Performance of Selected Agents in Suppressing Explosions of Near-Stoichiometric Methane-Air Mixtures

FRANCESCO TAMANINI, JEFFREY L. CHAFFEE AND RICHARD L. JAMBOR
Factory Mutual Research Corporation
Norwood, MA 02062 USA

ABSTRACT

This study was carried out to obtain data on the performance characteristics of two powders (sodium bicarbonate [SB] and monoammonium phosphate [MAP]) and water as explosion suppression agents, and to understand the effects of geometric variables on suppression system performance. Tests were carried out in a 2.5-m^3 test vessel with 10% (by volume) methane/air mixtures, both under initially quiescent and turbulent conditions. Tests with the two powder agents (SB and MAP) at a concentration of 1200 g/m^3 resulted in similarly successful suppression of quiescent mixtures, with small increases in final overpressures as the detection/system trigger pressure was increased (from 0.07 to 0.55 barg [1 to 8 psig]). Successful suppressions were also obtained with turbulent mixtures, although with greater overpressures than for quiescent mixtures. Water at ambient temperature (approximately 20°C) was not successful at suppressing the explosion, even when carbon dioxide was added to the charge. In tests where the suppression failed, the pressure inside the vessel reached the value corresponding to fully unvented conditions. Heated water (at or above 230°C [446°F]) performed reasonably well as a suppression agent, both in quiescent and turbulent tests, for trigger pressures up to 0.55 barg (8 psig). The introduction of the superheated water into the vessel, however, contributed about 0.83 barg (12 psig) to the total pressure increase.

KEYWORDS: Explosion suppression, Sodium bicarbonate, Monoammonium phosphate, Heated water, Methane/air explosions.

I   INTRODUCTION

The existence of hazardous materials in industrial applications that could potentially be involved in a catastrophic explosion has generally led to designs of new equipment and buildings that incorporate damage limiting construction (explosion venting relief systems). Other possible protective measures include the location of hazardous material-handling equipment or areas to remote locations, or the utilization of ventilation systems with safety shutdown interlocks. There are some situations, however, where none of these measures can afford suitable protection from a

catastrophic failure, or when older equipment or buildings cannot be economically retrofitted with explosion venting relief devices. In these cases, there is a role for a protective system that can detect an explosion in its early phases and suppress it quickly and safely before it can produce dangerous overpressures. Explosion suppression systems are intended to fulfill this need by detecting an incipient explosion and quickly delivering sufficient amounts of extinguishing agent to quench the combustion before damaging overpressures can develop. The most important installation requirements of a successful suppression system are early detection, rapid deployment of the agent, sufficient throw distance, and sufficient agent mass.

II BACKGROUND

2.1 Published Work

The characterization of the behavior of explosion suppression systems presents significant technical challenges. This is due not only to the limited understanding of the interaction between the extinguishing agent and the flame front, but also to the fact that the modeling of the unsuppressed explosion is still somewhat approximate. This situation is reflected in the results of research published on this subject, which show a focus on measurements of the performance of specific systems engineered for selected protection conditions. Not surprisingly, much of the test work has been done directly by or under the sponsorship of manufacturers of explosion suppression systems[1-3]. Highlights of results can usually be found in reference books on explosions[4].

Methods have been developed by each manufacturer to guide the selection of the type and location of equipment necessary to protect a specific installation. Some take the approach that the system requirements should be set by the need to flood the protected volume with a sufficient mass of agent so as to extinguish the explosion flame front and provide sustained inerting after extinguishment is achieved. Others, by considering the dynamic aspects of the suppression process, have developed design rules that relate the amount of agent to the flame surface area. This results in scaling of the suppressant by the 2/3 power of the protected volume, rather than by straight proportionality, as implied by the first design approach. Much of this technology has not been subjected to detailed peer review and is typically presented in the form of calculated predictions for cases of interest[3]. At this time, use of a suppression system for applications beyond those for which experimental data have been obtained requires validation by testing.

2.2 Current Explosion Suppression Systems

Several systems are commercially available for use in the suppression of explosions in equipment and buildings. These systems utilize powder agents, typically sodium bicarbonate (SB) or monoammonium phosphate (MAP) and, in some cases, water. Halogenated hydrocarbon compounds, particularly Halon 1301 (bromotrifluoromethane), are being phased out due to their contribution to ozone depletion in the stratosphere. An additional reason for the replacement of Halon agents is their capacity to produce toxicological responses in humans, and their potential for actually enhancing the explosion if the flame front is not extinguished in the first stages of its development. This effect was observed in a test program undertaken by Factory Mutual Research Corporation (FMRC) in 1991[5], in which a Halon 1301 system was used to suppress explosions of homogeneous stoichiometric propane/air and isobutane/air mixtures in a 63.7-m^3 (2250-ft^3) chamber.

Suitable Halon replacements are being sought, with considerable effort currently being expended in the development of new chemical agents, mostly hydrogenated chloro-fluorocarbons (HCFC). Unfortunately, the effectiveness of HCFCs is lower than that of the Halons, generally not allowing for their use as drop-in replacements. Powders, such as SB or MAP, are effective at suppressing explosions for a wide range of conditions. However, the clean up associated with their discharge can limit their use.

Water is a potentially attractive agent, since it provides a much cleaner method of suppression. The difficulty in this case is that the details of the interaction between the water droplets and the flame front introduce added complexity in the deployment of the agent to achieve the desired effectiveness. In practice, water has been found to be unsuccessful in the reliable suppression of gas explosions and its use has been limited to the protection of systems with dust/air mixtures.

2.3   Program Objectives

In view of the background provided in the previous section, the focus of the present research was placed on the study of the effectiveness of suppression systems in high-challenge explosions. This implied the use of a gaseous fuel (methane) and the introduction of turbulence as a parameter. The effect of selected variables, such as the location of the ignition source and the actuation pressure of the system, on the effectiveness of the agent was also of interest. Finally, one last objective involved the determination of the conditions under which water could provide acceptable performance.

III   DETERMINATION OF AGENT INERTING REQUIREMENTS

Tests were performed in the FMRC 20-liter sphere to determine the minimum concentration of the two powder agents required to inert 10% methane/air mixtures. These inerting tests were run using the methodology and criteria for determining the go/no-go condition of ignition outlined in the ASTM E1515 standard[6]. They involved the use of a 30 ms delay, and a single 5000-Joule chemical ignitor. The tests showed that the minimum concentration of SB (Ansul Plus 50C*) used) required to inert the turbulent 10% methane/air mixture was 975 g/m^3, while that for MAP (Ansul Foray* used) was determined to be 575 g/m^3.

IV   FACILITIES USED FOR EXPLOSION SUPPRESSION TESTS

4.1   The 2.5-m^3 Test Vessel

All the explosion suppression tests for this study were performed in the FMRC 2.5-m^3 vessel. This facility, shown in Fig. 1, was originally built for high-pressure modeling of polymer combustion, can be operated up to pressures of 41 barg (600 psig) and temperatures of 343°C (650°F), and was modified to allow for the performance of closed-vessel explosion tests. It consists of a cylindrical enclosure, with an internal diameter of 1.22 m (48 in.), and an internal length of 2.57 m (101 in.). Penetrations are available to introduce gases into the test volume and

---

* Tradename, Ansul Fire Protection. Reference to specific products is not and should not be construed as opinion, evaluation, or judgment by Factory Mutual Research Corporation. Factory Mutual Research Corporation (a) makes no warranty, express or implied, with respect to any referenced products, or with respect to their use, and (b) assumes no liabilities with respect to any referenced products, or with respect to their use.

to connect ignition devices and instrumentation. Four 150-mm (6-in.) diameter, 0.11 m³/sec (235 ft³/min) shaded-pole motor fans, symmetrically located inside the vessel, provide for gas mixing and turbulence. The vessel has a 102-mm (4-in.) flanged pipe entry at the center of the closed-end hemispherical vessel head, which was used for the suppression system assembly. The full-diameter hinged door facilitated the performance of pre-test vessel inspections and post-test vessel clean-outs.

4.2   High-Rate of Discharge (HRD) Vessel and Delivery System

A high-pressure container was fabricated to serve as a high-rate of discharge (HRD) vessel for the suppression system (see Figs. 1 and 2). It was intended for use with different methods of releasing the agent, all of which included some form of bursting metal disc. The vessel, which has an internal volume of 5.9 liters (360 in.³), is fitted with several penetrations to connect various instruments and accessories and is designed for a working pressure of 103 barg (1500 psig). The inside walls are coated with a layer of Teflon† paint.
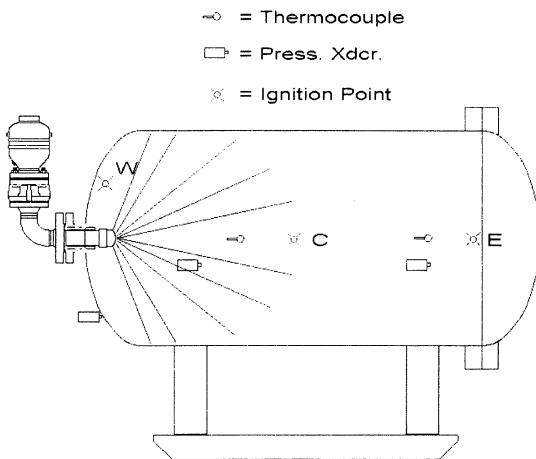

FIGURE 1 – FMRC 2.5-m³ Vessel Showing Suppression System and Ignition Locations.

4.3   Burst-Disc Designs

4.3.1   Fenwal detonated burst discs. The primary release mechanism used for the suppression agent was a detonated burst disc, obtained from Fenwal Safety Systems. It consists of a pre-bulged and scored, non-fragmenting metal disc, mounted in a base unit from a Fenwal liquid-agent HRD, modified by FMRC and fitted with a mating flange for mounting to the HRD described above (see Fig. 2). The burst disc is designed to release at a pressure between 59 and 69 barg (850 and 1000 psig), and is deployed by an explosive actuator. The explosive actuator is triggered by an electrical discharge, which is released by a control system, receiving input from a variable-setting pressure switch.

4.3.2   Fike pre-bulged rupture discs. A second release mechanism was used for a number of tests with heated water. It consists of a 76-mm (3-in.) size pre-bulged Poly-SD Rupture Disc from Fike Metal Products, rated at 49 barg (709 psig) at 200°C (392°F), and at 52.6 barg (762 psig) at 22°C (72°F). This non-fragmenting disc is mounted in a Fike 76-mm (3-in.) rupture disc holder. This release system requires a means of developing a pressurized charge within the HRD, since no explosive actuator is provided with it. Accordingly, a gas mixture, formed in the ullage space of the HRD and ignited by a spark discharge, was used as a driver of the suppressant

---

† Tradename, DuPont, De Nemours.

484

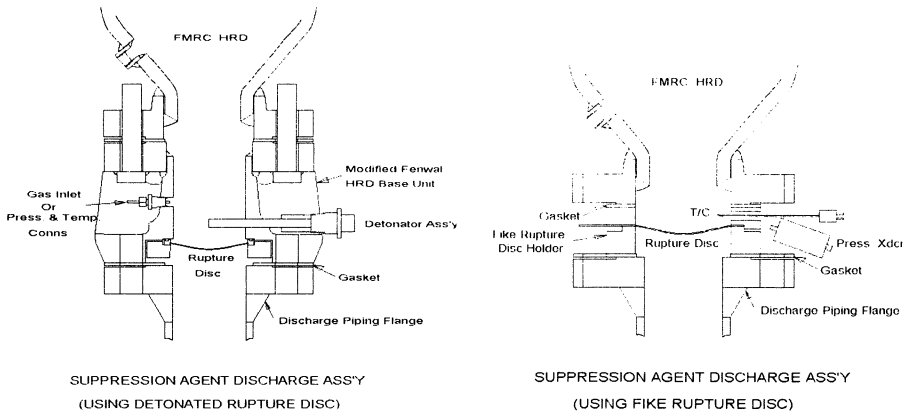|SUPPRESSION AGENT DISCHARGE ASS'Y | SUPPRESSION AGENT DISCHARGE ASS'Y |
|(USING DETONATED RUPTURE DISC) | (USING FIKE RUPTURE DISC) |

FIGURE 2 –Suppression Agent Rupture Disc Assemblies.

charge. The spark discharge was triggered by the same pressure switch, used in the explosively actuated system described above.

4.3.3   Agent delivery nozzles.   Two hemispherical nozzles were designed for delivery of the suppression agent. One had large holes (ranging from 9.5-mm [3/8-in] to 17.5-mm [11/16-in.] in size), while the second nozzle had small holes (3.2 mm [1/8 in.] in diameter). The large-hole nozzle provided a total of 23.7 cm^2 (3.67 in.^{2}) of open area, while the open area of the small-hole nozzle was 22.3 cm^2 (3.46-in.^{2}).

4.4   Instrumentation and Measurements

Pressures within the HRD vessel and the test vessel were measured using amplified strain-gage transducers, while temperatures within each vessel were measured using ANSI Type K thermocouples. A UNIX-based Hewlett-Packard system handled the data acquisition. Readings were acquired at a rate of 2000 scans per second, with post-test conversion of the files using an average of every 10 scans, resulting in an effective rate of 200 scans per second. Events such as time of ignition and time of suppression system activation were also recorded. The data were further analyzed to extract the maximum pressure, the normalized peak rate of pressure rise, K_G, and the burning velocity, u_{f0}. This latter quantity was calculated from the early portion of the pressure curve (pressure rise, Δp, from 1.9 to 550 mbar [0.027 to 8 psig]), using the following formula derived from an adiabatic model of vented explosions[7]:

$$\frac{\Delta p}{p_0} \cong \frac{4\pi}{3V} \frac{p_m - p_0}{p_0} \left(\frac{1}{\gamma} \frac{p_m - p_0}{p_0} + 1 \right)^2 \left(u_{f0} t \right)^3 \ , \tag{1}$$

where V is the vessel volume, p_m is the maximum unvented pressure, p_0 is initial pressure and γ is the specific heat ratio. The quantity K_G was derived from its usual definition, which reads:

$$K_G = V^{1/3} \left(\frac{dp}{dt} \right)_{max} . \tag{2}$$

485

V TEST RESULTS AND ANALYSIS

5.1 Effects of Ignition Location and Turbulence

Experiments were carried out without suppression to characterize the progress of the explosion in the FMRC 2.5-m^3 vessel. In the first test of this series (Test No. 1 in Table 1), an initially quiescent mixture of 10% methane in air was ignited in the center of the vessel. It produced a maximum pressure rise of 6.7 barg (97.6 psig), a normalized rate of pressure rise, K_G, of 45 bar·m/s and a burning velocity, u_{f0}, of 0.55 m/s (1.8 ft/s). Subsequent runs, in which the ignition location was moved to the east end of the vessel (in front of the hinged door), produced somewhat lower peak pressures (about 6.3 barg [91.5 psig]), but very similar levels for K_G (48 bar·m/s) and for the burning velocity (0.56-0.58 m/s [1.8-1.9 ft/s]). The lowest values for K_G (~25 bar·m/s) and u_{f0} (~0.43 m/s [1.4 ft/s]) were obtained from the tests with the ignition located at the west end of the vessel. The main reason for this result is attributable to the proximity of the ignition source to the wall of the vessel. The laminar burning velocities measured in these tests should be compared to typical literature values from small-scale vessel data of 0.4-0.45 m/s.

TABLE 1 - Unsuppressed Tests

Test No.	Quiesc. or Turb. (Q or T)	Ignition Location (C,E,W)	Δp_{max} [barg]	K_G [bar·m/s]	Burning Velocity u_{f0} [m/s]	Pr. Sw. Setting [barg]	Pr. Sw. Trip-Pt. [barg]
1	Q	C	6.73	44.7	0.55	0.07	0.09
2	Q	W	6.28	25.7	0.42	0.07	0.09
3	Q	W	6.26	25.2	0.44	0.21	0.21
4	Q	E	6.24	48.2	0.58	0.21	0.21
6	Q	E	6.37	48.2	0.56	0.34	0.32
32	T	C	7.35	159.1	1.25	0.21	0.18
33	T	C	7.34	163.8	1.15	0.21	0.21
34	T	W	6.88	62.7	1.14	0.21	0.22
5	T	E	7.11	83.3	1.42	0.34	0.34
35	T	E	6.87	81.4	1.71	0.21	0.20

As expected, the tests with turbulent conditions (all four mixing fans left running) resulted in substantially increased values of the quantities discussed above. The highest values of maximum pressure rise (7.3 barg [106.5 psig]) and K_G (160-165 bar·m/s) were obtained with the ignition source centrally located (Test Nos. 32 and 33). For these conditions the burning velocity was about 1.2 m/s (4 ft/s). Higher burning velocities (1.4-1.7 m/s [4.6-5.6 ft/s]), however, were obtained with ignition at the east end of the vessel. This is probably due to locally higher turbulence influencing the initial stage of flame propagation, as the axes of the mixing fans are closer to this ignition location than to the center of the vessel. In the turbulent tests, off-center ignition produced significantly lower values for the normalized peak rate of pressure rise, K_G.

5.2 Powder Suppression Agent Results

5.2.1 Sodium bicarbonate (SB). The data from tests carried out with the SB powder agent are shown in the left plot of Fig. 3. The tests conducted with 3.0 kg of this agent (nominal concentration of 1200 g/m^3 in the FMRC 2.5-m^3 vessel) under quiescent conditions were all considered successful suppressions of the explosion. Although slight increases in suppressed

Explosion Suppression Tests, 2.5 m³ Vessel, 10% CH₄
Agent = 3.0 Kg Sodium Bicarbonate at 50 barg

Explosion Suppression Tests, 2.5 m³ Vessel, 10% CH₄
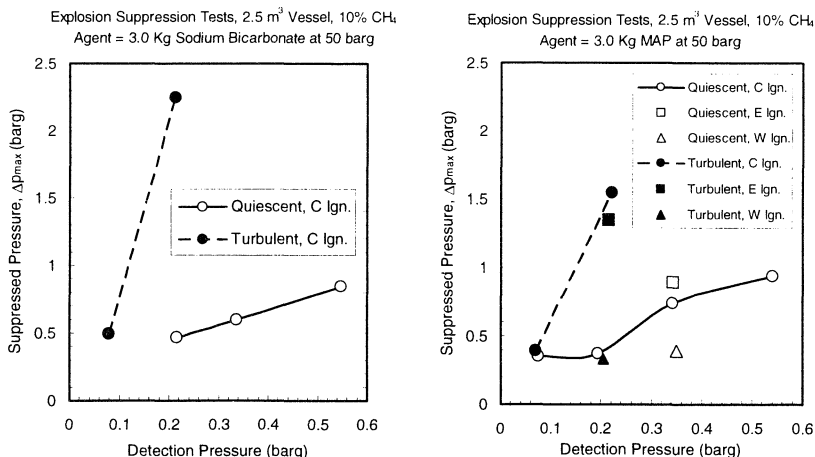**Agent = 3.0 Kg MAP at 50 barg**

FIGURE 3 – Tests with Sodium Bicarbonate (SB, left) and Monoammonium Phosphate (MAP, right) for Varying Pressure Switch Settings.

maximum explosion pressure, Δp_{max}, were observed as the system activation pressure was increased (0.21, 0.34 and 0.55 barg [3, 5 and 8 psig]), the variation was modest, ranging from 0.47 to 0.84 bar (6.8 to 12.2 psi). When expressed as an increase above the system activation level, the pressure rises were all about 0.28 barg (4 psig). Calculated values for the maximum suppressed rate of pressure rise (post-agent delivery) also remained fairly constant (independent of system deployment pressure) at about 3.5 bar/s.

The results of the suppression tests with sodium bicarbonate run under turbulent conditions indicated successful suppression with the system activation pressure set at 0.07 barg (1.0 psig). In this case, the suppressed pressure, Δp_{max}, reached 0.50 barg [7.2 psig], and the maximum rate of pressure rise was 5 bar/s. However, when the system activation pressure was raised to 0.21 barg (3.0 psig), the delivery of the suppression agent appeared to have occurred too late, resulting in a Δp_{max} of 2.3 barg [32.8 psig], and a rate of pressure rise (dp/dt)$_{max}$ of 31.0 bar/s. All of the tests conducted with the SB agent used an ignition location at the geometric center of the vessel.

Post-suppression ignition attempts were made after each test. These experiments showed that successfully suppressed explosions left behind a sufficient amount of unburnt fuel so that the mixture could be re-ignited. In some cases, direct measurements were made of the post-suppression methane concentration. These data are generally consistent with the outcome of the ignition attempt on the mixture. One exception is a test, which was considered a successful suppression and had 7.3% methane left. Failure of this mixture to re-ignite was probably due to residual inerting by the agent.

5.2.2 <u>Monoammonium phosphate (MAP)</u>. The six quiescent suppression tests run with the MAP agent with a loading of 3.0 kg of material (nominal concentration of 1200 g/m³) were all considered successful suppressions (see Fig. 3). As in the case of SB, the values of Δp_{max} and (dp/dt)$_{max}$ increased as the system activation pressure set-point was increased ($\Delta p_{max} = 0.4$ to 0.9

barg [5.2 to 13.6 psig], $(dp/dt)_{max}$ = 4.0 to 13.8 bar/s, at set-points of 0.07, 0.21, 0.34 and 0.55 barg [1.0, 3.0, 5.0 and 8.0 psig]). The tests with pressure set-points of 0.07, 0.21 and 0.55 barg (1.0, 3.0 and 8.0 psig) were conducted with the ignition located only at the geometric center of the vessel. The tests run with a pressure set-point of 0.34 barg (5.0 psig) were carried out with the ignition source at each of the three possible locations (center, east end and west end). Of these three tests, the one which had been estimated to represent the highest challenge (west end ignition, above and behind the agent discharge nozzle) actually resulted in the lowest values of Δp_{max} and $(dp/dt)_{max}$ obtained under these pressure set-point conditions.

One of the turbulent tests, which was run for a set-point of 0.07 barg (1.0 psig) and with an ignition location at the center of the vessel, resulted in Δp_{max} = 0.39 barg (5.7 psig) and $(dp/dt)_{max}$ = 5.7 bar/s. This is a result very similar to that observed in the case of quiescent conditions. Three tests were run with a pressure set-point of 0.21 barg (3.0 psig), with each of the three ignition locations. As in the quiescent case, the lowest values of Δp_{max} and $(dp/dt)_{max}$ were obtained in the test with the ignition source located at the west end of the vessel (see Fig. 3). On the other hand, relatively high suppressed pressures (1.4-1.5 barg [20-22 psig]) were measured for central and east end ignitions. For the conditions of these tests, both SB and MAP should be considered to have failed in suppressing turbulent mixtures with a detection threshold of 0.21 barg (3 psig). The post-suppression ignition attempts made after each test with MAP essentially confirmed the results obtained after the SB runs.

5.3   Cold Water Suppression Agent Results

The results of the suppression tests with cold water (all conducted under quiescent conditions) were considered to be failures of the explosion suppression system, with the exception of two
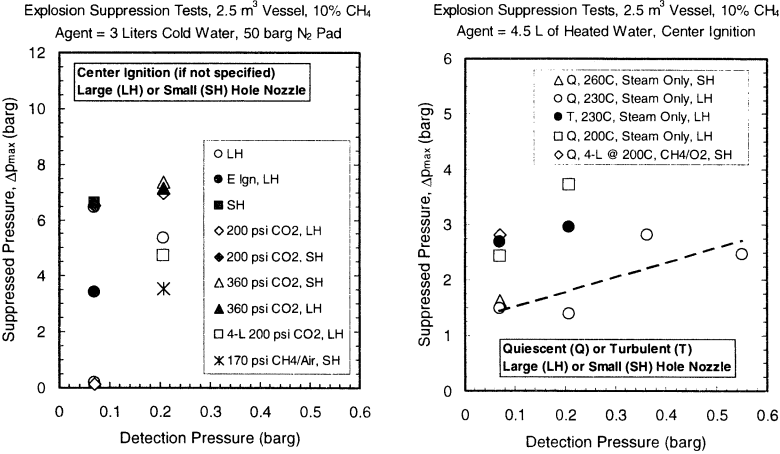

FIGURE 4 – Suppression Tests with Unheated (left) and Heated (right) Water, for Varying Pressure Switch Settings.

runs (see Fig. 4) performed with an activation pressure set-point of 0.07 barg (1.0 psig). All other tests carried out with 3 or even 4 liters of water (pressure switch set-points of 0.07 or 0.21 barg [1.0 or 3.0 psig]), large or small hole nozzle, did not result in suppressions of the explosion.

Six tests were also performed by adding carbon dioxide (CO_2) to the driver mixture to enhance the effectiveness of cold water as a suppression agent. The idea was to to take advantage of the expansion on agent delivery of the dissolved CO_2, to promote fragmentation of the water stream into droplets. The CO_2 was added to the HRD by bubbling it through the water charge up to maximum pressures of either 13.8 or 24.8 barg (200 or 360 psig). The pressure in the HRD was then raised by nitrogen addition to a final value of 50 barg (725 psig). In one test, special care was taken to ensure that the water charge would be saturated by CO_2. This was achieved by shaking of the HRD during charging. In addition, saturation conditions were confirmed by weight measurements.

These tests with carbonated water produced a single, non-repeatable suppression. This is considered a random result, with minor impact on the general conclusion that the presence of the CO_2 had a negligible effect on the performance of the system. Lack of suppression was marked by the attainment of full explosion pressures and high rates of pressure rise, to an extent very similar to what was observed with the non-carbonated water.

5.4   Heated Water Suppression Agent Results

Prior to testing with heated water, an exploding methane/air mixture was developed as the driver. This method of agent deployment was found to be relatively slow, as it involved times of the order of 50-60 msec from triggering of the system to the moment of actual agent release. The first suppression run with the explosive mixture as the driver was for an initial pressure of the mixture of 10.7 barg (155 psig) and used cold water. This test confirmed the expectation that cold water would not perform any better with a methane/air mixture driver than in the previous instances where a compressed-gas charge was used. The delay in system actuation caused the agent to discharge when the pressure in the vessel had reached about 0.8 barg (12 psig), even though the set trigger pressure was 0.21 barg (3.0 psig), further reducing the possibility of a successful suppression. All subsequent testing was carried out with heated water.

The presence of steam above the heated water charge required replacement of the air by oxygen to obtain a sufficiently reactive mixture for the driver. Four tests were performed under these conditions with a system trigger pressure of 0.07 barg (1.0 psig) and water temperatures of 170, 200 and 230°C (338, 392 and 446°F). As already discussed, the performance of the system was degraded by the relatively slow response of the driver. This was particularly deficient in the case of one test, in which the resulting activation delay, of the order of 120 msec, led to agent deployment by the time the explosion pressure in the test vessel had reached about 1.4 barg (20 psig). In the other two tests where data were obtained, the activation delay was of the order of 30 msec, and the system performed in a manner similar to that of later tests with explosively-actuated burst discs. There was no indication from these experiments of the hot driver gases having a negative impact on the effectiveness of the suppression process.

Eventually, a solution was found that allowed for use of the Fenwal explosive actuator and its associated rupture disc with the HRD filled with heated water. All remaining tests were, therefore, performed with the agent deployed by hardware that provided the same response to the triggering signal as that of the tests with the powder agents and with the cold water. With the exception of two runs, in which the steam pressure was topped off to 50 barg (725 psig) by
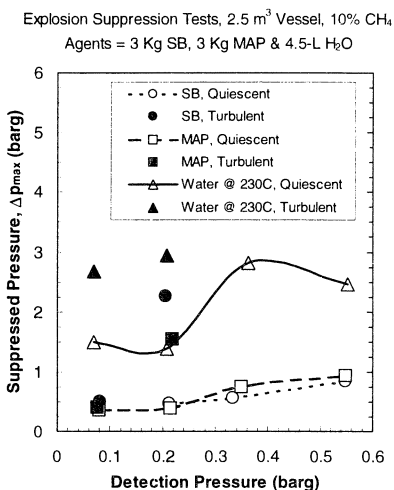
Explosion Suppression Tests, 2.5 m³ Vessel, 10% CH₄
Agents = 3 Kg SB, 3 Kg MAP & 4.5-L H₂O

FIGURE 5 – Comparison of the Effectiveness of Different Suppression Agents.

addition of nitrogen, in all other tests the agent was expelled by the steam pressure alone. This factor did not appear to have had a major impact on the effectiveness of the suppression system. The data from these hot water tests are summarized in the right plot of Fig. 4, with the exception of the one test in which the activation of the system was much delayed, as discussed earlier. Analysis of the data has led to the judgment that successful suppression was achieved by hot water only in cases where the temperature of the charge was 230°C (446°F) or higher. Furthermore, better results were obtained using the large-hole discharge nozzle, possibly due to less clogging of the nozzle holes from the explosive actuator debris (brass shrapnel).

Interpretation of the outcome of these tests is complicated by the fact that the introduction of the agent alone causes a significant temperature and pressure rise in the protected volume. This effect was quantified by a test, in which the HRD filled with 4.5 liters of 230°C (446°F) water was discharged in the test volume filled with an ambient pressure methane/air mixture. This release produced a maximum temperature in the vessel of about 100°C (212°F), which settled down to 85°C (185°F) within 0.5 sec, and a 0.83 barg (12 psig) pressure rise. This contribution to the overall pressure rise from the steam complicates the definition of what should be assumed to constitute successful suppression when heated water is involved. It was noted, however, that in the tests where suppression was achieved, the temperature in the vessel settled very rapidly (within 0.5 sec from injection) to 100°C (212°F). Higher temperatures were recorded in tests where significant combustion occurred after introduction of the agent.

In the two tests performed under turbulent conditions, further increases were measured for the suppressed explosion pressure. A possible factor with an important impact on overall system performance is the fact that agent release under steam pressure alone appears to take about 200 msec, twice the time required when a pressurized nitrogen driver is used. The reduced speed in agent deployment obviously causes delayed extinction of the flame front and allows for higher pressure development in the protected volume.

5.5   Comparison of Agent Performance

An overview of the test results is given by the data summary provided by the plot in Fig. 5. As can be seen, both SB and MAP have similar effectiveness in the case of quiescent mixtures. However, for the conditions of the tests with turbulence, these agents start to display unsatisfactory performance at a detection pressure of 0.21 barg (3.0 psig), as indicated by suppressed pressures of 1.5-2.3 barg (22-33 psig). This points to the strong possibility that even these agents may encounter some difficulty in suppressing high-challenge gas explosions.

On the basis of the measured suppressed pressures, the data indicate that hot water is significantly less effective than the powder agents. However, if the pressure associated with steam addition is deducted from the measurement, the total pressure rise in the heated water tests at low trigger pressures (0.07 and 0.21 barg [1.0 and 3.0 psig]) becomes comparable to that measured with powder agents, i.e. of the order of 0.34-0.59 barg (5-8.5 psig). While increasing substantially as the system trigger point is raised, the suppressed pressure does so gradually. This is taken as an indication that some degree of flame extinguishment is achieved with hot water in all cases, even when the suppression cannot be considered successful. One final observation is that the presence of initial turbulence in the mixture causes an increase in suppressed pressure similar to that observed in the case of the powder agents.

VI   SUMMARY AND CONCLUSIONS

The data obtained in this work confirm the results from other studies, which have indicated that explosion suppression systems can be effective in suppressing both quiescent and moderately turbulent homogeneous gas/air explosions. The experiments described in this paper have involved methane-air mixtures with burning velocities in the range of 0.4 to 1.7 m/s, and sodium bicarbonate (SB) and monoammonium phosphate (MAP) as agents. Under turbulent conditions, however, the tests from this program have underscored the fact that reliable suppression requires early detection of the explosion. While the testing did not address the question of the effect of agent charge, it would seem reasonable to require that the delivered concentration of agent be at least equal to that necessary to inert the mixture in order to provide some degree of post-suppression protection. A quantitative definition of this requirement can be based on inerting data of the type obtained in this study from tests in a 20-liter apparatus, combined with estimates of the effect of settling on the residence time of the powder agent.

Ambient-temperature water does not appear to be an effective agent, as it failed to suppress explosions of the 10% methane/air mixtures used in the tests. The performance of this agent was not improved by the addition of carbon dioxide dissolved in the water. This result, which essentially confirms the findings of other studies, is probably attributable to the fact that the droplets (estimated at 100-150 μm diameter[8]) produced by the fragmentation of the water jet are too large to allow for sufficient heat extraction from the flame front. Better performance was obtained with heated water, with successful suppression requiring temperatures of 230°C (446°F) or higher and early detection of the explosion (trigger pressure of 0.07 barg [1.0 psig]). An undesirable aspect of the use of heated water is the fact that suppressed pressure levels are high, owing to the contribution from the steam introduced in the protected volume, which can typically represent about 1 bar (14.5 psi) of the total pressure rise. This fact alone may well limit the use of hot water for the suppression of vapor/air explosions to cases where the protected volume is strong or where suppression is used in combination with explosion venting.

Other details of the explosion suppression system were considered by the study. For example, the effectiveness of a smaller-holed agent discharge nozzle (intended to better break up the water particles) was found to be substantially equivalent to that of a large-hole nozzle. The lack of improved performance may be in part attributable to the fact that the smaller holes had some tendency to become clogged by debris from the rupture disc or the explosive actuator. The location of the ignition source had a small effect on the performance of the suppression system, with the observation of better performance when the ignition was located behind the agent discharge nozzle. Finally, turbulence in the mixture consistently increased the challenge

presented to the suppression system, as shown by the higher pressures developed in the suppressed explosion.

ACKNOWLEDGMENTS

REFERENCES

1. Senecal, J. A., "Deflagration Suppression of High K_{st} Dusts," Plant/Operations Progress, Vol. 8, No. 3, pp. 147-151, July 1989.

2. Chatrathi, K. and Siwek, R., "Use Suppression Systems to Mitigate Explosions," Chemical Engineering Progress, pp. 22-31, March 1996.

3. Siwek, R. and Moore, P. E., "Extended Design Practice for Explosion Suppression Systems," Loss Prevention and Safety Promotion in the Process Industries, Vol. I, Edited by J. J. Mewis, H. J. Pasman and E. E. de Rademaeker, pp. 539-550, Elsevier 1995.

4. Bartknecht, W., "Dust Explosions - Course, Prevention, Protection," Springer Verlag, 1989.

5. Chaffee, J. L., "The Venting and Suppression of Explosions in Aerosol Gas Filling Rooms", FMRC Technical Report J.I. 0R0J7.RK, Short-Range Research Program - Project 90-19, September 1991.

6. ASTM, "Standard Test Method for Minimum Explosible Concentration of Combustible Dusts," E 1515-93, Feb. 15, 1993.

7. Tamanini, F., "Modeling of Turbulent Unvented Gas-Air Explosions," AIAA Progress in Aeronautics and Astronautics, Dynamics Aspects of Explosion Phenomena, A. L. Kuhl, J.-C. Leyer, A. A. Borisov and W. A. Sirignano, Editors, Vol. 154, pp. 3-30, May 1993.

8. Bowen, P. J. and Shirvill, L. C., "Combustion Hazards Posed by the Pressurized Atomization of High-Flashpoint Liquids," J. Loss Prev. Process Ind., Vol. 7, No. 3, pp. 233-241, 1994.