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Mine Fire Detection by Ultrasonic Ranging Systems

By Gene F. Friel and John C. Edwards

UNITED STATES DEPARTMENT OF ENERGY

PITTSBURGH RESEARCH CENTER

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	kW	kilowatt
ac	alternating current	L	liter
cm	centimeter	m	meter
cm^2	square centimeter	m^2	square meter
dB	decibel	m/min	meter per minute
dc	direct current	m^3/min	cubic meter per minute
g	gram	m/s	meter per second
Hz	hertz	mm Hg	millimeter of mercury
J	joule	min	minute
J/kg	joule per kilogram	μm	micrometer
J/(kg·K)	joule per kilogram kelvin	ms	millisecond
J/(kgmole·K)	joule per kilogrammole kelvin	pct	percent
K	kelvin	s	second
kg	kilogram	V	volt
kHz	kilohertz	°C	degree Celsius

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

MINE FIRE DETECTION BY ULTRASONIC RANGING SYSTEMS

By Gene F. Friel[1] and John C. Edwards[2]

ABSTRACT

Two commercially available, ultrasonic ranging systems were used to detect experimental fires in a mine entry and a fire research tunnel. Each ranging system, located downwind of the fires, detected the fires within paths between the system and a reflecting surface across the width or height of the entry. The ranging systems emitted waves which, when reflected from surfaces, accurately indicated the distances between the systems and the surfaces at an ambient temperature of 25 °C. Experimental fires in the mine entry were observed to produce four types of changes in the indicated distance. The fires produced fluctuations about the indicated distance, steady changes in the indicated distance, intermittent doubling of the indicated distance, and overranging of the indicated distance. Measurements from these fires were supported by models based upon the gaseous temperature dependency of sound velocity and Snell's law of refraction of acoustic waves. Also, absorption of acoustic energy by smoke particles and gas molecules accounted for some of the overranged indicated distances. The capabilities of these systems to sense changes in gas temperature and the presence of smoke are features for the design of sensors to be included in mine monitoring systems for improving underground mine safety.

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INTRODUCTION

Fire detection systems in mines rely upon the sensing of fire signatures such as carbon monoxide (CO), smoke, or temperature changes. Although subject to airflow dilution, CO and smoke generally can be detected at significant distances from a fire because of insignificant mass loss into the surface of entries. On the other hand, heat transfer from air into the roof, ribs, and floor of an entry and thermal dispersion of heat through the air along an entry can significantly reduce gas temperature a relatively short distance from a mine fire. This phenomenon requires that thermal detection occur relatively near the fire. Also, because of the point-measurement characteristic of most thermal sensors, channeling of hot gas past most thermal sensors can go undetected. Significant advantages of thermal sensors, however, are their low purchase and maintenance costs. An improvement over point thermal sensors is a distributed thermal sensor that can detect an increase in gas temperature along a path. A sensor of this type would be able to detect channeling of hot gas near a mine roof if the channeling occurred along the path. Distributed temperature sensing systems that rely on wires or optical fibers extended along an entry are two types of systems that would eventually detect channeling of hot gas along an entry. This detection would occur after the gas dispersed across the width of the entry at some point where a sensor wire or optical fiber existed (*1*).

Other principles on which a fire detection sensor could be based are the changes in the velocity of sound caused by both gas temperature and compositional changes and the refraction of acoustic waves travelling from an air stream through channeled hot gas or channeled gas of a different composition than the air stream. An increase in gas temperature or concentration of low-molecular-weight species of a gas generally increases the sound velocity through the gas. This results in a decrease in the distance indicated by an ultrasonic ranging system. Refraction will have the effect of increasing the travel distance of an acoustic wave to a parallel reflecting surface and of increasing the indicated distance. The combined result of these effects is that the distance indicated by an ultrasonic ranging system will increase or decrease from the initial value depending on the relative magnitudes of the effects present at any particular time. In turbulent channeled-gas flow, the erratic refractions would increase the noise superimposed on the average distance indication. Absorption of acoustic energy by smoke particles and gas molecules could also prevent the return of an echo to the ranging system and result in an overranged distance indication. These principles were investigated experimentally with two commercial, ultrasonic ranging systems as part of an effort to improve underground, mine fire detection technology.

ULTRASONIC RANGING SYSTEMS

An ultrasonic ranging system, manufactured by the Polaroid Corporation and having part number 603972, was selected first. This ranging system emits ultrasonic waves at four frequencies: 60 kHz, 57 kHz, 53 kHz, and 50 kHz. These frequencies were chosen by the manufacturer to avoid sound absorption of all emitted frequencies by surfaces having different topographical characteristics. The ultrasonic waves are emitted over a 1.06-ms interval by applying 300 V ac to a parallel-plate capacitor in an electrostatic transducer. These voltage waves change the distance separating the capacitor plates which, as a consequence, generate the acoustic waves. The echo received by the transducer compresses the capacitor-plate separation distance and, consequently, increases the capacitance. This capacitance change is detected and amplified by the electronics of the ranging system. The round-trip travel time of the waves is then converted into a distance measurement that is indicated by a light-emitting-diode display. A measured distance of 3.05 m was found to be the same as the indicated distance at 25 °C. The manufacturer stated that this ranging system had the capability of measuring distances from 0.3 m to 10.7 m in an atmosphere with relative humidity ranging from 5% to 95% and temperature of the electronic components ranging from 0 °C to 60 °C (*2*). For extended periods of operation and to avoid corrosion from high humidity, a stainless-steel housing for the transducer was available from the manufacturer. Also, sealing the electronics components and installing a small resistive heater near the transducer would reduce dust and condensation problems that may occur in mining environments.

Altogether, this ranging system was composed of four main parts. A 6-V dc, 2.5-A, Polapulse battery and holder unit was connected by wires to an experimental demonstration circuit board (EDB) that processed the round-trip times and displayed the distances. The EDB was connected by ribbon wire to an ultrasonic circuit board (UB) that generated the 300-volt pulses and relayed the echo signal to the EDB. The UB was then connected to the electrostatic transducer through a coaxial cable that could extend to a maximum of 30 m. This ranging system's components are shown in figure 1. For these experiments, the

[3]Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

EDB, UB, and battery of the system were mounted on a perforated board. The transducer was mounted in another perforated board that was attached to a plywood board. The coaxial cable connected the transducer to the electronics perforated board. The perforated board holding the circuit boards and battery of the system was subsequently attached to another piece of plywood for further protection.

A second Polaroid ranging system, part number 617810, was found to be electronically compatible with a mine monitoring system that was in the Safety Research Coal Mine (SRCM) at the U.S. Bureau of Mines (USBM) Pittsburgh Research Center (PRC). An output voltage range of 0 to 5 V dc from connections to the ranging system was proportional to the indicated distance range. This voltage range could be sampled and recorded by the mine monitoring system. The second ranging system only emitted a single frequency, but this frequency could be selected from 10 frequencies, ranging from 24 kHz to 78 kHz. This selection was accomplished by connecting the electronics board of the second system through an RS-232 interface cable to the COM1 port of a computer and running configuration software that came with the system. Seven other parameters could also be adjusted remotely from within this software. These parameters are the number of wave cycles in each packet of waves emitted, the blanking time after emission of a packet of waves before the system tries to detect an echo, the source of the trigger (internal or external) for emission of the acoustic waves, the rate of sampling of the echoes from the wave packets, the units of the indicated distance, whether the gain of the echo signal would be fixed or determined automatically, and, if fixed, which of 11 gain steps should be chosen. For the electrostatic transducer, a frequency of 52 kHz typically yielded the least energy dissipation of the acoustic signal. The blanking time was typically adjusted to eliminate the detection of transducer ringing after transmission of a wave packet. This adjustment enabled small distances to be measured. The maximum rate of sampling of echoes from the wave packets before interference occurred was limited by the round-trip travel time of the acoustic waves.

Similar voltage pulses were applied to the electrostatic transducer with the second system as were applied to the electrostatic transducer with the first system. However, the voltage of the second system could be increased to 400 V, peak to peak, by adjusting a transformer on the electronics board. The receiver gain of the echo signal to the second system and the level of detection of this echo signal were also adjustable on the electronics board. A required range of alternating current, driving voltages to a piezoelectric (piezo) transducer, which also came with the system, was 5 to 40 V, peak-to-peak. Power to the second system was supplied by a transformer-rectifier unit which converted 120 V ac to 15 V dc. This power supply did not come in the developer's kit of the system. Distance indications were converted from analog to digital signals on the electronics board and indicated by a liquid crystal display (LCD). Polaroid claimed that distance measurements with the second system could be made from 0.025 to 15.2 m and displayed with an accuracy of ±1% of the measurement (*3*). Analog signals were also converted from the voltage range, 0 to 5 V dc, to digital signals through an accessory circuit board before being transmitted to the mine monitoring system for storage. An overranging condition resulted in a 0 voltage being recorded. The electrostatic transducer of the second system, the electronics board, and the accessory circuit board all were mounted on one piece of plywood and are shown in figure 2.

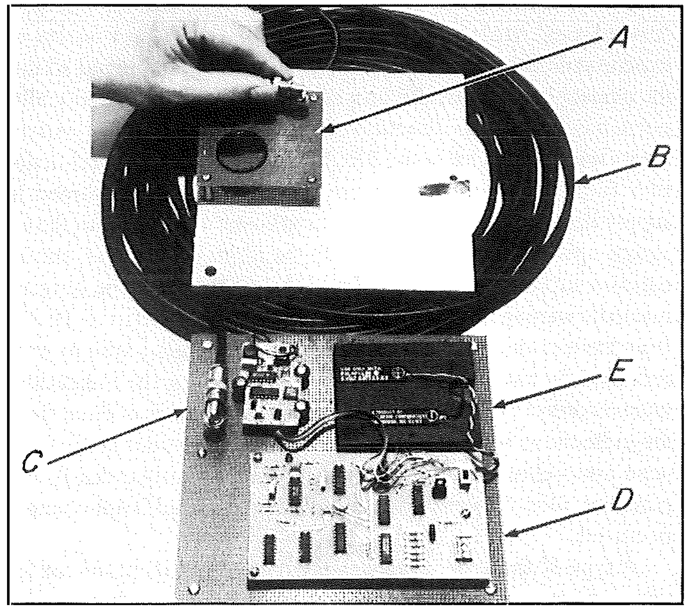

Figure 1.—Component of first ultrasonic ranging system: *A*, electrostatic transducer; *B*, coaxial cable; *C*, ultrasonic circuit board; *D*, experimental demonstration circuit board; *E*, battery.

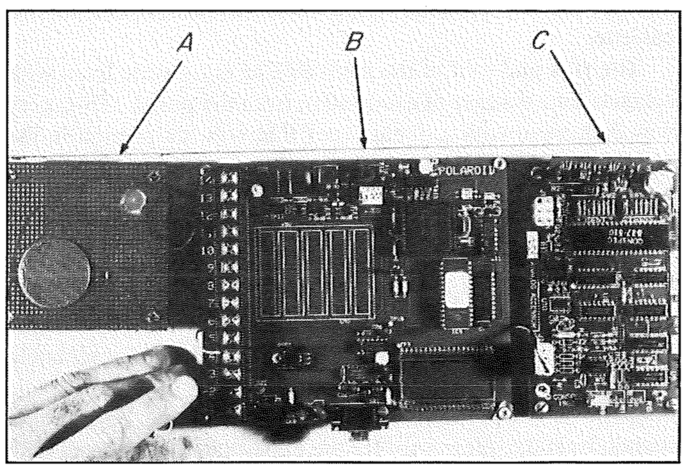

Figure 2—Components of second ultrasonic ranging system: *A*, electrostatic transducer; *B*, electronics circuit board; *C*, accessory circuit board.

EXPERIMENTAL ARRANGEMENTS

FIRST ULTRASONIC RANGING SYSTEM

The first system was initially tested in a laboratory to determine if the distance indicated by the system would decrease when the air in the path of the ultrasonic waves was heated by a Bunsen burner and, if so, would the indicated distance approximate the distance calculated from an estimate of the average temperature along the path. Full-scale mine testing was performed next within an entry of the SRCM. In a series of experiments, the transducer of the system was positioned so that the ultrasonic waves would propagate, horizontally or vertically, perpendicular to the direction of the airflow. Nine fire experiments were conducted in the SRCM. In eight of the experiments, two fuels (diesel fuel and conveyor belting) were burned to supply heat, smoke, and gaseous combustion products to the air stream upwind of the transducer. In the ninth experiment, smoke candles supplied mainly smoke to the air stream. The burning materials were ignited at distances ranging from 3.0 m to 19.2 m from the transducer. The indications of the ranging system were recorded by two means. For the first five fires, the indications were recorded by hand at 30-s intervals. For the next three fires, the indications were recorded by a video camcorder at the 0.2-s scan interval of the ranging system. For the smoke-candle experiment, records were made by hand when significant changes occurred.

A type-K thermocouple was positioned in the middle of the entry and near the acoustic wave path of the transducer to indicate gas temperatures which, with airflow rates, could be used to estimate heat generation rates of the fires. The voltage of the thermocouple was converted by a digital thermometer into temperature, displayed, and recorded by two means. For the first five fires, the temperature was recorded by hand at 30-s intervals. For the next three fires, the temperature was recorded on a video cassette.

The ribs and roof of the main SRCM entry were lined with concrete for a distance of nearly 30 m from the portal. This entry was 3 m wide with a domed roof that was 2.4 m high in the middle and 1.7 m high along the ribs. Concrete covered the floor a distance of 19 m from the portal and the remaining distance along the entry throughout the SRCM was left uncovered. All of the fires in the SRCM were set in square steel trays positioned on the concrete at the edge of the uncovered floor. At 11.3 m from the edge of the concrete floor, the domed roof abruptly became flat with a height of 2 m. The roof remained at approximately this height along the rest of the entry. Figure 3 is a schematic diagram of the positions of the fuel tray, circuit boards, and transducer in the mine entry for the experiments conducted with the first system. This figure displays the transducer distance downwind of the fire, D, and the height of the transducer above the mine floor, H.

In the first five experiments, fires were set in the middle of the entry in a tray measuring 46 cm square (46 cm^2) and 13 cm deep. First, 5 L of water (to reduce thermal warping of the tray) and then, 2 L of No. 1 diesel fuel were poured into this tray for each of these experiments. In the first three experiments (1, 2, and 3), only diesel fuel was burned. In each of the next two experiments (4 and 5), diesel fuel and three pieces of rubber conveyor belting were burned. The conveyor belting was included in the fires to increase the concentration of CO for detection by downwind CO sensors. The pieces of conveyor belting each measured about 1 cm thick by 5 cm wide by 53 cm long. They were wired for rigid support to three iron rods lying on top of the tray. The downwind distance of the transducer from the fire varied from 3.0 m to 11.3 m in these first five experiments.

Three more tray fires with the first system, experiments 6 to 8, were set with the transducer positioned on a rib 19.2 m from the downwind edge of different trays. The first fire in this series was set in a 91-cm^2 tray that was laid in the middle of the concrete floor of the entry. Ten L of water and 4 L of diesel fuel were poured into this tray. The second fire was set in a 76-cm^2, bottomless tray which was inserted inside the 91-cm^2 tray. Three L of diesel fuel were poured onto the water remaining in the tray from the previous fire. The third fire was set in a 61-cm^2 tray also laid in the middle of the floor. Five L of water and 2 L of diesel fuel were poured into this tray. The 91-cm^2 and 76-cm^2 trays were 13 cm deep, while the 61-cm^2 tray was 15 cm deep.

One other experiment with the first system, experiment 9, was performed in the main SRCM entry. Three, 15.2-cm-long smoke candles with diameters of 3.8 cm were distributed evenly across the width of the entry on the uncovered floor. The transducer was positioned on a rib 12.2 m downwind from the candles. This experiment was performed to try to separate the effect of the heated gas from the effect of the smoke on the distance indicated by the system.

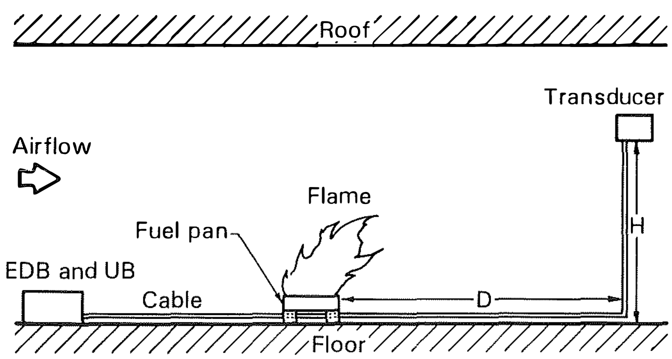

Figure 3.—Schematic diagram of positions of fire source and components of first ultrasonic ranging system in main entry of SRCM.

SECOND ULTRASONIC RANGING SYSTEM

The second system was tested in a manner similar to the tests of the first system. An electrostatic transducer, similar to the transducer used with the first system, was used for initial laboratory tests of the second system. The laboratory measurements were performed to verify that the second system could detect temperature changes along the wave path. The second system then was moved into the SRCM for a series of full-scale tests with the electrostatic and piezo transducers. The electronic components, in addition to the transducer, were protected during experiments 10 through 16 by a static-electricity-proof, clear plastic cover. The cover was removed during the last two experiments (17 and 18) to determine the effects of combustion products on the reliability of the system. For the tests with the electrostatic transducer, five diesel fuel fires (experiments 10 through 14) were set 19.2 m upwind of the transducer and one group of smoke candles (experiment 15) was ignited 12.2 m upwind of the transducer. The 19.2-m distance was selected to allow the trays to be easily placed in a level position on the edge of the concrete floor. A distance less than 19.2 m was chosen to allow the smoke candles to be positioned off the concrete floor to prevent thermal damage to the concrete. All of the fires with the second system consisted of various quantities of diesel fuel and 0.5 L of gasoline being burned on a layer of water about 4 cm thick in the trays. The gasoline was added to improve the speed of ignition of the fires. The response of the second system was recorded at 2-s intervals (the minimum sampling-time interval of the mine monitoring system) as well as the response of a thermocouple in the middle of the gas stream and near the acoustic wave path.

In experiments 10 and 11, 2 L of diesel fuel were burned in the 46-cm^2 tray. To try to separate the effects of heat and smoke from a fire on the second system, experiment 12 was performed using four smoke candles of the same size as were used in experiment 9. Experiment 13 was performed using 3 L of diesel fuel in the 76-cm^2 tray. In experiments 14 and 15, 2 L of diesel fuel were burned in the 61-cm^2 and 46-cm^2 trays, respectively.

Three experiments (16 through 18) were performed with the piezo transducer mounted at the same location as the electrostatic transducer on the plywood board of the second system. These experiments consisted of one group of smoke candles (experiment 16) that ignited 18.3 m upwind of the transducer and two diesel fuel fires (experiments 17 and 18) set 19.2 m upwind of the transducer. Experiment 16 used four smoke candles of the same size as were used in experiment 12. In experiment 17, 4 L of diesel fuel were burned in the 76-cm^2 tray. In experiment 18, 2 L of diesel fuel were burned in the 46-cm^2 tray. The data from the transducer and the thermocouple were collected at 2-s intervals. The latter two experiments were designed to try to bracket the minimum fire size necessary for detection by the piezo transducer at 19.2 m downwind from the fire.

The second system with the piezo transducer was also tested in a ventilated, fire research tunnel having an internal, cross section with dimensions, 76 cm by 76 cm. Two experiments (19 and 20) were conducted with 3.2-kg coal fires ignited by electrical heaters. The fires were located 7.6 m upwind of the transducer. The transducer was located on the floor of the tunnel and the acoustic signal was reflected from the inside roof of the tunnel. The physical configurations of these two experiments were similar. The second system was set for maximum sensitivity to combustion products in both experiments by adjusting the number of waves per packet emitted. Fewer waves per packet made the system more sensitive. A thermocouple was positioned near the middle of the tunnel, just downwind of the path of the vertical acoustic waves, to measure the gas temperature. The optical transmission of the gas-smoke stream was also measured near the thermocouple using an optical transmission assembly. Experimental data were digitized in an analog-to-digital converter and stored in a portable computer. In both experiments, after about 36 min, a water spray was applied to the coal to quench the fires. The configuration software parameters for all of the experiments in the SRCM and the fire research tunnel involving the second system are listed in table 1.

Table 1.—Configuration-software parameters for experiments with second ultrasonic ranging system

Transducer type and experiment	Frequency, kHz	Cycles per packet	Blanking time, ms	Sample rate, Hz	Gain step
Electrostatic:					
10	52	10	2.38	30	1
11	52	16	2.38	1	([1])
12	78	1	1.00	50	1
13	78	10	1.00	50	1
14	78	1	1.00	50	1
15	78	1	1.00	50	1
Piezo electric:					
16	52	16	10.00	30	11
17	52	16	10.00	30	11
18	52	16	10.00	30	11
19	45	5	3.10	100	5
20	45	5	3.10	100	5

[1]Varies.

RESULTS

FIRST ULTRASONIC RANGING SYSTEM

Laboratory experiments confirmed that both ranging systems were not temperature compensated. Hot air present along the wave path caused the systems to indicate a smaller distance than was indicated when cold air was present along the same wave path. The heated-air reductions in indicated distance of the first system averaged 13% greater than calculated from equation (A-3) in appendix A and the average temperatures of the experiments. The reductions in indicated distances were considered to be within experimental error.

The first experiment with the first system within the SRCM involved positioning the transducer 4.6 m downwind of the tray, 1.2 m above the floor, and next to a rib. A thermocouple was positioned 3 m downwind of the tray, 1.6 m above the floor, and in the middle of the entry. Before the fire was ignited, the ranging system indicated a steady, 3.14-m width of the entry and the thermocouple indicated 8 °C. The average air velocity through the entry upwind of and near to the tray was 111 m/min with a calculated airflow rate of 743 m^3/min. After the diesel fuel was ignited with a paper wick, the ranging system indicated an apparent random sequence of distances over a range from 3.08 to 3.20 m. Two min after the start of the fire, the thermocouple indicated a maximum temperature of 19 °C. When the fire was extinguished by placing a lid over the tray 4 min after ignition, the indicated distance returned to a steady 3.14-m value. The thermocouple also returned to its initial value of 8 °C.

The transducer was then moved for experiment 2 to a point 3 m downwind of the tray at the same height along the same rib as before. The ranging system indicated a steady distance of 3.11 m. After the fire was ignited, the ranging system indicated a range of distances from 3.08 to 3.17 m with intermittent overranging to 10.7 m. The overranged value indicated that the echoes were not strong enough to be detected. The thermocouple indicated a maximum value of 17 °C 1.5 min after the start of the fire. After 3.5 min from ignition, the fire was extinguished. The ranging system returned to its initial indication of a steady 3.11 m and the thermocouple indicated 9 °C.

For experiment 3, the transducer was moved 10.7 m downwind from the tray, at the same height, and along the same rib as were used in the previous experiments. The ranging system steadily indicated a distance of 3.14 m and the thermocouple indicated 9 °C. After the fire was ignited, the ranging system indicated a range of distances from 3.08 to 3.29 m. Distances of 6.2 m and 10.7 m were also intermittently displayed. The maximum thermocouple temperature, indicated 2 min after the start of the fire, was 25 °C. After the fire was extinguished 5 min from ignition, the ranging system indicated a steady 3.14 m and the thermocouple indicated 9 °C again.

To determine the capability of the ranging system to detect hot gases along the domed roof, a fourth experiment was conducted. In experiment 4, the transducer was placed on the floor in the middle of the entry, 4.6 m downwind from the tray, and pointed toward the apex of the domed roof. The thermocouple was placed 3.1 m downwind of the tray, 2 m above the floor, and in the middle of the entry. The thermocouple indicated an air temperature of 9 °C. An electronic hygrometer indicated 100% relative humidity in the entry. The average air velocity through the entry was 110 m/min with an airflow rate of 736 m^3/min. The initial height indication of the ranging system was a steady 2.41 m. After the diesel fuel below the conveyor belt strips was ignited, the ranging system indicated heights from 2.35 to 2.59 m. Heights of 4.8 m and 10.7 m were also intermittently displayed. The maximum thermocouple temperature displayed 4 min after the start of the fire was 17 °C. When the fire was extinguished 10 min after ignition, the ranging system and the thermocouple returned to their initial indicated values of 2.41 m and 9 °C, respectively.

The capability of the ranging system to detect hot gases along the roof where the roof flattened was measured in the fifth experiment. The transducer was positioned 11.3 m downwind of the tray, 1.7 m above the floor, and along the same rib as in experiments 1 to 3. Before the ignition of the fire, the ranging system indicated a steady 3.11 m. The thermocouple was at the same position as in the fourth experiment and indicated an initial temperature of 9 °C. The relative humidity indication was 100%. The average air velocity through the entry was the same as the velocity in the fourth experiment, 110 m/min. After the diesel fuel below the conveyor belt strips was ignited, the ranging system indicated distances from 3.05 to 3.20 m. Distances of about 6.2 m and 10.7 m were also intermittently displayed. The maximum thermocouple temperature displayed 2 min after the start of the fire was 12 °C. The average downwind tilt of the flames was observed to be about 45°. When the fire was extinguished 12 min after ignition, the ranging system and the thermocouple returned to their initial indicated values of 3.11 m and 9 °C, respectively.

The saturated humidity had no detectable effect on the operation of the ranging system during experiments 4 and 5. Based on the higher heat of combustion of No. 1 diesel fuel (*4*), 4.47×10^7 J/kg, and the average measured burning time of 2 L of this fuel in the entry, 15 min, a nominal heat generation rate of 87 kW was calculated for each of the first three underground fires. The effect of the conveyor belt strips on the heat generation rate of experimental fires 4 and 5 is not known. However, the flame size for all five fires was approximately the same.

Three additional experiments (6, 7, and 8) with the first system were conducted with larger fuel trays to determine the effect of larger fires and more concentrated smoke emissions on the indications of the ranging system. Also, the distance of the transducer was extended to 19.2 m from the fires, next to a rib, and 1.5 m above the floor. A length of 26 m of coaxial cable was connected between the UB and the transducer. The thermocouple was positioned 0.6 m upwind of the path of the acoustic waves, in the middle of the entry, and 1.6 m above the floor. Only diesel fuel was burned during these three experiments.

Before the ignition of the fire in the sixth experiment, the ranging system indicated 3.20 m and the thermocouple indicated 12 °C. The average air velocity was 98 m/min with an airflow rate of 653 m^3/min. Air pressure, converted from a measurement by an altimeter near the site of the fire, was 741 mm Hg. The distance indications began to change 10 s after the fuel was ignited. These indications ranged from 3.14 to 3.38 m before beginning to intermittently overrange to 10.7 m at 23 s after ignition. The temperature increased to 15 °C over this 23-s interval. The distance indications were uniformly overranging from 58 s until 90 s after ignition. After this time interval, the distance indications ranged from 2.96 to 3.38 m with intermittent overranging until the fire burned out. The peak temperature was 80 °C and occurred 79 s after ignition. The distance indications returned to a steady 3.20 m and the temperature measurement returned to 12 °C after 540 s from ignition.

In experiment 7 at 14.5 s after ignition, the distance indications began to change. Distances ranged from 3.14 to 3.32 m until 19.5 s after ignition when intermittent overranging began. The temperature increased from 12 to 15 °C during this 19.5-s interval. When a temperature of 48 °C was reached at 44 s after ignition, distance indications began to uniformly overrange and continued to overrange until 75 s after ignition. At 75 s after ignition and the peak temperature of 74 °C, one 2.96-m distance indication occurred. After 75 s and until 87 s, the uniformly overranging indications continued. At 87 s, when the temperature was 66 °C, and until 650 s, the distances ranged from 3.05 to 3.38 m with a diminishing frequency of overranging. The temperature decreased over this time interval to an approximate equilibrium value of 13 °C at 650 s.

In experiment 8 at 19 s after ignition, the distance indications began to change significantly. Distances ranged from 3.08 to 3.38 m with intermittent overranging until 480 s after ignition. At 480 s, the indications returned to the initial distance of 3.20 m. The temperature started at 12 °C, peaked 113 s after ignition at 33 °C, and reached an approximate equilibrium of 13 °C at 480 s from ignition. Only twice were the initial distance indications doubled during these three experiments. These doublings occurred during experiment 6 when the temperature was decreasing.

To obtain evidence that smoke and not the temperature of the gas was responsible for the continuous overranging of distance indications, a ninth experiment was conducted. In experiment 9, the flow rate of air through the entry was throttled by a brattice with a hole in it of 0.4-m^2 area. This brattice was positioned over the portal of the entry. The leaky brattice and an additional opening of an airway around the entry produced an airflow rate through the entry of approximately 40 m^3/min. The transducer was positioned at the same location along the entry as it was in the previous three experiments, but it was 1 m above the floor because lesser convective rise of smoke was anticipated. The length of coaxial cable remained at 26 m. Three, 15-cm-long, smoke candles were distributed evenly across the cross section of the entry 12.2 m from the transducer and then ignited. The smoke backed upwind to a point 23 m from the transducer before being moved downwind when the candles burned out. The transducer indications started at 3.17 m and increased to 3.30 m before overranging to 10.7 m. The overranging condition continued until the indicated distances decreased from 3.30 to a steady 3.17 m in a manner nearly symmetrical with the increase in indicated distances before overranging. The smoke at the transducer appeared to be fairly dense just before the wall of smoke moved past the transducer. Little dispersion of smoke occurred along the entry upwind of the smoke candles. When the smoke passed the transducer, the distance indications returned to the initial value of 3.17 m. The visibility of objects near the transducer when the smoke wall passed the transducer was estimated at less than 1 m. No doubling of the initial distance indications was observed during this experiment. The relative humidity in the entry was 100%, but no electrical problems from this humidity were detected. The maximum, plus-and-minus percentage changes in the initial indicated distances for experiments 1 to 9 are summarized in figure 4. The lack of significant heat from the smoke candles and, in turn, lack of significant air temperature increase is reflected in the lack of negative percent changes in the initial indicated distance for experiment 9 in this figure. Acoustic models to account for the effects summarized in figure 4 are presented in appendix A.

SECOND ULTRASONIC RANGING SYSTEM

The electronics board and the transducers in the fire experiments with the second ultrasonic ranging system (experiments 10, 11, 13, 14, 15, 17, and 18) were positioned 19.2 m from the fuel trays along the same rib that was used for the previous experiments with the first system. In experiment 10, the average air velocity in the entry near the fuel tray was 110 m/min. The thermocouple was positioned 0.7 m downwind from the transducer in the middle of the entry. Both the transducer and the thermocouple were positioned 0.4 m from the roof. The configuration software parameters were set to the values listed for experiment 10 in table 1. The initial air temperature

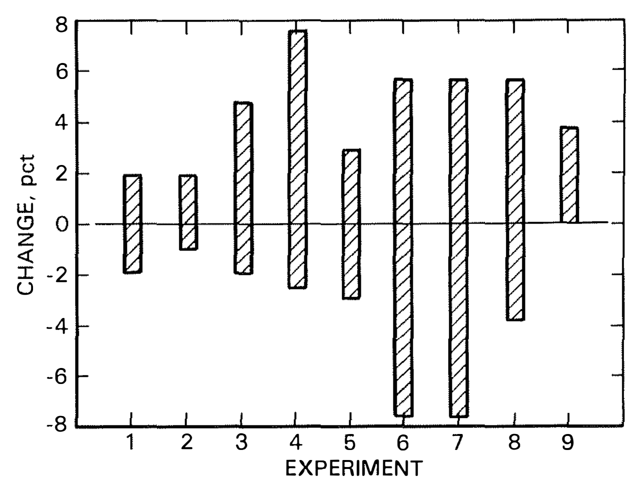

Figure 4.—Largest, plus-and-minus percentage changes of indicated distances of first ultrasonic ranging system.

and distance indication were 16 °C and 3.09 m, respectively. This initial distance, indicated by the LCD display, was recorded by hand. The initial indicated distance and its sampled voltage were used later to determine a conversion factor to convert sampled voltages during the experiment to indicated distances. After ignition of the fire, the gas temperature increased 270 s later to a maximum of 31 °C, while the indicated distance decreased to an average of 3.00 m. Soon after the maximum temperature occurred, the system overranged once to a value recorded as 0 volts. This overranged value was caused by an echo too weak to be detected. At about 550 s after ignition and after the fire burned out, the temperature decreased to an equilibrium value of 17 °C and the distance indications were approximately 3.07 m.

In experiment 11, the same-sized tray, quantity of fuels, and transducer location were used as in experiment 10, but the software parameters of the second system were set back to their default values. The initial air temperature and distance indications were 17 °C and 3.08 m, respectively. After ignition of the fire, the temperature rose to a maximum of 32 °C in about 230 s and the distance indications sagged to an average minimum of about 3.01 m. The noise level was greater in this experiment but was not great enough to obscure the general temperature effect on the distance indications.

To determine the effect of smoke without significant heat on the electrostatic transducer of the second system, four smoke candles were ignited during experiment 12 about 18.3 m from the transducer. The transducer was positioned 1.2 m from the floor at the same place along the entry as used in experiment 9. The airflow rate was determined to be 57 m^3/min. The initial distance indication was 3.14 m. The distance indications overranged for 230 s during the time the candles were burning with intermittent returns to indications of 3.14 m at the beginning and ending of the overranging period.

In experiment 13, the transducer was located 19.2 m from the fuel tray and 1.5 m from the floor. A thermocouple, positioned downwind of the acoustic wave path, initially indicated 16 °C and rose to a peak of 39 °C over a time span of 130 s. The initial distance indication of 3.08 m sagged to a low of 2.97 m with intermittent overranging during this period of rising temperature. Near the peak temperature, a period of about 15 s occurred when the indications were constantly overranging. After the peak temperature passed, intermittent overranging and increasing distance indications ensued until the distance indicated was the initial value of 3.08 m. The total time within which distance indications varied was about 300 s.

In experiment 14, the transducer was at a similar location in the entry as in experiment 13 but was 1.4 m from the floor. The initial temperature and distance indications were 8 °C and 3.16 m, respectively. During the fire, the temperature rose to a peak of 26 °C, while the indicated distance dipped to 3.07 m. Only two overranged indications were recorded during the 800 s of burning, although several low-voltage indications were recorded.

In experiment 15, the transducer was located as in experiment 14. The initial temperature and distance indications were also the same as in experiment 14, 8 °C and 3.16 m, respectively. During the fire, the temperature rose to 13 °C, while the indicated distance decreased to 3.12 m. No overranging occurred, but dips in indicated distance to a low value of 1.31 m occurred after the peak temperature and near the start of the water boiling in the tray. After a burn period of about 600 s, the indicated distance returned to the initial value of 3.16 m and the dips in indicated distance ceased. For the 19.2-m distance from the fire to the transducer, the fire size in this experiment was near the minimum size for detection.

The piezo transducer was connected to the second system for experiment 16, a smoke experiment. The airflow rate was the same as in experiment 12, 57 m^3/min. The transducer was located 1.1 m from the floor. Four smoke candles were ignited 18.3 m from the transducer. The initial distance indication of 3.19 m began to overrange when the smoke crossed the path of the acoustic waves. No intermittent returns to 3.19 m occurred until the smoke began to clear. After the smoke cleared, the system indicated the initial distance of 3.19 m.

Experiment 17 was a fire experiment to determine if the piezo transducer positioned 1.5 m from the floor would detect products of combustion generated 19.2 m upwind from the transducer. The initial air temperature of 2 °C rose to nearly 37 °C during the fire which lasted about 340 s. The distance indications overranged intermittently during the beginning of the burning period. Overranging occurred constantly for 240 s during the middle portion of this period and intermittently near the end of the period. After the fire burned out, the initial value of 3.21 m was steadily indicated. Figure 5 displays the gas temperature and indicated distance recorded during this experiment.

Experiment 18 was an effort to determine the minimum fire size that would be detectable by the piezo transducer located 19.2 m from the fire and 1.4 m from the floor. The initial distance indication of 3.19 m decreased to 3.10 m as the temperature increased from 2 to 19 °C. Extensive intermittent overranging occurred during the burning period. No periods of constant overranging occurred as happened in experiment 17. Spikes of noise were present during this experiment before and after the fire and above and below the indicated distance at equilibrium. These spikes were most likely caused by moisture condensing on the electronics board from a warm, water-saturated air stream entering the relatively cold entry.

Experiments 19 and 20 were performed to determine the response of the second system with the piezo transducer to a burning coal pile in a fire research tunnel. The airflow rate through the tunnel was set at about 15 m/min. For experiment 19, the initial gas temperature of 24 °C rose to 27 °C over a time span of 1,500 s during the smoldering period of the coal. The gas temperature then increased to a maximum of 42 °C over an additional time span of 100 s after the coal began to flame. The indicated distance during these time intervals fluctuated from an initial value of 73 cm before electrical heating to the overranged

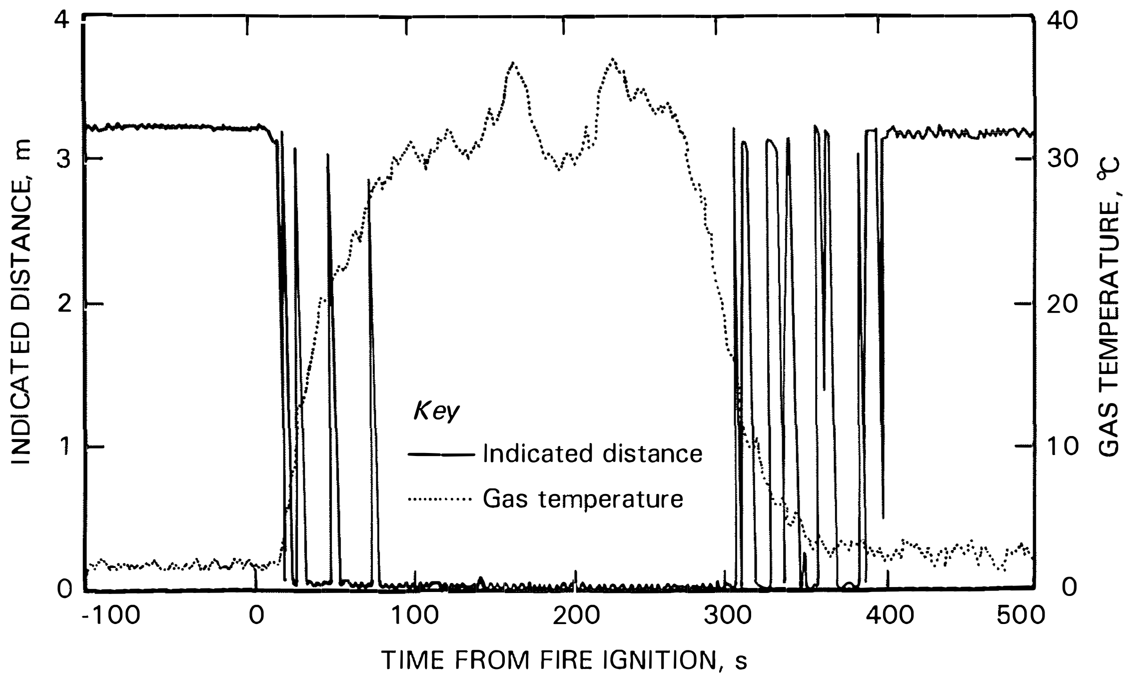

Figure 5.—Time variation of gas temperature and indicated distance of second ultrasonic ranging system with piezo transducer in experiment 17.

value of essentially 0 cm. This overranging occurred at an increasing rate as the gas temperature increased. When the fire was quenched, the indicated distance returned to 73 cm and the number of overranged fluctuations decreased.

Experiment 20 differed from experiment 19 in that the signal from the second system in experiment 20 was electronically filtered by a first-order, low-pass filter having a time constant of 16 s and a 3-dB, cutoff frequency of 0.01 Hz. The cutoff frequency was selected in order to dampen the frequencies of noise recorded in experiment 19. The initial gas temperature of 23 °C rose to 27 °C over a time span of 1,700 s during the coal smoldering phase. After the coal began to flame, the gas temperature increased to a maximum of 36 °C over an additional time span of about 400 s. The unfiltered, indicated distance, which was also recorded, responded in a manner similar to that in experiment 19 during the coal heating and flaming phases of the experiment. The optical transmission through the gas-smoke stream was measured near the thermocouple over a horizontal path at the middle of the height of the airway and transverse to the gas flow direction. The definition of the optical transmission was the fraction of the prefire optical transmission of the average of two visible electromagnetic wavelengths, 0.45 μm and 0.63 μm. From a measurement of the length of the optical path, optical density can be calculated from the following equation:

$$OD = -(\log_{10} I)/OL, \qquad (1)$$

where OD = optical density,

OL = optical path length (0.683 m in the case of the fire research tunnel),

and I = optical transmission.

Figure 6 compares normalized values of the filtered indicated distance with the optical transmission as they vary with time from ignition of the fire. The normalization was achieved by dividing the time variations of indicated distance by the initial indicated distance before plotting. This figure shows how closely the acoustic measurement follows the optical transmission during the initial burning period when fire detection is most important. Figure 7 compares the time variations of the filtered indicated distance and optical density. From figure 7 it can be seen that the filtered indicated distance begins an erratic decrease from the near-steady initial indicated distance when about 1,100 s have passed since the start of coal heating. The onset of this decreasing indicated distance corresponds to a detectible increase in the optical density. The time average of the filtered indicated distance before heating of the coal was 71.3 cm with a standard deviation of 0.878 cm. If an alarm value for the second system is set at the time average plus ten standard deviations to eliminate most false alarms, then the alarm would have occurred at an optical density of 0.0254 m^{-1}. This value of optical density falls within the alarm-level range for class 2 smoke detectors (*5*). Given the conditions of experiment 20 and utilizing the above alarm value, the second system would have alarmed 136 s after the alarm of a class 1 smoke detector. A class 1 smoke detector is set to alarm at an optical density of 0.022 m^{-1}. No significant refractive effects or doubling of distance from refractive effects were measured by the second system. It is possible that the shape of the transducer acoustic beam patterns, different sensitivities of detection, or the presence

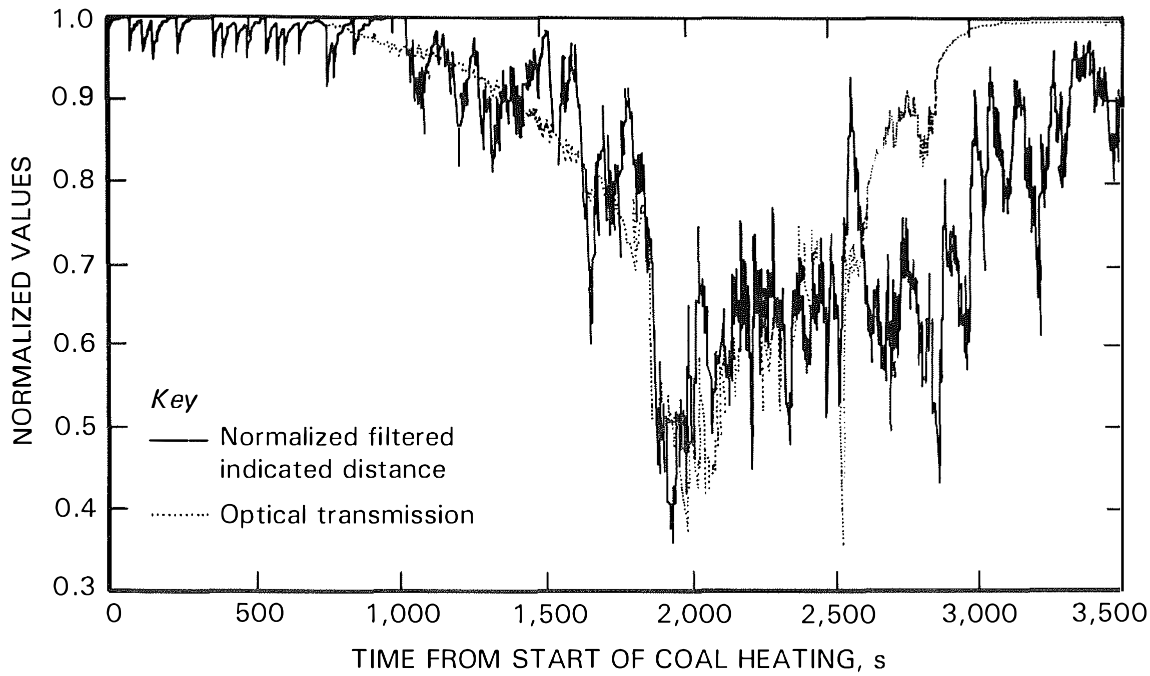

Figure 6—Time variation of normalized curves of filtered indicated distance and optical transmission.

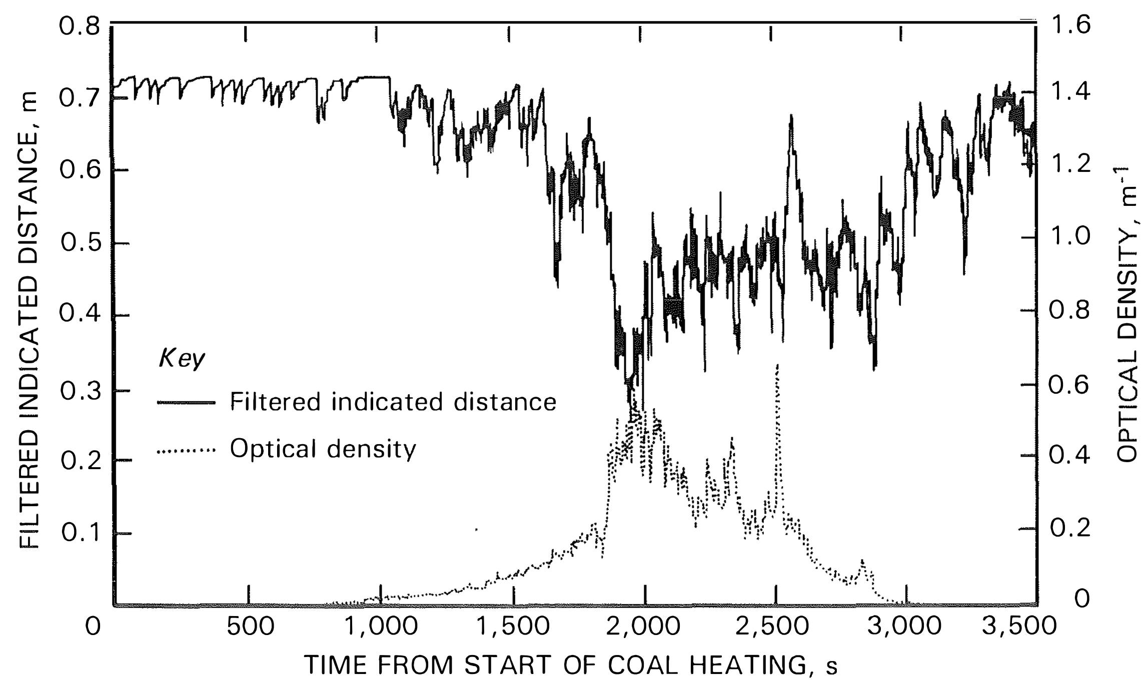

Figure 7.—Time variation of filtered indicated distance and optical density.

of the electronics boards near the transducer of the second system may have prevented refractive effects from being recorded. The temperature of the gas in the path of the waves, however, had the same predictable effect on the distance indicated as occurred with the first system.

Table 2 contains a summary of the indicated distance of the ranging systems before, during, and after the SRCM fires and the thermocouple temperature extremes in each of the 18 mine experiments.

Table 2.—Ranging system data for underground mine experiments

Transducer type and experiment	S, cm	D, m	H, m	Temperature, °C G_i	Temperature, °C G_p	Indicated distance,[1] m Before and after fire	Indicated distance,[1] m During fire[2]
			SYSTEM 1				
Electrostatic:							
1	46	4.6	1.2	8	19	3.14	3.08-3.20
2	46	3.0	1.2	8	17	3.11	[3]3.08-3.17
3	46	10.7	1.2	9	25	3.14	[3]3.08-3.29,
4	46	4.6	[4]0.0	9	17	2.41	[3]2.35-2.59,
5	46	11.3	1.7	9	12	3.11	[3]3.05-3.20,
6	91	19.2	1.7	12	80	3.20	[3]3.14-3.38
7	76	19.2	1.7	12	74	3.20	[3]3.14-3.32
8	61	19.2	1.4	12	33	3.20	3.08-3.38
9[5]	NAp	12.2	1.0	NAp	NAp	3.17	[3]3.17-3.30
			SYSTEM 2				
Electrostatic:							
10	46	19.2	1.4	16	31	3.09	3.00
11	46	19.2	1.4	17	33	3.09	2.99
12[5]	NAp	12.2	1.2	NAp	NAp	3.19	([3])
13	76	19.2	1.5	16	39	3.21	[3]2.97
14	61	19.2	1.4	8	26	3.16	[3]3.07
15	46	19.2	1.4	8	13	3.16	3.12, 1.31
Piezoelectric:							
16[5]	NAp	18.3	1.1	NAp	NAp	3.14	([3])
17	76	19.2	1.5	2	37	3.21	([3])
18	46	19.2	1.4	2	19	3.19	[3]3.10

D Distance between fire and acoustic transducer.
G_i Initial gas temperature.
G_p Peak gas temperature.
H Height of acoustic transducer above floor.
NAp Not applicable.
S Length of square tray side.
[1]Indicated distance of ultrasonic ranging system.
[2]Values of 4.8 m and 6.2 m during fires were infrequent.
[3]One or more overranged values.
[4]Transducer was on floor.
[5]Smoke-candle experiment.

CONCLUSIONS

In 18 underground mine fire experiments, it was demonstrated that 2 ultrasonic ranging systems indicated the occurrence of a fire in an entry through changes in measurements of distance transverse to the direction of entry airflow. In smoke-candle experiments, it was shown that the ranging systems would respond to dense smoke in the absence of significant generated heat. In the first eight experiments, the first system detected fires when positioned with acoustic paths that propagated either vertically or horizontally. The horizontal acoustic paths set in the experiments were positioned from 50% to 85% of the roof height above the mine floor. The experimental results were supported by acoustic principles described in appendix A which included the temperature dependency of sound velocity, the refraction of sound waves, and the absorption of acoustic energy by a smoke-filled gas.

The primary mode of fire detection by the first system was the generation of an erratic signal, caused mainly by thermal or concentration eddies in a gas that refracted the ultrasonic waves and resulted in variations in the distance indicated. The secondary mode of detection was the absorption of the acoustic energy emitted from the ranging system by a dense concentration of smoke that caused the system to overrange. The tertiary mode of detection was the reduction in distance indicated by the system caused by a uniformly heated gas.

The second ultrasonic ranging system also displayed the above modes of fire detection. However, the primary mode consisted of erratic excursions to an indicated distance of zero rather than erratic variations about an initial indicated distance. It was demonstrated in an experiment in a fire research tunnel that the second system with the piezoelectric transducer could alarm at an optical density of 0.025 m^{-1} when an appropriate alarm criterion was specified. In this experiment, with heat and smoke generated by flaming coal combustion, the alarm of the second system occurred 136 s after an optical density of 0.022 m^{-1} was measured. The observed tilt of flames caused by a nominal entry air velocity of 110 m/min was about 45°. If this air velocity is present in an entry, an ultrasonic sensor should be installed at least one roof height downwind from a potential fire source and preferably near the roof of the entry to detect the rising hot combustion products. From experimental evidence, this distance downwind from the fire source could be extended to about 20 m and still result in the detection of the fire by an ultrasonic sensor. This distance from a potential fire source could then be adjusted depending on the air velocity range through the entry and the physical characteristics of the location (*6*).

Based on this study, an ultrasonic sensor is a promising candidate for mine fire detection. It offers an improvement over a point thermal sensor in the sense that it can detect hot gas or smoke channeling that might bypass a point sensor. In underground mining applications, the sensor should be enclosed to resist shock, humidity, and dust. The piezo transducer was more rugged than the electrostatic transducer, both mechanically and chemically, and was more easily cleaned of dust. The piezo transducer should be the choice of the two transducers that were tested for inclusion in an underground ultrasonic sensor. Optimal locations for ultrasonic sensors could be downwind from mining installations such as belt drives and electrical transformers. The signal from the sensor could be converted into a signal for processing by a mine monitoring system to assure rapid detection of a mine fire.

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APPENDIX A.—ACOUSTIC MODELS

The velocity of sound, V, through an ideal gas can be calculated by the equation (*7*):

$$V = \sqrt{\frac{kRT}{M}}, \qquad \text{(A-1)}$$

where k = specific heat ratio of the gas ($k = C_p/C_v$, C_p is the constant-pressure heat capacity, and C_v is the constant- volume heat capacity,)

R = universal gas constant,

T = absolute temperature of the gas,

and M = molecular weight of the gas.

For the conditions of the first eight experiments, the mole-fraction average values of C_p and M are accurate values for these variables in the gas mixtures estimated to have occurred in the acoustic paths (*8*). The specific heat ratio of the gas mixture can be estimated from R and the average value of C_p. The average molecular weight of a typical gas and smoke mixture passing the transducer was calculated for the conditions of the first, eight mine experiments. It was found to be within 99% of that of air (*9-10*). An ideal gas model for this mixture is also an accurate model for the experimental conditions of the SRCM. Because the molecular weight of the mixture is essentially that of air, the contributions to k of the major components in the gas besides air (CO_2, H_2O, and smoke) do not significantly change the value of k from the value for air, 1.4. The result of these conditions is that the velocity of sound through gas downwind of the experimental fires did not change significantly because of changes in k and M, but was mainly a function of the gas temperature along the acoustic path.

The ultrasonic waves that passed through the gases downwind of the fires were refracted by differences in wave speeds in hot gas and cold air eddies. By combining the temperature dependency of sound velocity from equation A-1 and Snell's law (*11*), based on achieving the minimum time of travel of waves through media, the following equivalencies result:

$$\sqrt{\frac{T_1}{T_2}} = \frac{V_1}{V_2} = \frac{\sin \theta_1}{\sin \theta_2}. \qquad \text{(A-2)}$$

The subscripts 1 and 2 refer to the values of the variables in two gases. The θ's are the angles between the perpendicular to the interface between these gases and the paths of the ultrasonic waves through the gases. These equations were used to determine the minimum temperature difference for an angle of wave deflection that would not return an echo of sufficient energy to be detected by the first system. From measurements about 3 m from a brick wall, it was determined that, for transducer angles greater than 20° from the perpendicular to the wall, the echoes reflected to the transducer through air were too weak to be detected. Consequently, the first system would overrange to an indication of 10.7 m. The minimum temperature of a hot gas, next to air with a temperature of 9 °C that would cause a 20° deflection of the ultrasonic waves, was calculated to be 46 °C from equation A-2 with $\theta_1 = 70°$ and $\theta_2 = 90°$. This situation occurs when the waves are deflected along the interface between the two gases. An intermittent gas eddy temperature of 46 °C at a distance less than 20 m downwind of a fire does not seem unreasonable. Also, the absorption of acoustic energy by the gas and smoke would cause the gas and smoke temperature to be less than 46 °C when overranging would first occur.

The distance indicated by the ranging systems is directly proportional to the time period between the emission of a wave and the detection of an echo. X = Nt where X is the indicated distance, N is a constant, and t is the round-trip time of travel of the acoustic wave. If X_m is the real distance between an acoustic transducer and the reflecting surface, then the sound velocity along the acoustic wave path can be related to the indicated distance from the equation, $V = 2X_m/t = 2NX_m/X$. If this equation is substituted for each sound velocity in equation A-2 and the constant terms canceled, the following equation relating indicated distances and temperatures occurs:

$$X_2 = X_1\sqrt{\frac{T_1}{T_2}}. \qquad \text{(A-3)}$$

If the blanket of 46 °C gas had descended totally into the path of the ultrasonic waves, a distance indication, X_1 = 3.11 m, at absolute temperature, T_1 = 282 K, would have decreased to a value of X_2 = 2.92 m at T_2 = 319 K as calculated from equation A-3.

The intermittent values of twice the nonfire distances, that were indicated by the first system during the fires, were probably caused by the acoustic waves being refracted by the gas and reflected three times from the ribs. The first reflection would be from the far rib. The next reflection would be from the rib with the transducer, but not at the transducer because of refractions. The final reflection would be from the far rib again before being refracted back to the transducer with sufficient energy to be detected.

Since the lone 2.96-m distance indication at 75 s after ignition in experiment 7 was the lowest distance indication recorded during this fire, the most likely cause of this indication was a clear, hot air eddy that briefly passed in front of the transducer. If the peak temperature of 74 °C that had been measured at 75 s had been uniformly distributed across the acoustic path, the distance indication, calculated from equation A-3, should have been 2.90 m. A combination of cold mine ribs reducing the gas temperature near the ribs and refraction of the waves could account for the measured distance being larger than the calculated distance. If the temperature had affected the transducer or the reflective surface and caused the overranged indications, it is unlikely that a single indication at 74 °C that did not overrange, without any similar indications nearby on either side of the temperature peak, would have occurred. This is because temperature changes within the solid objects would occur more slowly than gas eddy changes within the entry.

The smoke in the ninth experiment was observed to be more concentrated than the smoke in the first eight experiments. Brief excursions were observed above the initial distance indication before overranging began. Similar brief excursions from overranging to values above the initial distance indication before returning to the initial distance indication also were observed. These excursions could have been caused by turbulent eddies of dense smoke concentration refracting the acoustic waves. These excursions also could have been attributed to increases in the average molecular weight of the mixtures caused by the dense smoke. When the dense smoke filled the entry, the smoke particles and the gas molecules absorbed the energy emitted by the transducer and caused the overranging. Smoke particles would oscillate over a smaller distance than the gas molecules, because of the larger inertia of the smoke particles, with friction between smoke and gas dissipating the acoustic energy as heat. By adjusting the voltage at the transducer to a level that just allows a steady distance indication with little noise present, a smaller concentration of smoke may have been detected by the first system.

APPENDIX B.—LIST OF SYMBOLS

C_p constant-pressure heat capacity, J/(kg-K)

C_v constant-volume heat capacity, J/(kg-K)

D distance between fire and acoustic transducer, m

G_i initial gas temperature, °C

G_p peak gas temperature, °C

H height of acoustic transducer above floor, m

I optical transmission

k specific heat ratio

OL optical path length, m

M molecular weight, kg

N proportionality constant, m/s

OD optical density, m^{-1}

R universal gas constant, $kg\text{-}m^2/(s^2\text{-}K)$

S length of square tray side, cm

T absolute temperature, K

V sound velocity, m/s

X indicated distance of ranging system, m

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