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# **Quenching Methane-Air Ignitions With Water Sprays**



**UNITED STATES DEPARTMENT OF THE INTERIOR**

**Report of Investigations 8214**

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**By M. J. Sapko, A. L. Furno, and J. M. Kuchta**



**UNITED STATES DEPARTMENT OF THE INTERIOR**  
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# QUENCHING METHANE-AIR IGNITIONS WITH WATER SPRAYS

by

M. J. Sapko,<sup>1</sup> A. L. Furno,<sup>1</sup> and J. M. Kuchta<sup>2</sup>

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## ABSTRACT

The Bureau of Mines conducted laboratory-scale flammability experiments to investigate the possible use of water spray systems for inerting or quenching mine-gas ignitions, such as those encountered at the working face of a coal mine. The inerting results for premixed methane-air-water mixtures indicated that water droplets of less than 10  $\mu\text{m}$  tend to be as effective as the vapor. Water requirements for inerting such mixtures were much smaller than those for quenching the sustained flame propagation by the application of water sprays. The minimum water mass concentration for quenching methane-air flames increased linearly with increasing droplet diameter (surface weighted mean) and decreased with increasing spray temperature, whereas the droplet surface area required per unit volume was essentially constant for a given gas mixture composition. Data extrapolations indicated that a quenching system may be feasible for the longwall mining application.

## INTRODUCTION

Frictional ignitions frequently occur during the mining of coal as a result of incendive sparks or overheated surfaces that are readily produced by continuous-mining machines. Two main approaches have been under study as a means of protecting against this ignition hazard. One involves the development of cutting tools of reduced incendivity<sup>3</sup> and the other, the development of an ignition suppression device utilizing a dry powder or vaporizable

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<sup>3</sup>Kaufman, L., and R. L. Pober. Process Optimization Study of Non-Sparking Titanium Diboride Tool Materials. BuMines Contract Rept. SO 231084 (Manlabs, Inc.), Oct. 20, 1973; BuMines Open File Rept. 11-74; available for consultation at Bureau of Mines libraries in Pittsburgh, Pa., Twin Cities, Minn., Denver, Colo., and Spokane, Wash.; at the Central Library, U.S. Department of the Interior, Washington, D.C.; and from National Technical Information Service, Springfield, Va., PB 229 485/AS.

extinguishant.<sup>4</sup> Since both approaches have certain practical limitations which may preclude their use, the present study was undertaken to explore the possible utilization of water spray quenching systems for protecting against ignitions of firedamp at the coal face.

The effectiveness of water vapor as an inerting agent is well known; about 26 volume-percent is required to render a stoichiometric methane-air mixture inert.<sup>5</sup> In practice, a steam generator is used to supply the inert, but the water vapor concentration will depend upon the liquid-vapor equilibrium at the particular ambient temperature. From the thermodynamic standpoint, water droplets should be more effective as an inerting or quenching agent than water vapor at the same mass concentration; however, such factors as droplet size and distribution and the residence time of droplets in the propagating flame can limit the effectiveness of a spray quenching system. Recent Bureau of Mines studies<sup>6</sup> have shown that finely dispersed water can be effective even in quenching full-scale mine explosions involving coal dust, providing the wind velocity is high enough to insure adequate dispersion. The present report describes the results of laboratory-scale experiments in which methane-air ignitions were quenched or rendered inert by fine water sprays or by a combination of sprays and steam. Variables of study included droplet size, droplet temperature, and the concentration of inert and fuel. The results are extrapolated to the mining situation to indicate the technical feasibility of developing spray quenching systems for longwall and room-and-pillar mining machines.

The inerting data of this report are similar to limit-of-flammability data obtained with premixed combustible-air-inert mixtures. Specifically, the inerting limits refer to the water-vapor-droplet concentrations that are required to prevent incipient ignitions of flammable methane-air mixtures from developing into self-propagating flames. In theory, they define the inert concentration necessary to keep the adiabatic temperature of the combustion products below the limit flame temperature of the particular gas mixture composition.

In comparison, the spray quenching limits refer to the extinguishment of fully established methane-air flames which propagate into an opposing water spray under relatively turbulent conditions. Thus, these conditions are more severe than those employed in the inerting experiments. In both cases, one can assume that the effectiveness of the inert will depend upon its ability

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<sup>4</sup>Burgess, D. S., W. F. Donaldson, A. L. Furno, J. M. Kuchta, and C. R. Summers. Spatial and Temporal Distributions of Halon 1301 From a Commercial Extinguisher. BuMines RI 7515, 1971, 17 pp.

Jamison, W. B., and H. Hadi. Ignition Suppression for Continuous Miners (BuMines Contract HO 122020, Lee Engineering Div. of Consol Coal Co.). Proc. NCA/BCR Coal Conf. and Exp II, v. 1, Oct. 21-23, 1975, p. 197.

<sup>5</sup>Zabetakis, M. G. Flammability Characteristics of Combustible Gases and Vapors. BuMines Bull. 627, 1965, 121 pp.

<sup>6</sup>Liebman, A., J. K. Richmond, and J. Grumer. Recent Developments in Passive and Triggered Explosion Barriers. Proc. 16th Internat. Conf. on Coal Mine Safety Research, Washington, D.C., Sept. 22-26, 1975, p. VII, 8.1.

to cool any flame that develops below the temperature required to sustain propagation.

#### EXPERIMENTAL APPARATUS AND PROCEDURES

Schematics of the experimental apparatus used in this work are shown in figure 1. The setup on the left was used for studying the spray quenching of methane-air flames, and the one on the right was used for the inerting experiments. The experiments were conducted in a 15.5-cm-ID by 100-cm-long plexiglass tube, which was equipped with one or more atomizing nozzles, a spark ignition source, a gas metering-mixing system with laminar flow elements, and a steam or water feed supply; instrumentation for measuring water droplet sizes was also included. The spark source in all runs was provided by the discharge from a 15,000-volt, 30-ma luminous tube transformer across a pair of brass electrodes; spark gas was 0.6 cm, and spark duration was held constant at 0.2 second.

In the inerting experiments, both steam and a fine water spray were used to provide the water concentration required for preventing the formation of flammable mixtures at the selected test temperature. The steam was generated by an electric boiler and helped to atomize the secondary water being fed through a Sonicore (035H) nozzle.<sup>7</sup> This nozzle was calibrated by collecting

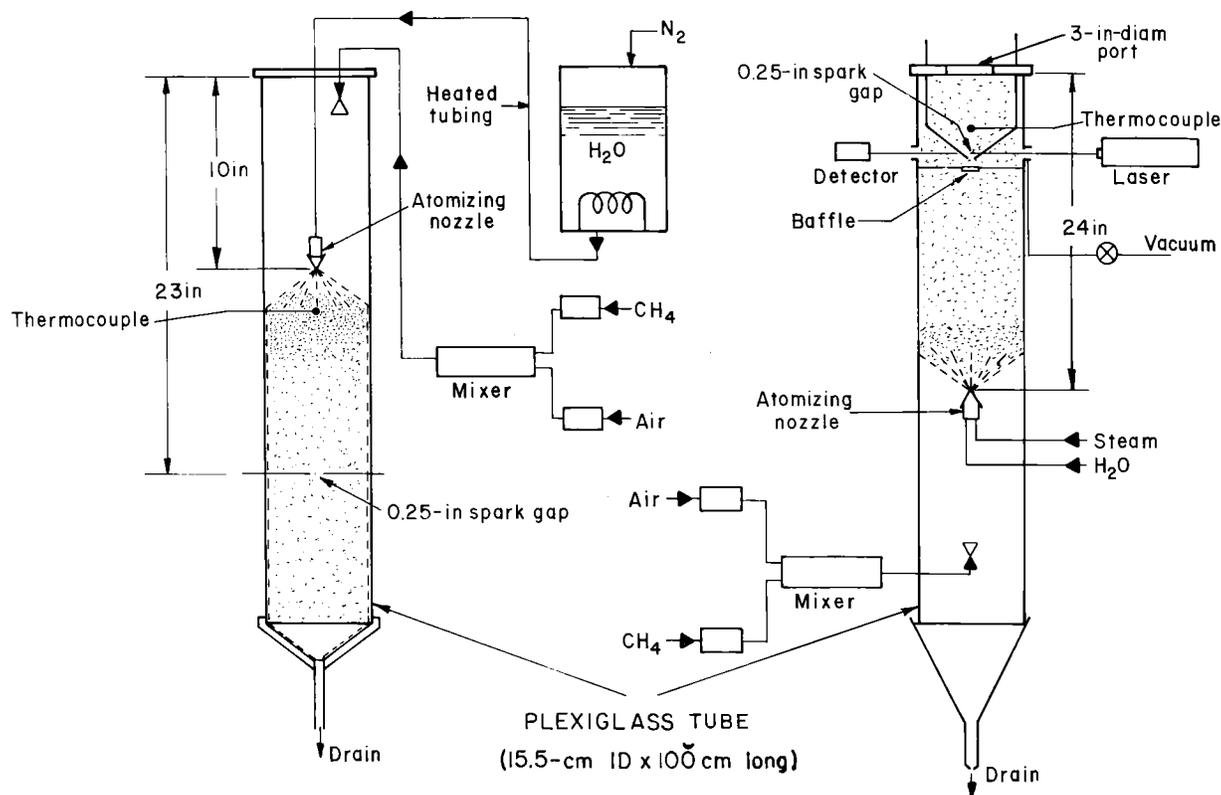


FIGURE 1. - Diagram of experimental apparatus for spray quenching (left) and inerting (right).

<sup>7</sup>Reference to specific trade names does not imply endorsement by the Bureau of Mines.

and weighing the condensate from a shell and tube heat exchanger. Droplet sizes and distributions were measured in preliminary experiments by the procedures described at the end of this section. The concentration of water during a run was determined by the difference between the mass rate of water input to the tube and the mass rate of water (condensed steam and secondary water) collected at the tube drain; this measurement was reproducible to within approximately 6 percent.

To conduct an inerting experiment, the methane-air mixture was metered into the bottom of the flammability tube, and the tube volume was purged approximately 10 times before adding the inert. Mixing of the combustible-air-inert constituents was effected by the turbulent spray action produced by the atomizing nozzle. After allowing a short time for the system to stabilize itself, as determined by wet-bulb temperature measurements, the ignition source located in the upper part of the flammability tube was actuated, and the extent of propagation was observed visually. A 1-inch-diameter baffle positioned upstream of the spark was used to dampen any flow turbulence in the vicinity of the spark gap. The criterion for a flammable mixture was upward propagation of flame which extended beyond the source of ignition and filled the tube cross section.

In the quenching experiments, the procedure differed in that the gas mixture and an atomized water spray were introduced in the upper part of the flammability tube with the top closed and ignited in the lower part where the droplet concentration was subcritical for flame suppression; also, both ignition and propagation were under more turbulent spray conditions. Water from a nitrogen-pressurized reservoir at normal or elevated temperatures was dispersed in the tube through Spray Systems Co. hydraulic atomizing nozzles. Nozzle size and pressure were varied to obtain different droplet sizes. Here, the droplet size was based upon the manufacturer's specified data, and the droplet concentration was calculated from the input of spray and flammable gas to the tube per unit time.

To conduct a quenching experiment, water was introduced at a constant nozzle pressure to the flowing gas mixture; in approximately 1 minute the drain was detached and the mixture was ignited. Ignition at the spark source was followed by both upward and downward flame propagation. Upward flame propagation in these experiments was opposed by the downward flow of the water spray which intimately mixed with the methane-air mixture. The criterion for flame quenching was defined as the minimum water flux required to prevent self-sustained flame propagation beyond the plane where the conical spray intersected the tube wall. To determine this quenching condition, the gas mixture mass flow rate was held constant at approximately 26 g/min, and the water flow rate was varied.

The droplet size distributions were determined in some of the experiments. Two techniques were employed, the magnesium oxide impact and laser light transmission methods. In the impact method,<sup>8</sup> the magnesium-oxide-coated slide was introduced into the tube downstream of the spark, exposed for 1 second, and

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<sup>8</sup>May, K. R. The Measurement of Airborne Droplets by the Magnesium Oxide Method. J. Sci. Instr., v. 27, No. 5, May 1950, p. 128.

withdrawn. Drop size and count were determined with a microscope using a calibrated eyepiece. Counts ranged from 500 to 2,000 drops per slide. In the light transmission method, measurements were made at a wavelength of 6328 angstroms using a Spectra Physics laser (5MW model 120) with a silicon photo diode detector. Water vapor does not absorb at this wavelength and therefore does not affect the measurements. The laser was positioned so that the beam passed through diametrically opposed 0.6-cm holes in the tube wall and as close to the spark as possible. Unfortunately, these openings disrupted the flow pattern across the tube and caused fluctuations in the light path. Therefore, "aspirators" were added to the outside tube wall and produced a suction normal to the light beam. Minimum suction was used to maintain a constant transmission path, approximately the tube diameter. By simultaneous measurement of mass concentration and transmission attenuation, the surface weighted mean droplet diameter was calculated from the Bouguer-Beer-Lambert transmission law:

$$I/I_0 = \exp \left( - \frac{3Kc\ell}{2\rho d} \right), \quad (1)$$

where  $I/I_0$  is fraction of light transmitted,  $K$  is extinction coefficient (2),  $c$  is droplet concentration ( $\text{g}/\text{cm}^3$ ),  $\ell$  is path length (17.2 cm),  $\rho$  is particle density ( $1.0 \text{ g}/\text{cm}^3$ ), and  $d$  is particle surface mean diameter (cm) based on monodispersed spheres.

## EXPERIMENTAL RESULTS

### Inerting

The limits of flammability of the methane-air-water vapor systems have been previously defined by Coward and Gleadall<sup>9</sup> and Yeaw and Shnidman<sup>10</sup> under quiescent conditions and are shown in figure 2. Also included in this figure are the inerting data from this study. As noted, the water vapor inerting limits from the earlier works (curves a and c) are approximately 26.5 and 32 mole-percent for approximately stoichiometric methane-air mixtures at water saturation temperatures of 67° C and 71° C, respectively. The higher inerting limit of Yeaw and Shnidman is most likely attributable to the fact that the combustible gas contained 3 percent ethane, which would enhance the flammability of methane more than the difference in mixture temperature. The present inerting experiments with stoichiometric and other methane-air mixtures gave intermediate results; curve b in figure 2 approximates these results.

The results of this work in which the inert consisted of steam and fine water droplets ( $<10 \mu\text{m}$ ) gave a stoichiometric inerting limit of approximately 28 mole-percent at 60° C. At this temperature the water vapor content, assuming 100-percent saturation, is approximately 19 mole-percent, and would not be

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<sup>9</sup>Coward, H. F., and J. J. Gleadall. Extinction of Methane Flames by Water Vapor. J. Chem. Soc., 1930, p. 243.

<sup>10</sup>Yeaw, J. S., and L. Shnidman. The Extinction of Gas Flames by Steam. AGA Proc., 1938, p. 717.

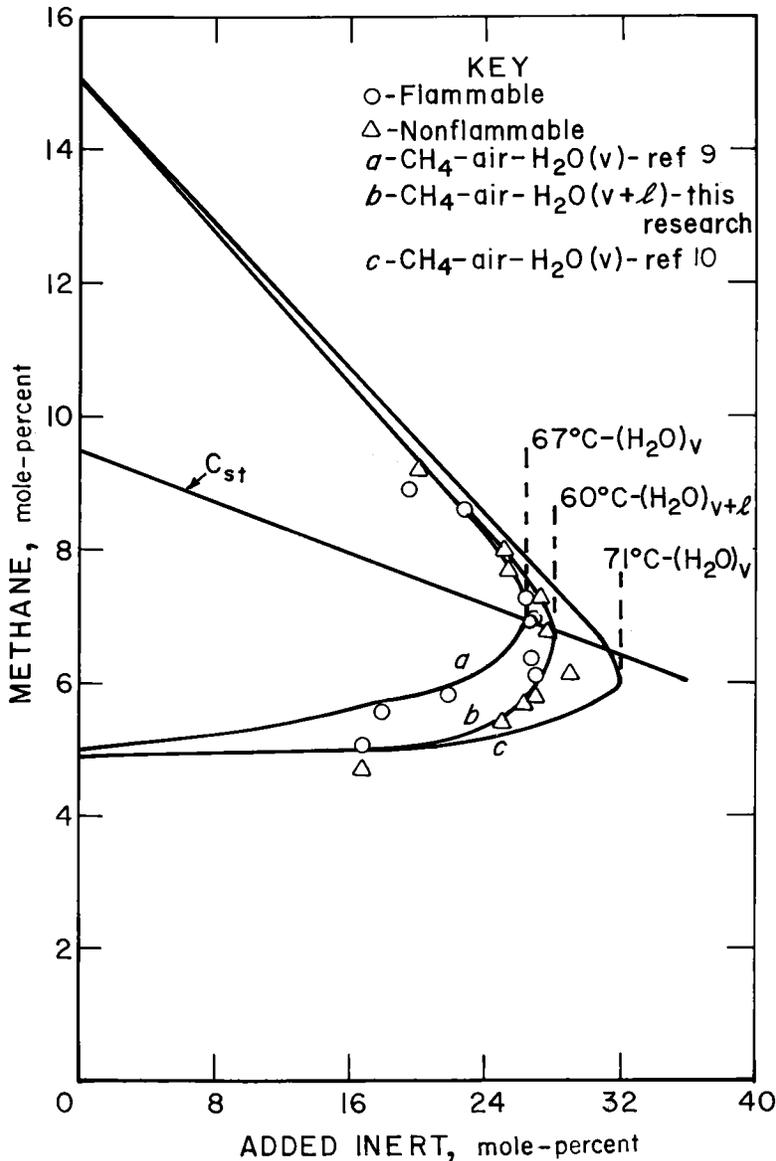


FIGURE 2. - Inerting methane-air mixtures with water vapor (v) and vapor + droplets (v+l).

27  $\mu\text{m}$  averaged over all samples. These data were in fair agreement with the nozzle manufacturer's specified range of droplet diameters for the two-fluid atomizing nozzle that was used.

#### Spray Quenching

The water requirements for quenching self-sustained vertical propagations of methane-air flames were much greater than those for inerting the ignitions. The critical water spray concentration for quenching varied with the fuel concentration, droplet size, and temperature. Figure 3 shows the mass concentration for quenching plotted as a function of the surfaced weighted mean (SWM)

sufficient to render the mixture nonflammable. Therefore it is apparent that the additional water required for inerting was in droplet form and would have been derived largely from the atomized water spray. These results indicate that droplets distributed with a number mean droplet diameter of  $<10 \mu\text{m}$  tend to behave the same as the vapor.

Several attempts were made to extend the inerting data down to room temperature. However, these attempts were of little success because of nozzle flow limitations and excessive droplet loss on the walls of the flammability tube.

In a few of the inerting experiments, particle sizes and distributions were determined by both the magnesium oxide (MgO) impact and laser transmission techniques. The droplet size distributions by the impact method were approximately log normal with an average number mean of  $\sim 10 \mu\text{m}$  and a surface mean droplet diameter of  $22 \mu\text{m}$ . In comparison, the laser method gave a surface mean diameter of

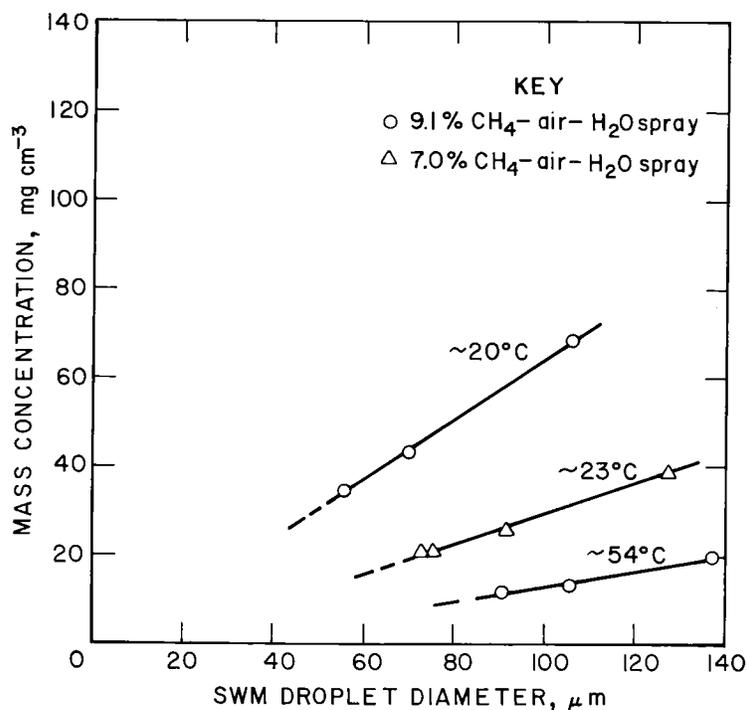


FIGURE 3. - Minimum water spray mass concentrations versus SWM droplet diameter for quenching vertically propagating methane-air flames in 15.5-cm-ID tube.

droplet diameter defined in equation 4. These data were obtained at a gas-mixture mass flow rate of approximately 26 g/min. At a spray temperature of 20° C, a 9.1-percent methane-air flame was quenched at a droplet concentration of 35 mg/cm<sup>3</sup> and a SWM droplet diameter of 56 μm; increasing the SWM diameter to 106 μm increased the required droplet concentration to approximately 68 mg/cm<sup>3</sup>. These droplet quenching concentrations were reduced by approximately one-half when the methane concentration of the gas mixture was decreased to 7 percent while maintaining the same gas flow rate. This reduction is almost the same as the reduction in normal burning velocity between such methane-air compositions, 42 versus 22 cm/sec.<sup>11</sup>

Also shown in figure 3 are corresponding results obtained for a 9.1-percent methane-air mixture at an increased spray temperature of 54° C, which increased the water vapor concentration in the spray zone. At this temperature, the quenching mass concentration was reduced and less sensitive to the SWM droplet diameter. With a SWM diameter of 106 μm, the propagation was quenched at a droplet concentration of 13.5 mg/cm<sup>3</sup> at 54° C, compared with 68 mg/cm<sup>3</sup> at 20° C. The water vapor content at 54° C, assuming 100-percent saturation, was ~15 mole-percent of the vapor-phase mixture, in which case the burning velocity of the vapor phase in the spray zone would have been noticeably reduced, 42 versus 18 cm/sec.<sup>12</sup> Therefore, lowering the methane concentration or increasing the temperature of the spray will decrease the flame speed and increase the thickness of the reaction zone, consequently increasing the residence time of the droplets. This probably accounts for the reduced sensitivity to droplet size that is indicated by the quenching data in figure 3. In any event, it is evident from these data that the effectiveness of water spray systems can be greatly increased by a rather moderate increase of the system temperature.

<sup>11</sup>Work cited in footnote 5.

<sup>12</sup>Babkin, V. S., and A. V. V'yun. Effect of Water Vapor on the Normal Burning Velocity of a Methane-Air Mixture at High Pressures. *Combustion Explosion and Shockwave*, v. 11, No. 1, January 1975, p. 339.

## DISCUSSION

Droplet Vaporization

From a thermodynamic viewpoint, water droplets should be more effective than water vapor in quenching flames because of the latent heat associated with droplet vaporization. However, the extent of vaporization depends upon the droplet size and residence time in the flame, which can be very short for a spray quenching system. For example, a 9.0-percent methane-air flame has about a 1-mm-thick reaction zone and propagates at a flame speed of approximately 230 cm/sec with respect to a stationary observer. Under these conditions a stationary droplet would be in contact with the moving flame front for about  $4.3 \times 10^{-4}$  second; furthermore, the contact times should be even shorter when the droplets are not stationary and flowing opposite to the flame front, as in the present experiments. With such short droplet residence times, the droplets are unlikely to be fully vaporized; thus, their latent heat of vaporization would not necessarily be a great fraction of the total heat abstracted from the flame front. This can be shown by considering the evaporation times for various size droplets.

According to the simplified steady state expression given by Kumm<sup>13</sup> for vaporizing droplets,

$$R_0^2 = \left[ 2 t_0 K_a \text{Ln} \frac{(1 + c_p (T_a - T_b))}{\Delta H_v} \right] / \rho_l c_p, \quad (2)$$

where  $R_0$  is initial droplet radius (cm),  $t_0$  is total droplet evaporation time (second),  $K_a$  is average thermal conductivity of the vapor between the droplet surface and flame front (cal/cm-sec),  $T_a$  is adiabatic flame temperature ( $^{\circ}$  K),  $T_b$  is liquid boiling point ( $^{\circ}$  K),  $\Delta H_v$  is the latent heat of vaporization at  $T_b$  (cal/g),  $\rho_l$  is droplet density (g/cm<sup>3</sup>), and  $c_p$  is heat capacity (average) of the droplet vapor at  $(T_a - T_b)/2$  (cal/g  $^{\circ}$  K). This equation predicts that water droplets of 8  $\mu$ m or less at their boiling point would be completely vaporized if they are in contact with a 9.0-percent methane-air flame ( $T_a = 2,185^{\circ}$  K) for  $4.3 \times 10^{-4}$  second; it was assumed that  $K_a$  is of the order of  $1 \times 10^{-4}$  cal/cm-sec- $^{\circ}$  K and  $\Delta H_v$  is 540 cal/g at 373 $^{\circ}$  K. According to Williams,<sup>14</sup> the unsteady state heat-up period (sensible heat transfer) to bring a droplet to its boiling point can be a noticeable fraction of its lifetime and can be at least 20 percent of the evaporation time approximated by equation 2.

Figure 4 illustrates the time scale involved in vaporizing various size water droplets, as approximated by equation 2, and that associated with the unsteady heat-up period (~20 percent) required to bring the droplets to their boiling point; a 9.0-percent methane-air flame is assumed as the heat source. Based on this figure, an 18- $\mu$ m droplet would just heat to its boiling point in

<sup>13</sup>Kumm, E. L. Calculations on the Evaporation Rate of Sprays in Rapidly Moving Gases. Report AL 916, June 23, 1949, North American Aviation, Inc., Aerophysics Laboratory, Project MX-770.

<sup>14</sup>Williams, F. A. On the Assumptions Underlying Droplet Vaporization and Combustion Theories. Journal of Chem. Physics, v. 33, No. 1, July 1960, p. 133.

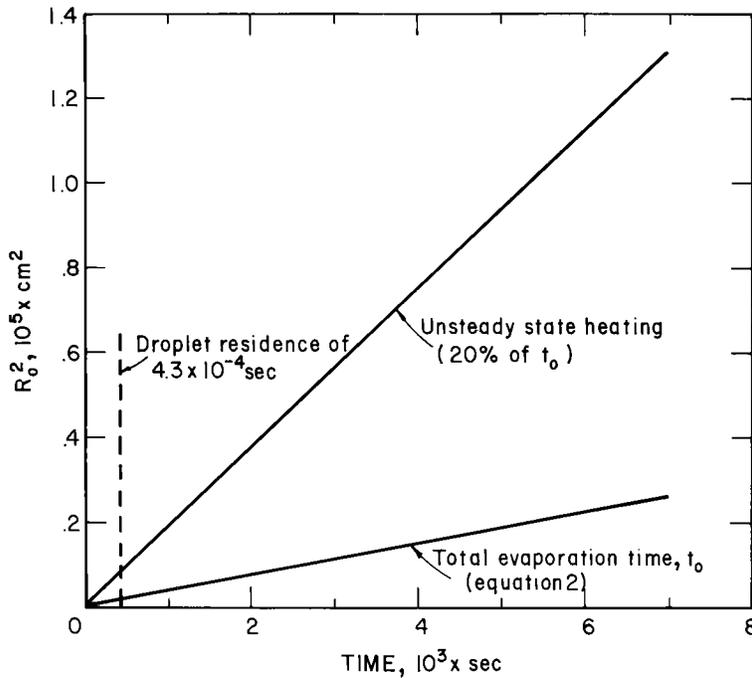


FIGURE 4. - Droplet radius square versus total evaporation time and approximate unsteady state heating time to boiling point for water droplets exposed to 2,185° K methane-air flame.

$4.3 \times 10^{-4}$  second, whereas the total time required for evaporation is approximately  $2.2 \times 10^{-3}$  second. Even greater heat transfer and vaporization times would have been required in the spray-quenching experiments where the average droplet size was much greater than  $18 \mu\text{m}$  (fig. 3). Thus, a relatively small amount of heat was apparently abstracted by each droplet during its exposure to flame ( $\sim 4.3 \times 10^{-4}$  second), thereby requiring unusually high water mass concentration for quenching. With increased  $T_0$  or decreased droplet size, the droplet lifetime will decrease and the contribution due to latent heat of vaporization would increase, thus making the spray quench system more effective.

#### Spray Surface Area for Quenching

In quenching a flame with water vapor, the most important consideration is that the water vapor concentration be sufficient to reduce the flame temperature below the limiting value required for flame propagation; for methane-air mixtures, the limit flame temperature is about 1,200° C. In quenching with a water spray, the distribution, size, and residence time of the droplets are additionally important to insure that the flame does not propagate through the narrow paths separating the droplets; a separation path of approximately 0.25 cm is critical for propagation of methane-air flames, based on ignition quenching distance data for quiescent mixtures. Since in equation 2  $R_0^2$  is directly proportional to the surface area of the droplet and to the exposure time of the droplet in the reaction zone, the quenching requirements for a given flammable mixture should correlate with the surface area of the spray.

The effective surface area of the spray per unit volume (S) of flammable gas mixture can be calculated from the expression

$$S = \frac{6 C_m}{\rho l D_{32}}, \quad (3)$$

where  $C_m$  is the mass of droplets per unit volume of mixture (mg/cm) and  $\rho_l$  is the density of the liquid (mg/cm<sup>3</sup>).  $D_{32}$  is referred to as the surface weighted mean droplet diameter and is defined by the following expression:

$$D_{32} = \frac{\int_0^m x^3 f(x) dx}{\int_0^m x^2 f(x) dx}, \quad (4)$$

where  $x$  is the characteristic droplet diameter and  $f(x)$  is the number distribution. The SWM droplet diameters for correlating the present spray quenching results were calculated from the manufacturer's nozzle specifications for unconfined sprays. It should be mentioned that when the spray is confined in the tube, as in this work, spray turbulence causes multiple droplet collisions; consequently the actual SWM diameter will be larger than those reported by the manufacturer. Nevertheless, the relative effect of SWM droplet diameter on quenching requirements should still be valid in making the present comparison. The calculated  $S$  values were relatively constant for a given gas mixture composition, regardless of droplet size and droplet concentration. Table 1 compares the spray surface area per unit mixture volume, droplet diameter, and mass concentration required for quenching the methane-air mixtures investigated; these data are based on the quenching requirements shown in figure 3. The average  $S$  values for the 9.1- and 7.0-percent-methane tests at approximately room temperature are 37.6 and 17.4 cm<sup>2</sup>/cm<sup>3</sup>, respectively. Elevating the temperature to approximately 54° C reduced the required quenching  $S$  value for the 9.1-percent methane-air mixture from an average of 37.6 to 8.2 cm<sup>2</sup>/cm<sup>3</sup>.

TABLE 1. - Droplet mass concentration and spray surface area per unit volume required for quenching methane-air flames with water sprays of various droplet diameters

Methane, volume-percent	Droplet diameter (SWM), $\mu\text{m}$	Water flow rate, g/min	Water spray temperature, ° C	Droplet quenching concentration, mg/cm <sup>3</sup>	Spray surface area per unit volume, <sup>1</sup> cm <sup>2</sup> /cm <sup>3</sup>
9.1	56	775	21	34.6	37.1
9.1	70	995	21	43.3	37.1
9.1	106	1,530	27	68.3	38.7
7.0	73	475	24	20.8	17.1
7.0	75	485	21	20.9	16.7
7.0	92	585	24	25.7	16.8
7.0	127	890	24	39.8	18.8
9.1	91	360	53	12.3	8.1
9.1	106	435	54	13.5	7.6
9.1	137	680	56	20.0	8.8

<sup>1</sup>Calculated values using manufacturer's nozzle specifications.

The constancy of the surface area quenching parameter ( $S$ ) for a given gas mixture composition and various droplet mass concentrations is consistent in that the total heat transfer is expected to be in direct proportion to the total surface area of the spray. The variation of this parameter with mixture

composition is not unexpected since the heat transferred will also vary with the residence time of the spray droplets in the flame, and therefore the required spray surface area should be less for flames of lower enthalpy and burning velocity. Although the data are meager, it appears that this surface area parameter should be a convenient design guideline for water spray quenching systems.

## APPLICATION TO MINING MACHINES

### Longwall Miner--Spray Quenching

The design of a water spray quenching system for coal mining machines requires consideration of the waterflow requirement, the nozzle sizes and locations, and the total area to be protected. Laboratory-scale data can be used to obtain preliminary estimates of the design guidelines, although simulated full-scale testing is necessary to determine the reliability of any such predictions. The gravimetric and volumetric spray flux required for quenching methane-air flames in this work are shown in figure 5 as a function of the SWM droplet diameter. These data were used to extrapolate to the longwall mining situation, neglecting the interaction that can occur with multiple sprays.

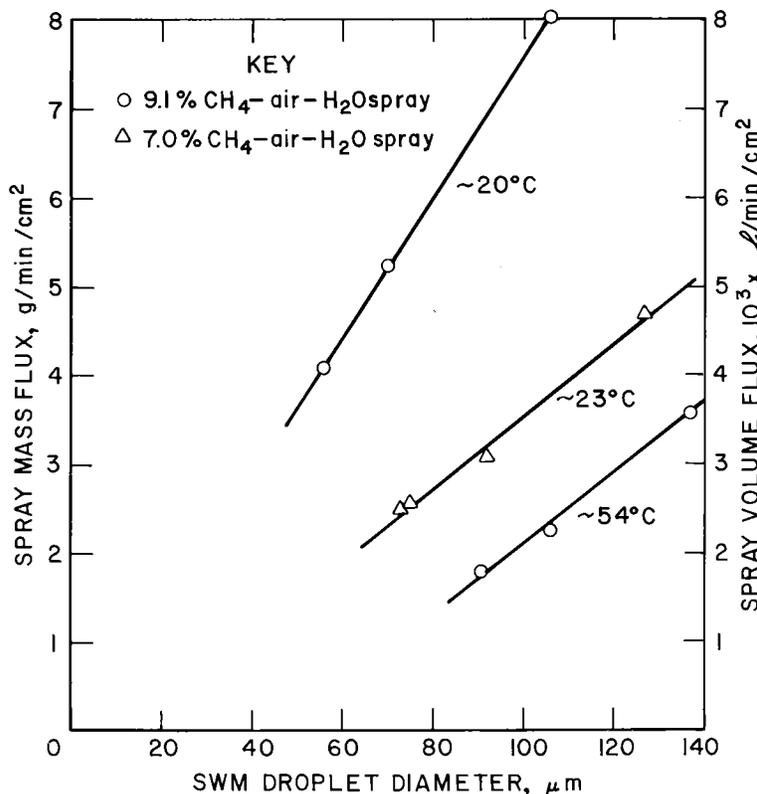


FIGURE 5. - Minimum spray flux versus SWM droplet diameter for quenching methane-air flames propagating vertically in 15.5-cm-ID tube.

One possible method of protecting the longwall miner against frictional ignitions is providing a water spray in the immediate vicinity of the cutting tools. For the purpose of calculation, a double-drum longwall shearer was assumed with 62 cutter bits per drum (135-cm diameter by 75-cm length) and with a spray nozzle shrouding each bit. At a temperature of 20° C and with nozzles providing a SWM droplet diameter of 56 μm, figure 5 shows that the minimum mass flux of water required for quenching would be  $4.1 \times 10^{-3}$  l/min/cm<sup>2</sup> or 0.774 l/min per nozzle for a near-stoichiometric methane-air mixture; each nozzle is assumed to cover approximately 190 cm<sup>2</sup>. This mass flux corresponds to a maximum total flow rate of approximately 96 l/min

(~25.3 gal/min) for the two drums, which is within range of that currently being supplied to longwall miners (~25 gal/min); the rate varies with the manufacturer's miner design and the mining situation. However, there are several disadvantages to this method of spray application; namely, (1) nozzle destruction is inevitable because of nozzle proximity to the cutting tool, (2) nozzle clogging can occur frequently, and (3) spray coverage can be greatly restricted by contact of spray with sheared coal moving between the cutting face and drum.

A second method is to prevent flame propagation external to the annular volume between the cylindrical drum and the coal face and drum cowling. The minimum requirement would be a water spray curtain to cover the outer ring area available for flame propagation. For a 135-cm-diameter drum, the annular volume would be about  $0.45 \text{ m}^3$  and the total outer ring area to be covered by the water sprays would be about  $0.6 \text{ m}^2$ . To confine ignitions of near-stoichiometric mixtures within this annular volume at  $20^\circ \text{ C}$  would require a minimum volumetric water flow rate of  $34 \text{ l/min}$  ( $9 \text{ gal/min}$ ), assuming the use of spray nozzles with a  $56\text{-}\mu\text{m}$  SWM droplet diameter and the data in figure 5; for this calculation, 32 nozzles were distributed around the periphery of the drum and 10 nozzles on the drum cowling. This method appears to be simpler in design and requires a smaller water supply than the previous one, although it may be less practically feasible to apply to the trailing drum of a double-drum longwall miner. In any case, the water requirements by either method can be expected to decrease noticeably if the spray temperature can be increased or the droplet diameter decreased. Full-scale evaluation studies are needed to determine the practical limitations of the two proposed spray quenching techniques.

#### Longwall Miner--Steam Inerting

If steam is available, the water vapor requirements for inerting the above described annular volume of a longwall miner can be determined by the use of figure 2. Assuming that the steam can be uniformly distributed throughout the annular volume ( $0.45 \text{ m}^3$ ), the mass rate of steam was calculated for inerting a stoichiometric methane-air mixture in the annular volume with the space being purged every other revolution of the drum. Using a water vapor inerting limit of 31 volume-percent, this would require a total of  $485 \text{ kg/hr}$  ( $1,070 \text{ lb/hr}$ ) of steam for the two drums. More importantly the electrical power requirements for producing the steam would be  $242 \text{ kw}$ . This power requirement is prohibitive considering that a typical longwall miner needs about  $186 \text{ kw}$  to operate three motors at maximum horsepower ( $250 \text{ hp}$ ). Furthermore, it is highly unlikely that the steam could be adequately distributed because of the physical limitations imposed by the coal within the annular volume.

#### Continuous Room-and-Pillar Miners

The inerting or quenching requirements for room-and-pillar mining operations can be expected to be much more difficult to meet than those for longwall mining because of the great differences in mining areas that need to be protected. The longwall miner is limited to a drum width of approximately

75 cm (2.5 feet), whereas room-and-pillar mining can involve drum widths up to at least 460 cm (15 feet); furthermore, the latter involves mining over a greater vertical distance during an operating cycle (about 6 feet versus 4.5 feet). Because of these differences, the use of water sprays or steam for protecting against frictional ignitions appears to be practical only for the longwall mining application where the water requirements could be met.

#### CONCLUSIONS

Limits of flammability for methane-air-water vapor mixtures are in fair agreement with those obtained with a combination of steam and water sprays of about 10- $\mu$ m droplet diameter or less. Water requirements for inerting these mixtures were much less than those for quenching their flame propagation with water sprays. The minimum mass quenching concentration increased linearly with increasing SWM droplet diameter, but the droplet surface area required per unit volume of gas mixture was relatively constant for a given mixture composition. Furthermore, although only two methane-air mixtures were investigated, this effective droplet surface area appeared to correlate with mixture burning velocity or residence time of the droplets in the reaction zone. The water quenching requirements were sensitive to the spray temperature because of the increased saturated water vapor concentration and corresponding reduction of burning velocity.

Extrapolation of the laboratory flame quenching data to the mining situation indicates that the water requirements for protecting a longwall miner would not be prohibitive, although full-scale testing is needed to determine the practicality of such spray quenching systems. Steam inerting for this application does not appear to be practical because of the high power requirements.