

where $\tau_{\Sigma} = \tau_{обн} + \tau_{ин}$ is the time from flame appearance to extinguishing agent supply in a sealed chamber; $\tau_{обн}$ is the time needed to find a source of ignition; $\tau_{ин}$ is the time needed to activate fire-extinguishing means; $\tau_{туш.}$ is the time needed to extinguish a source of ignition; $\tau_{кр}$ is time, needed to achieve critical fire hazard values in a sealed chamber; K_1 и K_2 are reserve coefficients, whose values are greater than unity (they consider ambiguity of critical conditions time determination and fire extinguishment time).

The inequality (4) should be generated for the two groups of the most dangerous fires mentioned above.

For local fire-extinguishing means, time $\tau_{\Sigma л}$ depends on the speed of identifying the source of the fire and the time required by the operator to prepare for use. If local fire-extinguishing means are located close (nearly 4 m) to the fire source, time $\tau_{\Sigma л}$ differs slightly from the analogous time τ_{Σ} for conditions of a water spray fire-extinguishing unit used in a medical altitude chamber [11]. The last is listed in Table 1.

In relation to clothes ignition, a minimum time of hazardous burn formation and burn surface area ($\tau_{кр.1}$, $S_{кр.1}$) correspond with the free burning of cloth oriented upright. For sealed chambers, the time $\tau_{кр.1}$ can be calculated according to the study data [10]. We can take a maximum surface area of fire ignition $S_{кр.1}$ as 0.45 m^2, considering certain reserves. This value corresponds with hazardous burns from the closest double-layer cloth of a form-fitting garment. The data let us define from inequality (4) the maximum fire extinguishing time needed for firefighting on human clothes.

Table 1

No.	Atmosphere pressure, MPa	Gaseous atmosphere composition, oxygen concentration, vol% .	Time, τ_{Σ}, s	Sprinkling intensity I, kg/(m^2c)
1	Under 0.4	N_2–O_2, 23%	14	0.15
2	From 0.4 to 0.8	–	10	0.3
3	From 0.8 to 1.1	–	7	0.48