REMOTE EXTINGUISHING OF LARGE FIRES WITH POWDER AEROSOLS

Mikhail Krasnyansky, Independent Scientist, PhD (USA)

Abstract

A new method for distant extinguishing of fire spreading in an extended closed volume such as a mine working, storehouse, subway tunnel, electric cable channels *etc is proposed. A novel extinguishing agent based on a stable mixture of superfine ammonium phosphate [$NH_4H_2PO_4$] (or ammophos) and modified fumed silica (or aerosil) [SiO_2---CH_3] is supplied to the fire by a powerful ventilator. The properties of the extinguishing agent (average particle size, airborne residence time, distance of transfer by the air stream) have been studied in an experimental chamber (100 m^3). A test extinguishing of a large-scale fire has been performed in an experimental tunnel 180 m in length. Extinguishing agent consumption, dynamics of temperature change over the tunnel length and composition of fire gases were recorded in this test. The influence of foam concentration, addition of nitrogen and halons to aerosol, were also studied.*

<u>***Key words***</u>*: powdered aerosol, distant extinguishing.*

1. Introduction

Extinguishing large fires in industrial objects such as mine workings, subway tunnels, electric cable channels, storehouses etc. is a complicated problem. Firstly, it is difficult to approach such fires closely and hence the task of remotely supplying fire-suppressants arises. Secondly, extinguishing an established large fire requires a continuous supply of fire-suppressing agent over a long period. For this reason, neither manual nor automatic fire-extinguishers may be used in such cases. If an underground fire is not suppressed by automatic or other means within the first 10-12 hours, it may carry on for many years [1].

Aerosols, prepared by combustion of special pyrotechnic compositions, have been increasingly used for fire extinguishing during the past five years [2]. Automatic systems using them have proved to be very effective in fire protection in small closed volumes. However, pyro-aerosols produce large flame-ejection and high temperature combustion products. Besides, they cannot be used to extinguish class "A" fires (e.g. smoldering wood, rubber, coal etc), as they do not produce a polyphosphate layer able to insulate hot surfaces. This insulating effect is particularly beneficial when ammonium phosphate is used. Automatic pyro-aerosol systems are suitable for fire prevention or extinguishing only in the first few minutes after ignition.

The method of fire suppression proposed here includes remote supply of a fire-suppressing powdered aerosol (average particle size 5μ), by special installations using powerful ventilators. The system provides the following advantages:

a) the ability to deliver aerosol into a fire from distances of up to 200 m by air flow, if the fire takes place in a closed volume, or through a wide tarpaulin hose if sufficient space around the fire is available.

b) the possibility to combine powder aerosol with nitrogen, foam, halons $[C_xH_y(ClBr)_z]$ and other agents.

It should be noted that the common factory-made powders employed in extinguishers have an average particle size of ca. 40 μ [3]. Particles of these dimensions are too large to be used for remote fire extinguishing, as their airborne residence times (precipitation times) are too short to travel the necessary 100-150 m in our air flow conditions. Further, they result in surface areas too small to extinguish fires efficiently. To obtain the necessary dispersion, such powders need to be additionally milled. Interest in using finer-grained powders as fire suppressants has been evident for many years [4]. The specialist literature contains numerous theoretical articles. However, mostly with only little experimental support and often with incorrect calculations and conclusions. For example, in reference [5] the opinion is expressed, that "If, in mine work the ventilating flow rate is greater than 0.2 m/s there will be practically no particle deposition". Our experiments, described below, completely negate this conclusion.

2. Experimental

The average particle sizes of the powders studied were determined using an optical microscope operating in the phase-contrast regime with a magnification of up to 950. Electron microscopy (magnification ~1800) was applied to study details of the morphology of the conglomerate $[NH_4H_2PO_4]$- $[SiO_2---CH_3]$. The airborne residence time of aerosols and their extinguishing efficiency (both individual and in combination with foam, nitrogen and halon) were studied in the specially designed closed, though not completely airtight, chamber (5.8×5.8×3 m; 100 m^3) shown in Fig. 1. The system for spraying powder was installed in the upper part of the chamber. It consisted of a

metallic vessel filled with powder and two parallel horizontal pipes (diameter 30 mm) mounted 1 m apart from the central axis of the chamber.
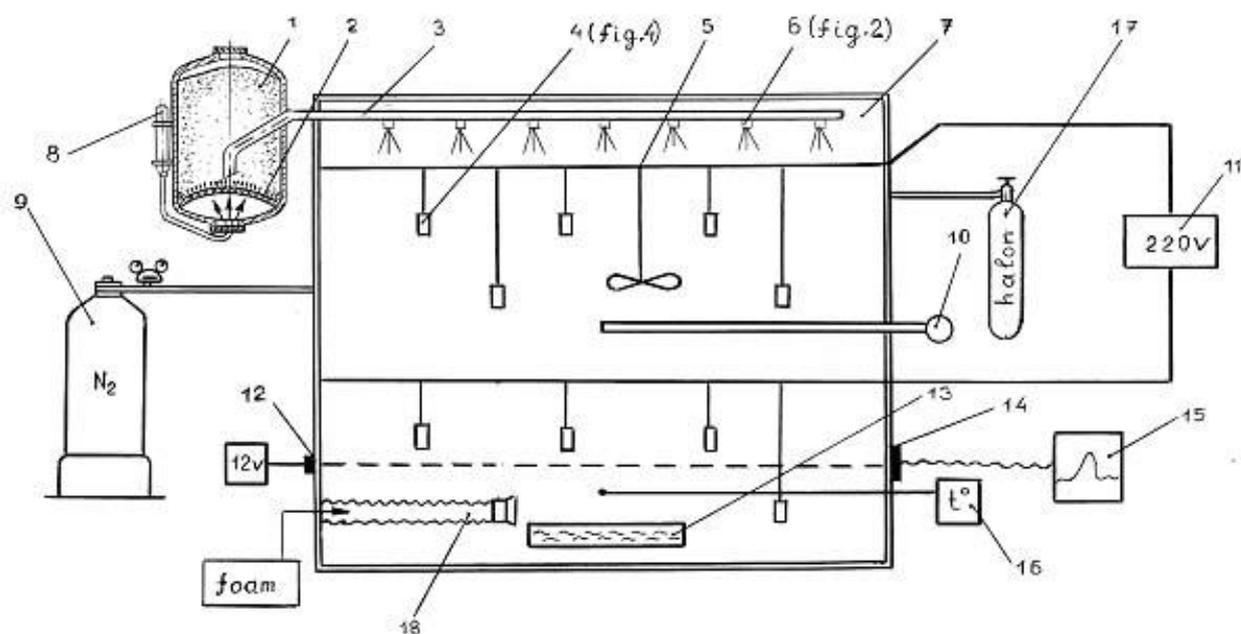

Fig. 1. Chamber used for measurement of aerosol properties
1 - vessel with finely pounded extinguishing powder, volume 0,5 m^3; 2 - porous flexible membrane (for example, thick canvas); 3 - spraying-system for a powdered aerosol; 4 - automatic aerosol samplers (see main text: used only in "cold" experiments; removed for the "hot" experiments); 5 - ventilator for a gas interfusing (off during injection of aerosol); 6 - sprayer; 7 - chamber; 8 - compressed air cylinder r; 9 - nitrogen cylinder; 10 - gas analysis; 11 – electrical power source; 12 - light source; 13 - steel pan with gasoline (30 liters); 14 - photoelectric resistance; 15 - photoelectric registering device; 16 - thermocouple 17 - halon ($C_2Br_2F_4$) cylinder; 18 - foam outlet.

Each pipe was supplied with sprayers situated equidistant at 0.5 m along its length. The chamber was equipped with systems for measurement and control. A steel pan (1x1 m) was placed in the center of the chamber floor. For an experiment, liquid gasoline filled the pan to a depth of 10 cm. Extinguishing was started 60 s after igniting the gasoline.

We designed a special sprayer (Fig. 2) through which fine powder could be injected into the chamber. Coagulation of the particles was prevented by their impacts on the walls of intermediate and outlet bells. In addition, particles of the powder passed through 4-6 tangential channels where they acquired electrical charges of the same sign and also rotation around variable axes. This facilitated higher aerosol stability and increased the airborne residence time.

Foam (see Fig. 1; position 18) was prepared from an aqueous solution of sodium alkylsulphate (5%); the multiples of air/foam used were 20.
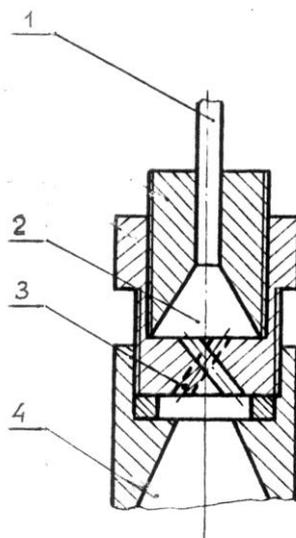
Fig. 2. The sprayer for powder aerosol
1 - input; 2 - intermediate bell; 3 - tangential channels; 4 - outlet bell.

Experiments in distant fire suppression were carried out in a tunnel (concrete; cross section 1,7 x 1,8 m; $S = 3$ m^2; length 180 m (see Fig. 3). Aerosol was supplied to the tunnel by air flow from a powerful ventilator providing a pressure more 1000 mm H$_2$O. The minimal powder consumption Q_{min} was calculated as: $Q_{min} = 4 \cdot S \cdot V \cdot C_p$, where S is the cross-sectional area of the tunnel (m^2), V - is the airflow (m/sec); and C_p the fire-
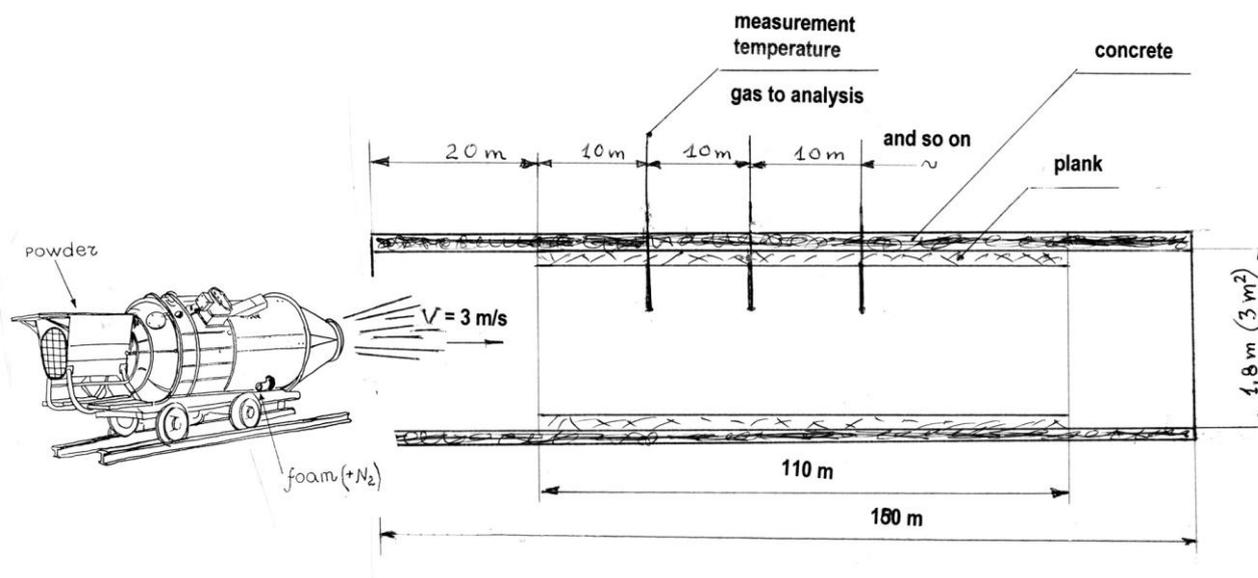

Fig. 3. Scheme of tests carried out in the experimental tunnel

suppression concentration of a powder aerosol, kg/m^3. However, it is important to note that, at low flow rates (V<1m/s), a larger fraction of a powder will be precipitated before it reaches the remote center of a fire. For our experimental conditions:

Q_{min} = 4·3·3·0.1 = 3,6 kg/s.

In large-scale extinguishing tests, timber comprised of pine (planks, logs; one m^3 of dry wood / per meter tunnel; total <u>ca</u>. 100 m^3), previously thoroughly moistened with gasoline, was fixed along 110 m of the tunnel length. Thermocouples and gas samplers were installed at 10 m intervals along this section. An aerosol-foam extinguishing installation including a powerful ventilator and a foam generator was used to deliver extinguishing agent into the tunnel. The installation injected ammonium phosphate powder at a rate of 3.5 kg/s or generated 5 m^3/s of foam. The air velocity was ca. 3 m/s. Sodium alkylsulphate solution was used at a rate of 0.015 m^3/s, the air/foam multiple being 500. Foam was generated using only air. Extinguishing was begun 40 min after the initiation of timber combustion (gasoline have used for kindling).

Measurements of aerosol concentration (in both the chamber and tunnel) were carried out in a blank set of experiments, in the absence of burning gasoline. Aerosol samples were taken simultaneously at different points inside the chamber using the devices shown in Fig. 4. The samplers instantaneously (0.5 s) retrieve small volumes of aerosol (6.2 sm^3) at selected locations in the chamber.
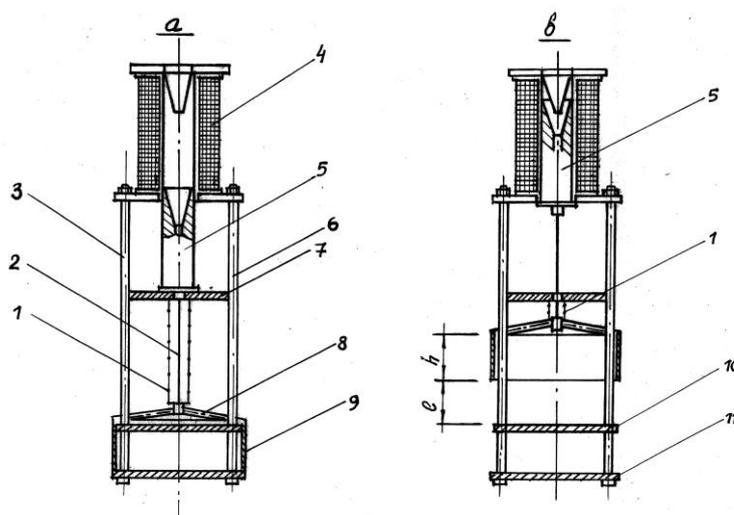
Fig. 4 - The apparatus for automatic withdrawal of aerosol samples
1 - spring; 2 - rod; 3, 6 - directing cores; 4 - electromagnetic coil; 5 - anchor; 7 - tier; 8, 9 - lid;
10 - top partition; 11 - base covered with a demountable "adhesive" filter paper (2x2 sm).
$l = h = 1,55$ sm; **a** - apparatus inactive;   **b** - apparatus activated (0,5 s)

The particles were collected on filter paper and their total mass determined gravimetrically. The aerosol concentration was calculated as a mean of five measurements (probability P = 0,97, a dispersion ss = 0,76).

In addition, the maximum settling time of aerosol in the chamber was monitored (in "cold" experiments) by a photoelectric method. As the white powder disperses light strongly, we used the effect to measure the maximum aerosol settling time. The latter was defined as the time at which the cursor of the recording device (Fig. 1; position 15) returns to zero after deflection.

Gas compositions, during and after extinguishing, were analyzed using a chromatograph "Model-3700" (manufactured by "Chromatograph", Moscow, Russia); the chromatography column was packed with molecular sieves. Chemical gas detectors ("indicator tubes") produced by "Dräger" (Germany) were also employed.

Note: Foam was only delivered to the fire *after* burning had been suppressed by a powder. The overall objectives of applying additional foam were: a) to achieve accelerated local cooling of the site of the fire and prevention of its renewed ignition, b) to curb unnecessary use of the expensive fine-pounded powder.

3. Results and Discussion

3.1. Microscopic studies

Typical results of the microscopic examination of the as-received fire-suppressant powder – a mixture of ammonium phosphate [$NH_4H_2PO_4$] and modified fumed silica [SiO_2---CH_3] are shown in the photography in Fig. 5. For comparison, Fig. 6 shows photography of the powder after additional milling using a jet-type mill. The mean particle size was reduced 5-10 times after this treatment. At the higher magnification obtained with the electron microscope, crystal arrangements on the surface of the ammonium phosphate particles (Fig. 7) can be seen more clearly (magnification: 1800×). This surface is not uniformly covered with fumed silica particles (or rather with their aggregates in the form of white clouds). Fumed silica is added to the milled ammonium phosphate at ca. 1-3% to prevent the absorption of
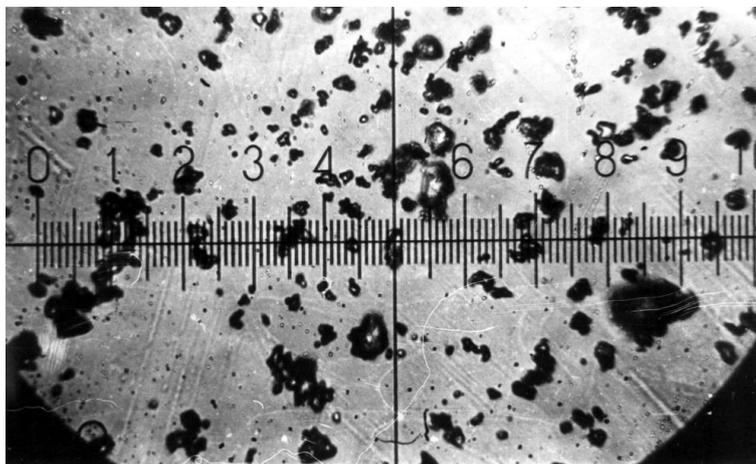
Fig. 5. Photography of a particles of factory-made ammonium phosphate powder taken in an optical microscope at 945× magnification
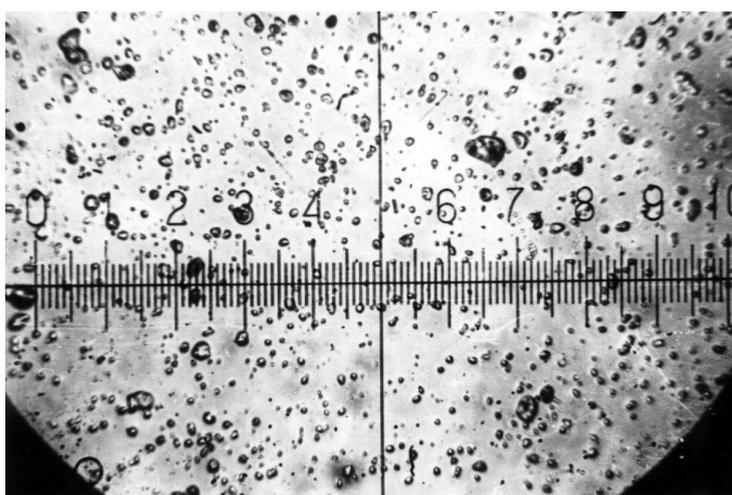
Fig. 6. Photography of a ammonium phosphate particle after additional milling (optical microscope at 945× magnification)

Note: The small division on the scale (for Fig. 5, 6) represents 5 micron; for example, between figures 1 and 2 on a scale - is 50 micron.


Fig. 7. Photography of surface of a conglomerate $[NH_4H_2PO_4]$- $[SiO_2{-}{-}{-}CH_3]$ in the electronic microscope at 1800× magnification

moisture and coagulation of the ammonium phosphate particles. Bearing in mind that the particles of fumed silica are 50-100 times smaller and 30-50 times lighter than particles of ammonium phosphate, we conclude that the technology of mixing these ingredients is not yet perfect.

3.2. Experiments in the chamber

Two sets of experiments using burning gasoline were carried out in the 100 m^3 experimental chamber. The first series was intended to study the residence time of airborne particulates, while the second had, as its goal, a comparison of the extinguishing efficiency of aerosols in combination with gaseous fire-fighting agents.

The study of the dynamics of powder precipitation in aerosol shows that the initial mass concentration (200 g/m^3) decreases twofold within 10 s and fourfold within 40 s (Fig.8).
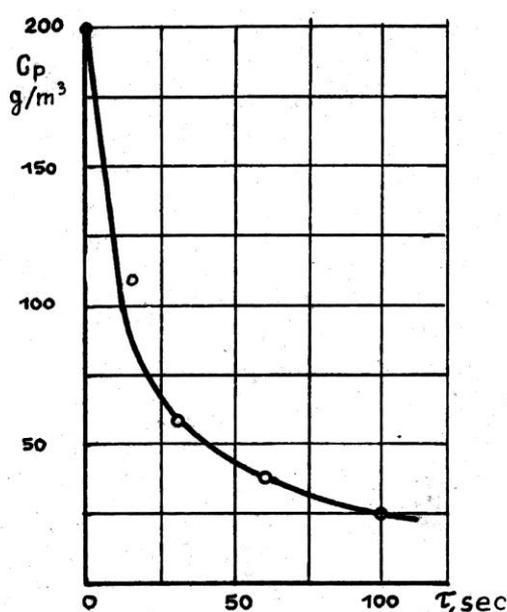
**Fig. 8. Dynamics of precipitation of ammonium phosphate particles
(d = 5 microns) in the 100 m^3 chamber**

The values of the precipitation velocity calculated from the well-known Stokes law for *single particles* of ammonium phosphate of 100, 50 and 5 microns diameter are 63, 15 and 0.3 sm/s, respectively. However, the precipitation of an *aerosol cloud* is a much more complex process. The number of particles *N* remaining in a unit volume of aerosol after a precipitation time τ may be expressed as:

$$N_\tau = N_o [1 - v\tau/(ha)^{0,5}] , \quad \text{where:}$$

v - precipitation velocity; h - height of precipitation; a - distance between particles in an aerosol cloud..

In experimental fire extinguishing, the effectiveness of powder aerosol alone and in combination with nitrogen and halon [$C_2Br_2F_4$] added to the stream, was studied. Note: the authors are aware that the use of halons is limited by the Kyoto Agreement. However, it seems likely that their use will be allowed in such extreme situations as large and dangerous fires.

The gasoline fire in the 1x1 m pan was extinguished in 65 s using aerosol with a powder concentration of 95-100 g/m^3. The total amount of powder used was 51 kg. However, after ceasing aerosol loading, the hot metal pan re-ignited the gasoline. To cool the pan, the supply of aerosol had to be continued for another 3-4 minutes, thus increasing the total amount of powder used by 4-5 times, to 200-250 kg.

This fact encouraged us to use a foam fire-extinguisher *after* the aerosol had suppressed the flame. To cool the pan after suppression of the flame with aerosol, foam (air/foam multiple 20) was supplied for 200 s. This resulted in the total consumption of 50 kg of the powder and 0.25 m^3 of foam for complete extinguishing of the fire.

Addition of 0.4 vol.% of halon $C_2Br_2F_4$ permitted us to reduce the concentration of extinguishing powder to 84 g/m^3. While maintaining the concentration of halon at this level, nitrogen was added to the chamber in the following volumes: 5, 10, 15 and 20 m^3. This led to a decrease in the oxygen concentration from 21 to 16.5 vol.% (Fig.9). However, by far the most important effect was the crucial reduction in the necessary concentration of the powder. For example, on addition of 10 m^3 of nitrogen, which also lowered the oxygen concentration in the chamber to 19 vol.%, it reduced to 18 g/m^3.
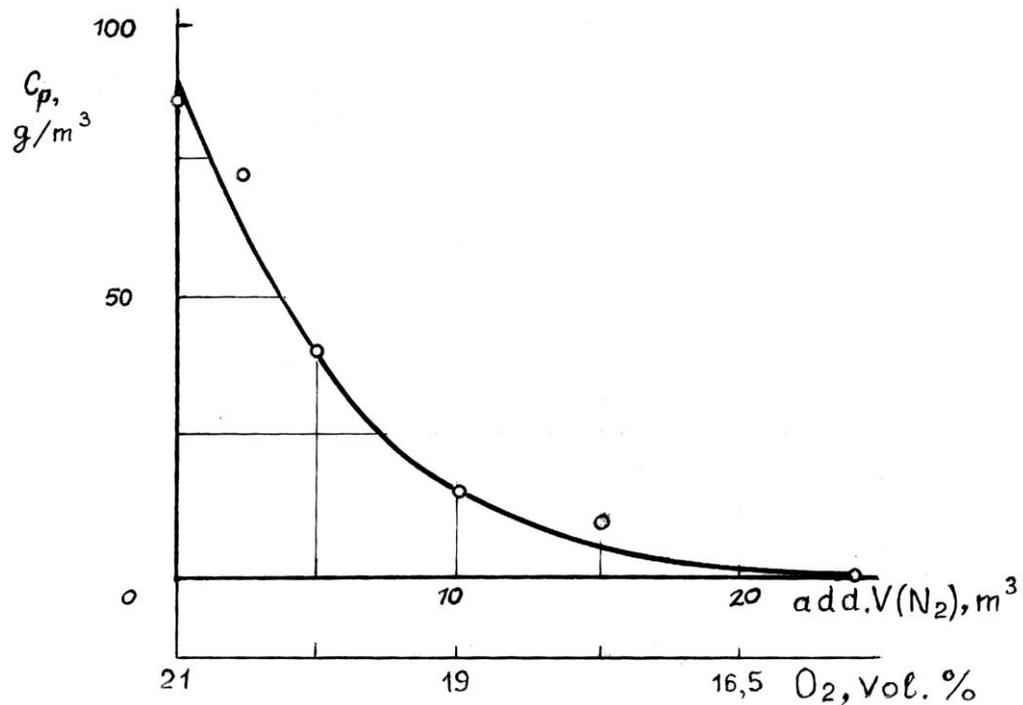
Fig. 9. Dependence of fire-fighting concentration of ammonium phosphate (C_p) on N_2 in the presence of halon ($C_2Br_2F_4$ - 0.4 vol.%)

3.3. Experiments in the tunnel

The transfer of ammonium phosphate aerosol by ventilator was studied in the experimental tunnel (Fig. 3). The results of this part of the study are presented in Fig.10. Clearly, the lower the average size of powder particles, the more efficiently they are transported in the air flow. At 150 m from the ventilator, the concentration of larger particles of powder (average size 40 μ) decreases by a factor of 13 from the initial value of 220 down to 17 g/m^3 (curve 2), whereas the concentration of smaller powder particles (average size 5 μ) decreases only threefold, from 160 to 48 g/m^3 (curve 1). Aerosol concentrations of fine particles (d = 5 μ) at ca. 150 m are almost three times higher than those for powders with d = 40 μ. This indicates that only the fine fraction of the powder (< 5 μ) can be transferred in the air flow over distances of ≥ ca. 100 m.

The experimentally observed concentration, 48 g/m^3 correlates with the data on precipitation rate in Fig. 8. This concentration was observed after 45 s of precipitation, during which time the aerosol traveled ca. 144 m (i.e. 3 m/s x 48 s).
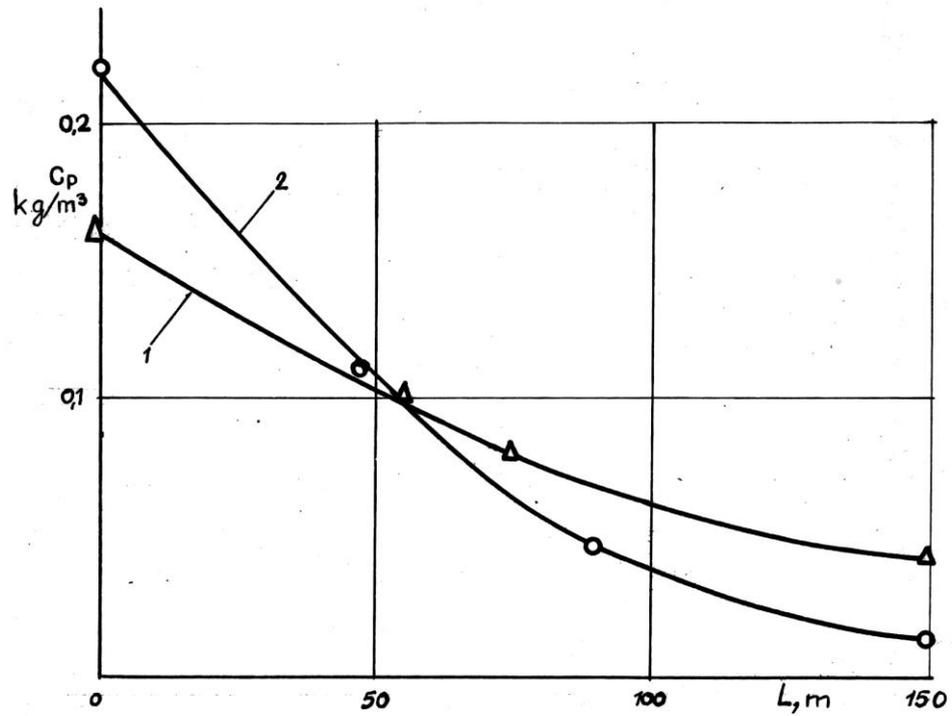
Fig. 10. Relationship between concentration (C_p, kg/m³) of powder in concurrent air stream and distance from the fire-fighting installation
1 - ammonium phosphate (diam. = 5 microns); 2 - ammonium phosphate (diam. = 40 micron).
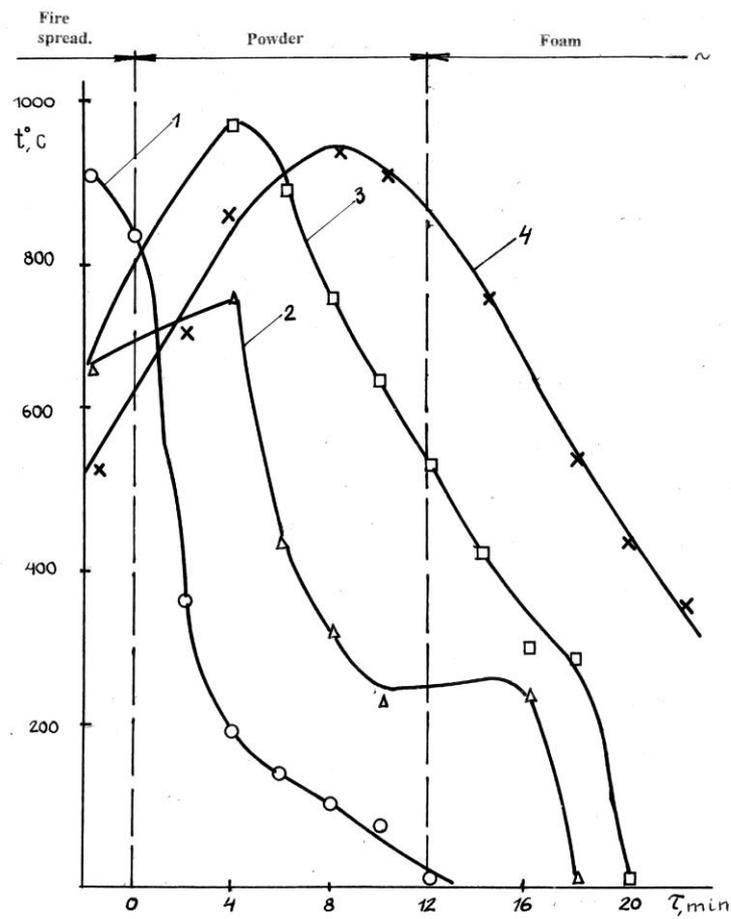
**Fig. 11. Temperature change along the tunnel length as a function of time:
combined powder-and-foam extinguishing**
(before 0 min - fire spread; 0-12 min - supply of a powder; 13-30 min - supply of a foam)
1 - distance 30 m from the "fire-inception" (or 50 m from the ventilator); 2 - 50 m;
3 - 70 m; 4 - 100 m.

In the initial experiment we used only powder aerosol as the extinguishing agent. However, after 15 minutes of extinguishing, the temperature ca 100 m from the "fire-initiation" slowly decreased and remained high (700-800 °C). Even after 25 min of continued extinguishing it remained in the range 300-350 °C and within the next ten minutes did not decrease in spite of the fact that suppression by powder aerosol was uninterrupted.

In the experiments which followed, the fire was extinguished by the combined successive use of powder aerosol and foam supplied with the extinguishing installation. The results of temperature measurements are shown in Fig. 11. When extinguishing started, the temperature 30 m from the "fire-inception" (and 50 m from the ventilator) was about 850°C. It decreased to 200°C after 4 min of aerosol supply (curve 1). However, at distances of 50, 70 and 100 m (curves 2, 3, 4 respectively) the temperature was still increasing at this point. It indicates that the powdered aerosol does not "cover" the whole fire at once, but as if it traverses the flame, carrying out a kind of step-by-step fire-extinguishing over the whole tunnel length.

By the tenth minute of the experiments with powder, the temperature at 50 m had fallen to 250 ºC, while at the 70 m point it had only decreased to 650 ºC. At the 100 m point, the temperature still was increasing and reached a maximum of 930 ºC.

After twelve minutes of extinguishing by powder aerosol, the foam supply started. Note: no nitrogen was being supplied to the tunnel at this time. After 15 min of foam supply, the temperature had dropped to 30-50°C in the most of the tunnel, except at the distance of >=100 m. Foam had reached this section (100 m) after only 20 min of supply. The supply of foam into the tunnel continued for 30 min. The total consumption of powder after complete fire suppression was 2200 kg and of aqueous sodium alkylsulphate solution was 75 m^3.

The results of the gas analysis are in accord with the temperature data described above. During the first few minutes of powder injection the volume concentration of oxygen in fire gases is near zero, of CO_2 - 20%, of carbon monoxide and methane - about 4 and 1% correspondingly. After 12 minutes of ventilator operation with powder, the volume concentration of oxygen had grown from 0 to 10% but CO_2 had fallen from 20 to 10%. After 5-6 min of ventilator operation with foam the concentrations of CO_2 and CH_4 decreased to zero.

It should be noted that one of the most effective ways to increase the range of distant fire suppression by aerosol is to use it in combination with an inert gas (and/or halon) added to the air stream.
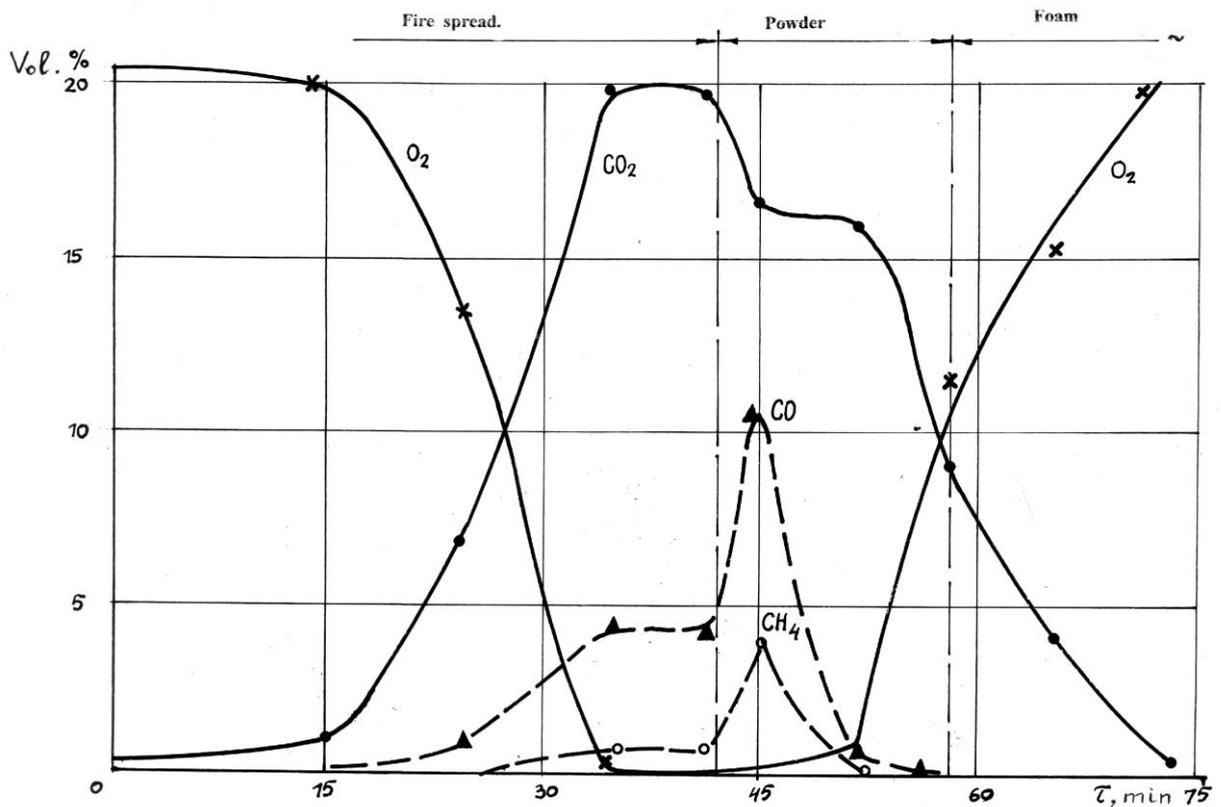
Fig. 12. Dynamics of change of fire gas composition during the extinguishing the burning timber support
(0-40 min - fire spread; 41-53 min - supply of powder;
after 55 min - supply of foam)

As can be seen in Fig. 10, initially the concentration of aerosol decreased from 220 g/m^3 to 48 g/m^3 in the section at 150 m. This is twofold lower than the fire-suppression concentration of this aerosol (95-100 g/m^3) and it is insufficient for fire-

suppression. However, if extinguishing is carried out by the aerosol in combination with nitrogen and halon (Fig. 9), the fire-suppression concentration is lowered to 15 g/m^3. This concentration of particles, at least those of ca 5 μ size, can easily reach up to the 200-th meter of the experimental tunnel.

4. Conclusions and Recommendations

1. Suppression of a large-scale fire spreading inside a closed volume demands a constant supply of aerosol over long periods.

2. The consumption of extinguishing powder increases 2-3 times for each successive 50 m from the main fire location. This drastically raises the consumption and cost of extinguishing powder.

3. The mean particle size of a powder in the aerosol and its fire-suppression concentration should not exceed 10 μ and 0.1-0.12 kg / m^3 respectively.

4. Powder aerosol does not "cover" the whole fire all at once, but rather, as it traverses the flame, it simulates a step-by-step extinguishing over the whole tunnel length. Thus, to an external viewer, it appears that a local fire-extinguishing effect is occurring which progressively spreads over the whole tunnel length.

5. The use of nitrogen and halon combined with powder aerosol considerably lowers both the fire-suppression concentration of a powder and the expenditure on fire extinguishing. An increase in the maximal distance of fire extinguishing is also observed.

6. In the case of a large spreading fire, after a maximum of thirty minutes of extinguishing by aerosol, it is expedient to continue the process using foam.

References

1. Matt Livingood, Jason Winicaties and Jared Stein. "Centralia Mine Fire Analysis" - Fundamental Techniques in Geology. - 1999, 15, p. 150-155.
2. V.V. Agafonov. and N.P. Kopylov "Aerosol Extinguishing System". - VNIIPO, Moscow, 1999, 232 p.
3. R. Balles. Tests of extinguishing powders. - Die Zeitschrift Feuerwehrp, V. 13, # 11, 1988, p. 634- 635.
4. M. Dewite, J. Vrebosch, A. van Tiggelen. Suppression of a flame by fine powders. - J. App. Chem., V. 8, # 12, 1964, p. 257-266.
5. V.V. Diakov. Use of ventilating streams for delivery of extinguishing agents during fires in tunnels of the metro. - "Fire-explosion-safety" (Moscow), # 1, 1996, p. 66-71.

*****