Effectiveness of Various Concentrations of an Inert Gas Mixture for Preventing and Suppressing Mining Equipment Cab Fires: Development of a Dual Cab Fire Inerting System

Maria I. De Rosa[*], *Industrial Hygienist, Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA*
Charles D. Litton, Research Physicist, Pittsburgh Research Laboratory, National Institute for Occupational Safety and Health, Pittsburgh, PA

Abstract. The National Institute for Occupational Safety and Health (NIOSH/PRL) conducted a series of large-scale experiments to evaluate the effectiveness and safety of various concentrations of an inert gas mixture (CO_2, 8%; N_2, 50%; Ar, 42%) for preventing and suppressing cab fires. Comparison of concentrations effectiveness in yielding safe times has led to the choice of an optimum gas mixture concentration, discharged in the cab through a muffled nozzle system, for the development of a dual cab fire inerting system. Of note is that safety training programs, including the synchronization of performed tasks, need to accompany this technology to enhance operator's efficiency and safety during fire emergencies within the safe times yielded by the cab fire inerting system.

Cab fires are caused by the ignition of flammable vapors and mists (ball of fire) that penetrate the cab during prolonged hydraulic fluid and fuel fires, and electrical malfunctions involving other cab combustible materials. Often, these fires force the operator to exit the cab under hazardous conditions during a time needed to perform emergency tasks. Hence, it is important to provide the operator, not only with an engine fire suppression system (dry chemical powder), but also with a cab fire protection system, effective both in preventing the ignition of flammable vapors in the cab, and suppressing cab material fires.

Keywords: fires, equipment, inert systems, fire suppression, fire prevention

---

[*] This paper details the results of the experiments, and presents the development of a dual cab fire inert system, using an optimum gas mixture concentration discharged in the cab through a muffled nozzle system. Of note is that the design of a gas mixture concentration volume according to cab volumes, and system fabrication/installation have been undertaken by cooperating industries.

Disclaimer: This information is distributed solely for the purpose of pre-dissemination peer review under applicable information quality guidelines. It has not been formally disseminated by NIOSH. It does not represent and should not be construed to represent any agency determination or policy.

Introduction

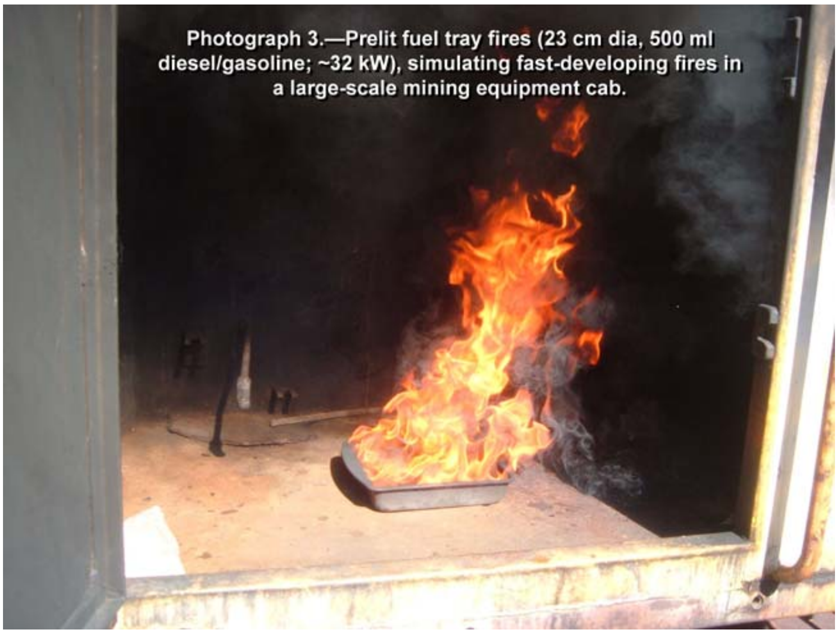
Background

An analysis of mining equipment fires from 1990–1999 showed that 172 of the 339 mobile equipment fires, with 72 injuries and 3 fatalities, were caused by the spraying of pressurized hydraulic fluid and fuel onto engine hot surfaces due to ruptured lines [1–3]. On 97 occasions, these fires grew out of control because of the continuous flow of fluids from the pumps due to engine shutoff failure, lack of an emergency line evacuation system and fire barriers or lack of effective local fire fighting capabilities. Often, these fires re-ignited fueled by the flow of pressurized fluids embedded in the lines. Furthermore, during these fires, at least sixteen times, flames rapidly erupted in the cab (ball of fire) due to the ignition of flammable vapors and mists that penetrated the cab, forcing the operator to exit under hazardous conditions during a time needed to perform emergency tasks. In addition to these incidents, at least ten fires were found to originate within the cab itself due to electrical malfunctions, involving other cab materials. Hence, it is important to provide the operator, not only with an engine fire suppression system (dry chemical powder), but also with a cab fire protection system, effective both in preventing and suppressing cab fires.

One possible solution to this problem is to discharge in the cab various concentrations of an inert gas mixture (CO_2, 8%, N_2, 50%, Ar, 42%; Inergen), through muffled (Photograph 1) and un-muffled nozzle systems, to evaluate their effectiveness in inerting the cab volume by reducing the oxygen concentrations to levels that inhibit combustion yet are sufficiently high to support life. For this purpose, unlit and prelit fuel trays (Photographs 2 and 3) were used in the cab (2.5 m^3 volume) (Figure 1) to simulate the accumulation of flammable

Photograph 1.—A dual cab fire inert system, using a 45 % gas mixture concentration (1.5 m^3 concentration volume in a cab volume of 2. 5 m^3) discharged into a cab volume through a muffled nozzle system.

Photograph 2.– Unlit fuel tray fires (23 cm dia, 500 ml diesel/gasoline), simulating the evolution of flammable vapors and mists in a large-scale mining equipment cab.



Photograph 3.—Prelit fuel tray fires (23 cm dia, 500 ml diesel/gasoline; ~32 kW), simulating fast-developing fires in a large-scale mining equipment cab.

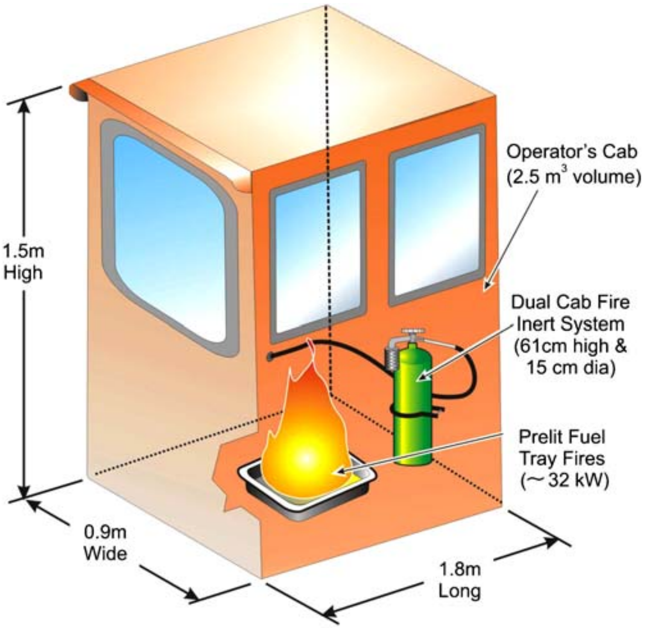


Figure 1. Schematic illustration of a large-scale mining equipment cab.

vapors and mists in the cab and cab material fires, respectively. In this study, the gas mixture concentrations tested were the 61%, 51%, 45%, 41%, 34%, and 25%, contained in pressurized canisters ($\sim 15 \times 10^6$ Pa) bolted to the cab rear wall, at cab open/closed vents (cab closed windows), and no forced airflow through the cab (winter conditions). For summer conditions (open cab windows or air conditioning), close or shutoff systems need to accompany the discharge in the cab of the inert gas mixture concentration. The expectations were that the experimental data would lead to the choice of an optimum gas mixture concentration and discharge nozzle system for the development of a dual cab fire inerting system, effective both in preventing the ignition of flammable vapors and mists in the cab, and in suppressing cab fires. Of note is that this technology needs to be accompanied by safety training programs, including the synchronization of performed tasks, to enhance operator's efficiency and safety during fire emergencies within the safe times yielded by the cab mixture concentrations. Also of note is that the system needs to be recharged after either usage:

1. At engine fire detection time, the operator needs to rapidly perform safe parking/engine shutoff and exit the cab. These operations may be preceded and accompanied (double engine fire suppression system) by the rapid automatic or manual activation of the engine fire suppression system and cab fire inerting system, synchronized with the activation of fire barriers to prevent any additional pressurized fluid from being sprayed onto engine hot surface.

2. At cab material fire detection time, the operator needs to rapidly perform safe parking/engine shutoff and exit the cab. These operations may be preceded by the automatic or manual activation of the cab fire inerting system.

The inert gas mixture concentrations, reported above, and their corresponding oxygen concentrations are reported in the NFPA Standard for Carbon Dioxide [4]. The mixture concentrations are derived by multiplying flooding factors (specific to each gas mixture concentration) by the cab volume. The flooding factor values, unit volume of gas mixture per unit space volume at 21°C, and the equation from which they were derived are reported in Table 3.5.1 of NFPA 2001 for Clean Agents Fire Extinguishing Systems [5]. Example: in order to design the concentration volume for the 45% gas mixture concentration, according to a cab volume of 2.5 m^3 at 21°C temperature, according to the Table reported above, one multiplies the given flooding factor (0.598) by the cab volume (2.5 m^3). Of note is that the design of concentration volumes according to cab volumes, and system fabrication/installation, have been undertaken by cooperating industries.

It has been found that a depletion of oxygen concentrations below certain limits may eliminate fire ignition [6, 7], and that most healthy individuals could tolerate a 12% oxygen level for a short period of time [6]. Studies have found that subjects exposed to atmospheres containing 10% oxygen concentrations and carbon dioxide concentrations up to 5% showed normal intellectual functions for a considerable period of time [8]. For inert atmospheric gases such as Ar, N_2 and CO_2, which are not inherently toxic, the first adverse effect observed as a result of the hypoxic atmosphere created will be a reduced oxygen supply to the brain, compensated in part by the improvement in brain blood flow produced by the carbon dioxide components [9–11]. Also it has been found that carbon dioxide, at concentrations typical of those obtained in these experiments (2 to 4%), has promptly improved tolerance to atmospheres with oxygen concentrations of 10% [12, 13]. This is the result of the combined effects of three main physiological mechanisms: stimulation of respiration, dilation of brain blood vessels, and shift in the hemoglobin dissociation curve which aids unloading of oxygen in all tissues [14].

Studies of a commercially available inert gas mixture (Inergen) have found that the agent at concentrations ranging between 30 to 50% dilutes the oxygen concentrations to a level that does not support combustion [15]. Furthermore, a 40% concentration of the inert gas mixture extinguished heptane liquid fuel fires, ranging between 200 kW and 1000 kW, within the first 50s of gas mixture discharge, yielding oxygen concentrations ranging between 11% and 9.5% and carbon dioxide concentrations of 4.1% and 4.9%, respectively [13]. Also, test results of *n*-heptane pan fires have shown that the fires were extinguished with this fire suppression agent at concentration of 31.5% by volume [16]. Of note is that a 51% design gas mixture concentration is the highest concentration of agent, for a 5 min exposure, resulting in atmospheres containing 10% oxygen and 4–5% carbon dioxide [15]. Carbon dioxide concentrations, within these limits, have been found to promptly improve tolerance to even severe degrees of hypoxia by preventing a decrease in the normal level of carbon dioxide in the lungs and arterial blood [18]. However, tenable O_2 levels may not be maintained during real fire suppression because the depletion of O_2 concentrations is dependent on the fire size; hence, O_2 concentrations may be much lower than the safe level [19]. Persons disabled by degrees of cardiac and pulmonary abnormalities will be able to exit during the gas mixture flooding with any transient exposure completely reversing itself upon exposure to the external atmosphere [20].

Experimental

In the present study, a total of sixteen experiments (five sets) with unlit and prelit fuel trays were conducted in a large-scale mining equipment cab (2.5 m^3;1.8 m long × 1.5 m high × 0.9 m wide), using various concentrations of an inert gas mixture (Inergen, 61%, 51%, 45%, 41%, 34%, and 25%). For comparison purposes, each gas mixture concentration was discharged into the cab through a muffled and un-muffled nozzle system at closed and open cab vents (two vents, 323 cm^2 surface area; average cab airflow leakage rates, 0.008 m^3/s and 0.011 m^3/s, respectively). For these experiments, the cab windows were closed with no forced airflow through the cab (winter conditions). As mentioned earlier, for summer conditions (open cab windows or air conditioning), close or shutoff systems need to accompany the discharge in the cab of the gas mixture concentration. The average airflow leakage rates were calculated according to a mathematical expression (Equation (1)) reported in the "Fire Prevention Experiments" section. Of note is that the noise levels of discharged nozzles ranged between ~85 db (muffled nozzles), and >115 db (un-muffled nozzles).

The experiments were conducted to evaluate the effectiveness of each gas mixture concentration in preventing the ignition of flammable vapors and mists in the cab (unlit fuel trays, simulating the accumulation of flammable vapors and mists in the cab), and in suppressing cab fires (prelit fuel trays, simulating cab material fires). The expectations were that the muffled nozzle discharge system would reduce the noise level, and slow the gas mixture discharge rates into the cab, allowing for a slower displacement of original cab air (oxygen) while preserving mixture inerting capabilities and safe cab atmospheres (breathable atmospheres).

The experimental concentrations were obtained by discharging into the 2.5 m^3 cab volume designed mixture concentration volumes of 2.5 m^3 (61% concentration); 1.9 m^3 (51% concentration); 1.5 m^3 (45% concentration); 1.4 m^3 (41% concentration); 1.1 m^3 (34% concentration); and, 0.8 m^3 (25% concentration) through appropriate size nozzles. Of note is that the quoted percentage of the inert gas mixture concentrations are the concentrations of the mixtures in the cab at the end of mixture discharge. During the experiments with the muffled nozzle system, each mixture concentration was discharged into the cab in approximately 120 s; 90% of the gas mixture was discharged within the first 70s, and the remaining 10% within the following 50s. During the experiments with the un-muffled nozzle system, the mixture concentration was discharged into the cab in approximately 100s; 90% of the gas mixture was discharged within the first 50s, and the remaining 10% within the following 50s.

For all experiments, a 23 cm diameter fuel tray, containing 250 ml of gasoline and 250 ml of no. 2 diesel fuel floating on the surface of 250 ml of water (fire size, ~32 kW; calculations of fire size are reported in this section), was placed at the center of the cab floor and equipped with electrical matches (for remote ignition), positioned 2.54 cm above the fuel surface. Three equidistant electrical matches for the unlit fuel tray experiments, and one electrical match for the pre-lit fuel tray experiments, were used. A gas sample was continuously drawn by a sample line located 28 cm above the center of the tray fuel surface and was analyzed for oxygen and carbon dioxide concentrations by MSA Lira Infrared Gas Analyzers (Model 3000; accuracy, ± 1%; ranges, 0–25% for oxygen; and, 0–10% for carbon dioxide). A thermocouple located 28 cm above the fuel surface was also used to measure the flame temperature. The noise measurements were made with a Larson Davis Spark Dosimeter with data recorder (maximum range, 130 db; Models 705, 706). Visual observations of fuel tray ignition and smoke obscuration were also made.

All experimental data were acquired with a PC-based acquisition system.

Fire size calculations:
$Q_f\ (kW) = (A_s)\ (H_s)\ (M_f)$
$= (0.041)_{\mathrm{m}}{}^2$ (40 k J/g (19.5 g/m^2 $\times$ g) = 32 kW
Where
A_s = fuel surface area
H_c = Heat of combustion; and
M_f = fuel loss rate

Fire Prevention Experiments (Unlit Fuel Trays)

The experiments with the unlit fuel trays (nine experiments; three sets), simulating the accumulation of flammable vapors and mists into the cab were conducted with the 61%, 51%, 45%, 41%, and 34% gas mixture concentrations to derive the total safe times (total time of cab inert volume), and the earliest safe time (earliest time of inert cab volume). The total safe times, time from gas mixture discharge-start to time of last failed ignition attempt following complete mixture discharge (∼120 s), are the critical times available for the operator to perform emergency tasks and exit the cab. The earliest safe times, time from gas mixture discharge-start to first failed ignition attempt during the earliest time of gas mixture discharge-start, are the earliest times at which no ignition of flammable vapors and mists in the cab will occur.

The first set of experiments was conducted with the 51%, 45% and 41% mixture concentrations, discharged into the cab through a muffled nozzle system at closed cab vents (0.008 m^3/s; noise level 85 db). The second set of experiments was conducted with the 61%, 51%, 41% and 34% mixture concentrations, discharged into the cab through the un-muffled nozzle system at open cab vents (0.011 m^3/s; noise level >115 db); and, the third set of experiments was conducted with the 45% and 41% mixture concentrations, using the muffled nozzle system at closed cab vents.

For the first and second sets experiments, three ignition attempts were carried out at 30s intervals, following complete gas mixture discharge (∼120th s, muffled nozzle system; and, 100th s, un-muffled nozzle system). Success was acknowledged if the fuel vapors did not ignite during the three ignition attempts, following complete gas mixture discharge, while maintaining safe cab atmospheres. For the third set of experiments, success was acknowledged if the fuel vapors did not ignite during the earliest stages of gas mixture discharge-start.

The following mathematical expression was used for the calculation of average cab airflow leakage rates at closed and open cab vents, using measured minimum oxygen concentrations:

$$Q_{\mathrm{LEAK}}(\mathrm{m}^3/\mathrm{s}) = [V_c(\Delta O_2/\Delta t)]/[20.95 - (\mathrm{O}_2)]_{\mathrm{MIN}} \tag{1}$$

V_c = cab volume in m^3 (2.5 m^3); $\Delta O_2/\Delta t$ = rate of increase of O_2 (percentage of oxygen concentration per second, %/s) subsequent to attainment of the minimum concentration, $(O_{2,})_{MIN}$ (%).

At constant pressure, and assuming uniform mixing, the increase in O_2 concentrations in the cab due to air leaking in, can be defined as:

$$\Delta O_2/(\Delta O_2)_{MAX} = Q_L^{Air}\Delta t/V_{cab}$$

where Q_L^{Air} is the air leakage rate (ft^3/s); V_{cab} is the volume of the cab (ft^3); $(\Delta O_2)_{MAX}$ is the maximum increase that can occur due to air leakage = 20.95% − $(O_2)_{MIN}$; Where $(O_2)_{MIN}$ is the minimum concentration subsequent to the dispersion of Inergen into the cab

$$\Delta O_2 = O_2(\Delta t) - (O_2)_{MIN}$$

where Δt is the time in seconds

This can be rearranged to yield Equation (1) in the paper.

Fire Suppression Experiments (Pre-lit Fuel Trays)

The prelit fuel tray experiments (seven experiments; two sets), simulating cab fires (~32 kW) were conducted with the 61%, 51%, 45%, 41%, 34% and 25% gas mixture concentrations to derive the earliest fire suppression time. Success was acknowledged if the fuel tray fires were suppressed at the earliest time of gas mixture discharge-start while maintaining safe cab atmospheres. Of note is that the earliest fire suppression time is the time from gas mixture discharge-start to time of fire suppression during the discharge of gas mixture.

The first set of experiments was conducted (twice) with the 45% gas mixture concentration, discharged into the cab through a muffled nozzle system at closed cab vents (0.008 m^3/s). For comparison purposes, the second set of experiments was conducted with the 61%, 51%, 41%, 34%, and 26% gas mixture concentrations, discharged into the cab through an un-muffled nozzle discharge system at open cab vents (0.011 m^3/s), after 30 s fuel preburn time.

Of note is that the 30 s fuel preburn time experiments were mainly carried out to measure oxygen depletion and to observe other fire parameters to advocate the development of rapid cab fire detection systems.

Results and Discussion

Fire Prevention Experiments

The experimental results are reported in Figures 2– 5 and Table 1.

For the first set of unlit fuel tray experiments (prevention of flammable vapors and mists ignition into the cab), results show that the gas mixture concentrations tested (51%, 45%, 41%), discharged in the cab through a muffled nozzle system at closed cab vents (0.008 m^3/s), with closed cab windows and no forced airflow (winter conditions), were effective in preventing the ignition of the fuel vapors while maintaining safe cab atmo-

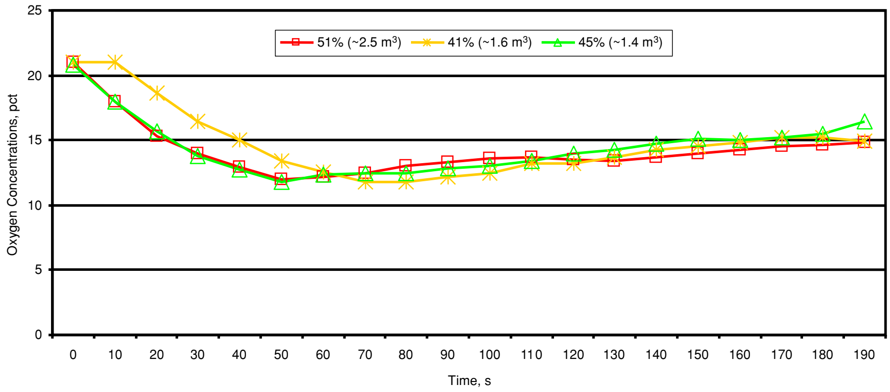


Figure 2. Oxygen concentrations for various concentrations of an inert gas mixture with unlit fuel trays (23 cm dia; 500 ml diesel/gasoline), at closed cab vents (0.008 m^3/s) and muffled nozzle discharge system.

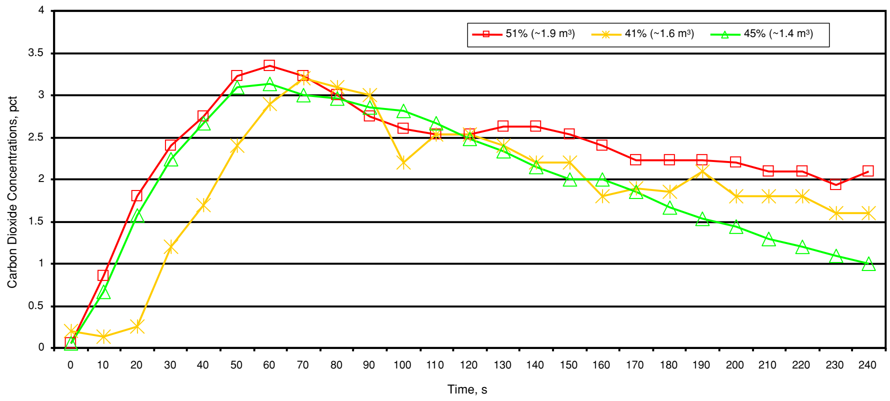


Figure 3. Carbon dioxide concentrations for various concentrations of an inert gas mixture with unlit fuel trays (23 cm dia; 500 ml diesel/gasoline), at closed cab vents (0.008 m^3/s) and muffled nozzle discharge system.

spheres. Evidently, the muffled nozzle system, together with lower cab airflow leakage rates, slowed the gas mixture discharge rates in the cab and the displacement of cab original air (oxygen) while preserving the mixture inerting capabilities and safe cab atmospheres (O_2, $>11\%$; noise level, 85 db). Of note is that for summer conditions (open cab windows or air conditioning), close or shutoff systems need to accompany the discharge in the cab of the mixture concentration.

The oxygen and carbon dioxide concentrations measured for these experiments are shown in Figures 2 and 3. The three gas mixture concentrations yielded total safe times of 180s and 160s (51%, 45%, and 41% concentrations, respectively), yielding minimum

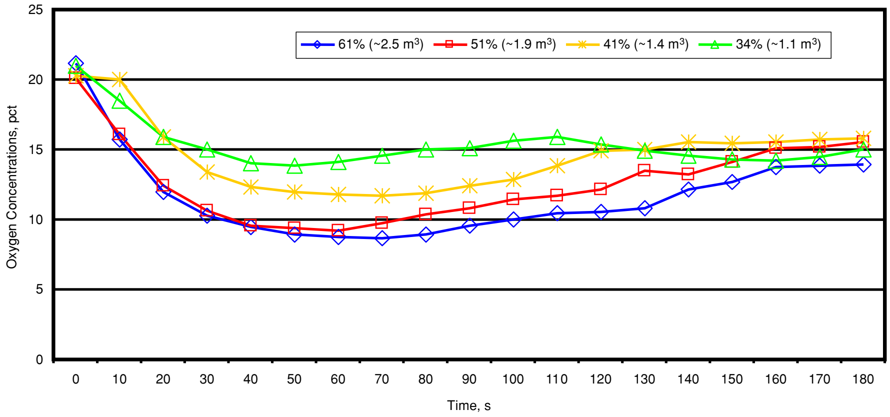


Figure 4. Oxygen concentrations for various concentrations of an inert gas mixture with unlit fuel trays (23 cm dia; 500 ml diesel/gasoline), at open cab vents (0.011 m^3/s) and muffled nozzle discharge system.

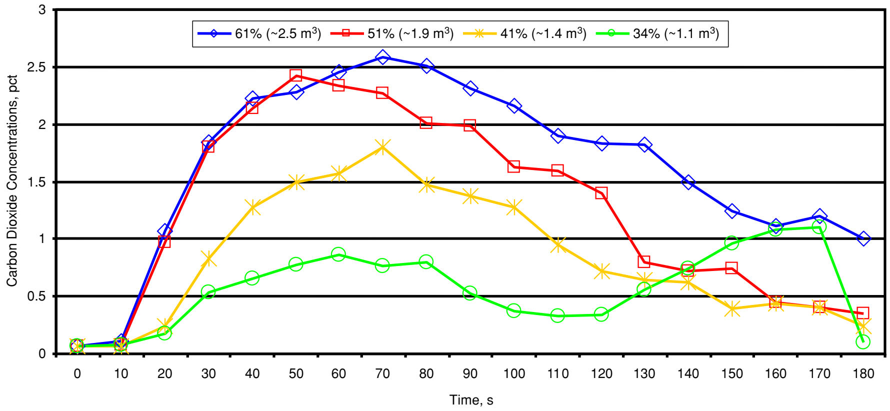


Figure 5. Carbon dioxide concentrations for various concentrations of an inert gas mixture with unlit fuel trays (23 cm dia; 500 ml diesel/gasoline), at open cab vents (0.011 m^3/s) and muffled nozzle discharge system.

O_2 concentrations of 11.8%, at the 50th s (maximum CO_2, 1.5%). The total safe times, reported above, are the critical times available for the operator to perform emergency tasks and exit the cab due to the possibility of ignition of newly accumulated flammable vapors evolved during a prolonged hydraulic fluid fire. Therefore, safety training programs, including the synchronization of performed tasks, need to accompany these technologies and methodologies to enhance operator's efficiency and safety during fire emergency within the safe times yielded by the mixture concentrations.

Table 1
Cab Fire Prevention Experiments Unlit Fuel Trays

Muffled nozzle system				Un-muffled nozzle system			
Gas mixture	$(O_2)_{MIN}$	$(CO_2)_{MAX}$	Safe time	Gas mixture	$(O_2)_{MIN}$	$(CO_2)_{MAX}$	Safe time
51%	12%*	1.4%	180 s	61%	8.64%	2.6%	160 s
45%	12%*	1.25%	180 s	51%	9.0%	2.6%	150 s
41%	11.8%*	1.5%	160 s	41%	11.8%*	1.75%	100 s
				34%	14.0%*	0.8%	NM
Noise level ~ 85 db				Noise level > 115 db			

*Denotes Breathable Atmosphere.

Of note is that the above results have led to the choice of an optimum gas mixture concentration for the development of a dual cab fire inerting system. The 45% concentration (1.5 m^3 concentration volume designed for a cab volume of 2.5 m^3), discharged into the cab through a muffled nozzle system, was effective both in preventing and suppressing cab fires (the system needs to be recharged after either usage). Also of note is that the design of the concentration volume according to cab volumes, and system fabrication/installation have been undertaken by cooperating industries.

For the second set of unlit fuel tray experiments, as shown in Figures 4 and 5, results show that some of the gas mixture concentrations tested (61% and 51%), discharged through the un-muffled nozzle system (noise level >115 db) at open cab vents (011 m^3/s), although, succeeded in preventing the ignition of the fuel vapors (total safe time, 160 s and 150 s), yielded minimum oxygen concentrations below 10% (8.64% and 9%, respectively), lasting 60 s (maximum CO_2, 2.6%). The 41% and 34% gas mixture concentrations, instead, failed to prevent the ignition of cab fuel vapors at the second and third ignition attempts, respectively, yielding minimum oxygen concentrations of 11.8% and 14%, respectively. As shown in Figures 6 and 7, for each experiment, the oxygen rapidly decreases and the carbon dioxide increases, reaching minimum oxygen (8.64%) and maximum carbon dioxide (2.6%) within 70 s of gas mixture discharge-start (61% mixture concentration). These changes result from the rapid displacement of cab air (oxygen), together with the mixture concentrations, brought about by the rapid gas mixture discharge rates and high cab airflow leakage rates. Comparing the experimental data, it can be seen that the rate of O_2 decrease and the rate of CO_2 increase are somewhat slower using the muffled nozzle system at closed cab vents. In addition, the minimum O_2 concentrations are greater and maximum CO_2 lower with closed cab vents compared to the open cab vents environment. It is also worth noting that at a lower cab airflow leakage rate, the O_2 and CO_2 concentrations change more slowly, following complete gas mixture discharge.

For the third set of unlit fuel tray experiments, results show that the 45% and 41% mixture concentrations (the only concentrations tested), discharged in the cab through a muffled nozzle system at closed cab vents, were effective in inerting the cab volume at the 10th s and 20th s of gas mixture discharge-start, respectively, while maintaining safe cab atmospheres (minimum O_2, ~12%). Also for the 45% mixture concentration, ignition attempts carried out at the 15th s, 20th s, and 25th s also failed to ignite the fuel tray, as expected. For the

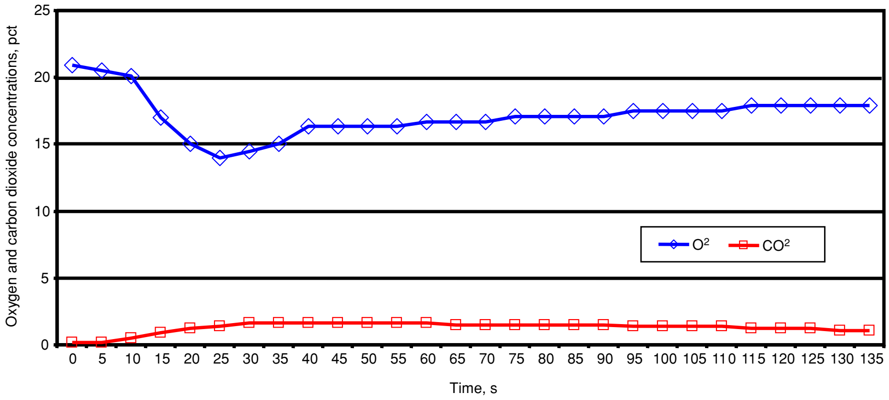


Figure 6. Oxygen and carbon dioxide concentrations for the 45% inert gas mixture concentration with prelit fuel trays (~32 kW), at closed cab vents (0.008 m^3/s) and muffled nozzle discharge system.

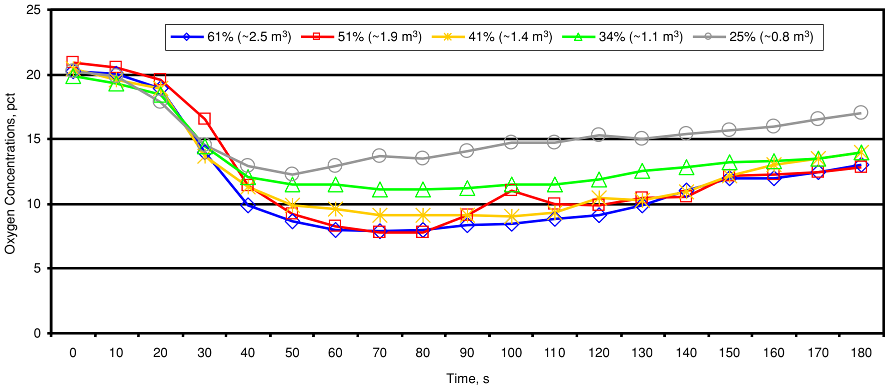


Figure 7. Oxygen concentrations for various concentrations of an inert gas mixture with prelit fuel trays (~32 kW), at open cab vents (0.011 m^3/s) and muffled nozzle discharge system.

41% mixture concentration, earlier ignition attempts carried out at the 8th s ignited the fuel vapors (O_2, 19%), although the flames extinguished themselves within 10 s (O_2, ~17%).

Fire Suppression Experiments

The experimental results are shown in Figures 6– 8 and Table 2.

For the first set of prelit fuel tray experiments (suppression of cab fires), using the 45% gas mixture concentration discharged in the cab through a muffled nozzle system at closed cab vents, results show that the concentration was effective in suppressing the fires within the first 20 s of gas mixture discharge-start (Figure 6). Of note is that at fire detection time, the operator needs to rapidly perform safe parking/engine shutoff and exit the cab; these operations may be preceded by automatic or manual activation of the cab

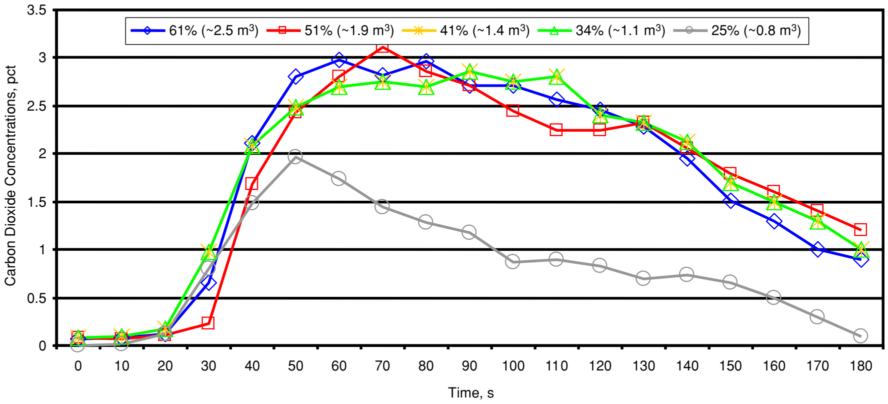


Figure 8. Carbon dioxide concentrations for various concentrations of an inert gas mixture with prelit fuel trays (~32 kW), at open cab vents (0.011 m^3/s) and un-muffled nozzle discharge systems.

fire inerting system. Minimum oxygen concentrations of approximately 13.8% (maximum CO_2, 1.65%) were recorded. For the second set of prelit fuel tray experiments, results show that the gas mixture concentrations tested (61%, 51%, 41%, 34%, and 25%), discharged in the cab through the un-muffled nozzle system at open cab vents, were effective in suppressing the fuel vapor fires within the first 20s of gas mixture discharge-start. However, as shown in Figures 7 and 8, the 61%, 51% and 41% mixture concentrations yielded minimum oxygen concentrations below 10% (~8% and 9%, respectively) at the 50th s, lasting 80th s (maximum CO_2, 3.1%). The 34% and 25%, instead, yielded minimum oxygen concentrations of ~11% and 13.5%, respectively (maximum CO_2, 2.8%). Evidently, the low oxygen concentrations are due to fast displacement of cab original air (oxygen), aggravated by the depletion of oxygen occurring during the 30 s fuel preburn time (O_2, <14%; flame temperature, ~400°C). As a footnote, it is worth mentioning that at flame temperatures of ~3000°C, carbon dioxide reverses to carbon dioxide (21).

Table 2
Cab Fire Suppression Experiments Prelit Fuel Trays

Muffled nozzle system				Un-muffled nozzle system			
Gas mixture	$(O_2)_{MIN}$	$(CO_2)_{MAX}$	Supp time	Gas mixture	$(O_2)_{MIN}$	$(CO_2)_{MAX}$	Supp time
45%	13.8%	1.65%	20 s	61%	8.0%	3.1%	10 s
45% (repeat)	13.9%	1.65%	20 s	51%	8.5%	3.1%	10 s
				41%	9.0%	2.85%	15 s
				34%	11.0%*	2.8%	20 s
				25%	13.5%*	2.0%	20 s

*Denotes Breathable Atmosphere.

According to these results, the importance of installing in the cab effective fire protection systems needs to be stressed, accompanied by rapid cab fire detection system (optical or photoelectric/ionization smoke detectors) for the early detection of cab fires. Similar fire detection systems also need to be installed within the engine compartment for the early detection of hydraulic fluid/fuel fires before large concentrations of flammable vapors and mists penetrate the cab.

Conclusions

For the prevention of flammable vapors and mists experiments, the 51%, 45% and 41% gas mixture concentrations, contained in pressurized canisters bolted to the cab rear wall, were effective in preventing the ignition of flammable vapors and mists in the cab while maintaining breathable atmospheres (O_2, $>11\%$; noise level, 85 db). Of note is that the mixture concentrations were discharged in the cab through a muffled nozzle system at cab closed vents (airflow leakage rate, 0.008 m^3/s), with closed cab windows and no forced airflow (winter conditions). For summer conditions (open cab windows or air conditioning), activation of close or shutoff systems need to accompany the discharge in the cab of the inert gas mixture concentration.

Evidently, the muffled discharge nozzle system was effective both in abating the noise level, and in slowing the mixture discharge rates in the cab, and, therefore, the displacement of cab original air (oxygen) while maintaining mixtures inerting capabilities and safe cab atmospheres. For these gas mixture concentrations, the total safe times, during which no ignition of flammable vapors occurred, ranged between 180 s (51% and 45% concentrations) and 160 s (41% concentration), yielding minimum oxygen concentrations of approximately 12% (maximum CO_2, 1.5%). Also, the 45% and 41% mixture concentrations (the only concentrations tested) yielded the earliest safe times at the 10th s and 20th s of concentration discharge-start (complete concentration discharge, 120th s). Of note is that the total safe times reported above are the critical times available for the operator to perform emergency tasks and exit the cab due to the accumulation of additional vapors and mists into the cab evolved during prolonged hydraulic fluid and fuel fires.

In view of the above reported results, the 45% gas mixture concentration (concentration volume 1.5 m^3 designed for a cab volume of 2.5 m^3), discharged into the cab through a muffled discharge nozzle system, was chosen as the optimum concentration for the development of a dual cab fire inerting system. Of note is that the design of the gas mixture concentration volume according to cab volumes, and system fabrication/installation have been undertaken by cooperating industries. Also of note is that safety training programs, including the synchronization of performed tasks, need to accompany this technology to enhance operator's efficiency and safety during fire emergencies within the safe times yielded by the cab fire inerting system.

For the cab fire suppression experiments (prelit fuel trays), results show that the 45% gas mixture concentration (the only concentration tested under these conditions, in view of previous results), discharged through a muffled nozzle system at closed cab vents, was effective in suppressing the cab fires ($\sim$32 kW) within the first 20 s of gas mixture discharge-start while maintaining safe cab atmospheres (minimum O_2, $\sim$13.8%). Of note is that, at fire detection time, the operator needs to rapidly perform safe parking/engine shutoff and exit the cab; these operations may be preceded by the automatic or manual activation of the cab fire inerting system. Finally, results of fire parameters obtained during the 30 s fuel preburn time such as oxygen depletion (O_2, $< 14\%$), and possible evolution of toxic gases at flame temperatures of $\sim 400^\circ C$, imply that any cab fire protection system should be accompanied by a rapid cab fire detection system (optical or photoelectric/ionization smoke detectors). Similar rapid detection systems may also be installed within the engine compartment for the rapid detection of incipient hydraulic fluid/fuel fires before large concentrations of flammable vapors penetrate the cab.

Acknowledgment

The authors wish to thank Richard A. Thomas, Electronic Technician, NIOSH DPRB/PRL, for his contributions in carrying out the experiments.

References

[1] M.I. De Rosa, "Analyses of Mobile Equipment Fires for all U.S. Surface and Underground Coal and Metal/Nonmetal Mining Categories, 1990–1999," *NIOSH IC 9467*, 2004, pp. 53.

[2] M.I. De Rosa, "Analysis of Mine Fires for all U.S. Underground and Surface Coal Mining Categories, 1990–1999," *NIOSH IC 9470, 2004*, pp. 36.

[3] M.I. De Rosa, "Analysis of Mine Fires for all U.S. Metal/Nonmetal Mining Categories, 1990–1999," *NIOSH IC 9476*, 2004, pp. 52.

[4] NFPA 12, *Standard on Carbon Dioxide*, National Fire Protection Association, Quincy, MA, Appendix A, 1998.

[5] NFPA 2001, *Standard on Clean Agent Fire Extinguishing Systems*, National Fire Protection Association, Quincy, MA, 2000.

[6] Laursen, "Overview of Toxicity/Effectiveness Issues," in *Proceedings and Technical Work Conference Halon Alternative*, Albuquerque, NM, 1993, pp. 357–367.

[7] M.G. Zabetakis, "Flammability Characteristics of Combustible Gases and Vapors," U.S. Bureau of Mines, Bulletin 627, 1965, pp. 120.

[8] F.A. Gibbs, E.L Gibbs, W.G. Lennox, and L.F. Nims, "The Value of Carbon Dioxide in Countering the Effects of Low Oxygen," *Aviation Medical Journal*, vol. 14, 1943, pp. 250–261.

[9] C.J. Lambertsen, *Hypoxia, Altitude, and Acclimatization*, Med. Physiol., (ed.), St. Louis MO, 1980, pp. 1844–1872.

[10] B. Slobodnik, M.T. Wallick, and J.M. Chimiak, "Effectiveness of Oxygen-Nitrogen Gas Mixtures in Inducing Hypoxia at 1 Atmosphere," Navy Experimental Division Unit, Panama City, Fla., Report 04–91, 1991, pp. 100.

[11] E. Gellhorn, "The effect of O_2-lack Variations in the CO_2 Content of the Inspired Air, and Hypernea on Visual Intensity Discrimination," *American Journal of Physics*, vol. 115, 1936, pp. 679–684.

[12] F.A. Gibbs, E.L. Gibbs, and W.G. Lennox, "Changes in Human Cerebral Blood Flow Consequent on Alterations in Blood Gases," *American Physics Journal*, vol. 111, 1943, pp 557–563.

[13] W.G. Lennox and E.L. Gibbs, "The Blood Flow in the Brain and Leg of Man and the Changes Induced by Alterations of Blood Gases," *Clinical Investigation Journal*, vol. 11, 1932, pp 1155–1177.

[14] C.J. Lambertsen, "Chemical Control of Respiration at Rest," *Medical Physics*, 1980, pp. 1774–1827.

[15] J.Z. Su, A.K. Kim, G.P. Crampton, and Z. Liu, "Fire Suppression With Inert Gas Agents," *Fire Protection Engineering Journal*, vol. 11, 2001, pp. 72–87.

[16] Underwriter Laboratories, "Summary: UL Fire Test Results Inergen Fire Extinguishing Agent," North Brook, IL, Project 93NK29239, File EX-4510, 1994, pp. 30.

[17] C.J. Lambersten, "Inergen: Summary of Relations, Physiological Factors and Fire Protection Engineering Design Scenario," Env. Biom. Res. Data Center, Inst. Env. Med., Univ. Pennsylvania Medical Center, College Park, PA, Report 4-14-94, 1994, pp. 1–21.

[18] G.B. Field, "The Physiological Effects on Humans Exposure to Gas Mixtures of Air and Inergen," Dept. of Resp. Med., The Prince of Wales Hospital, Sidney, Australia, Report and Supplementary Report, 1922, pp. 22.

[19] U.S. Environmental Protection Agency, "Questions and Answers on Halon and Their Substitutes," Revision 14, 1999, 10.

[20] C.J. Lambertsen, "Short Duration Inergen Exposures, Relation to Cardiovascular or Pulmonary Abnormalities," Env. Biom. Stress Data Center, Inst. Env. Med., Univ. of Pennsylvania Medical Center, College Park, PA, Report 2-1-93, 1993, pp. 13.

[21] M.W. Chase Jr., C.A. Davies, J.R. Downey Jr., D.J. Frurip, R.A. McDonald, and A.N. Syverud, "JANAF Thermochemical Tables, 3rd Ed.," *Journal of Physical and Chemical Reference Data,* 14 supplement, no. 1, 1985, pp. 626–628.