FEATURE

Failure Analysis and Prevention of Fires and Explosions with Plastic Gasoline Containers

Glen Stevick · Joseph Zicherman · David Rondinone · Allan Sagle

Abstract Explosions and fire incidents involving portable plastic gasoline containers manufactured for consumer use are known to occur frequently and are verified in databases, engineering literature, legal briefs, and newspapers. This project studied such incidents and presents findings from a comprehensive test program documenting conditions under which such incidents occur. Factors controlling resultant vapor headspace compositions and headspace ignitions and/or explosion occurrences include the following: mass of gasoline in relation to a particular container size, ambient temperature, and "age" of stored gasoline samples. Experimental results also demonstrated the effectiveness of flame arrestors to eliminate risk of explosion.

Keywords Portable plastic gasoline containers · Aging · Explosion · Flame arrestor · Flame arrester · Hydrocarbon vapor · ASTM F 852-86 · ASTM F 839-06

Background

Explosions and fires associated with pouring gasoline from a partially filled, portable plastic gasoline container (PPGC) the designs and manufacturing process of which comply with ASTM F-852 and F-839 have been reported

G. Stevick · D. Rondinone · A. Sagle
Berkeley Engineering and Research, 2216 Fifth Street, Berkeley, CA 94710, USA
e-mail: gstevick@gmail.com

J. Zicherman (⊠)
Fire Cause Analysis, 935 Pardee Street, Berkeley, CA 94710, USA
e-mail: joe@fcafire.com

and are the subject of this paper [1, 2]. It is generally accepted that the PPGCs which are the subject of this article are not subject to regulation according to the NFPA-30 document "Flammable and Combustible Liquids Code." More frequently than not, when such events occur and are reported, they have resulted in injuries, usually serious to individuals nearby. Many such incidents have involved use of PPGCs containing locally purchased gasoline blends to assist in the ignition and burning of trash or building of bon-fires [3]. Other similar mishaps resulting in injuries are reported in the accident and fire incidence literature and in reports from Federal agencies [4].

It is the objective of this article to review the occurrence of such incidents, characterize the physics and use patterns associated with their occurrence and consider possible mitigation features to such portable plastic gasoline containers (PPGC's) to reduce or eliminate these occurrences.

Literature Review

A review of peer-reviewed articles in engineering and fire science journals in search of references to explosions of gasoline stored in PPGCs revealed one on-point article by Hasselbring [5]. Her research and testing indicated that such phenomena are real, but her research was limited in terms of explaining how and why gasoline container explosions occur. Air entrainment during pouring was suggested as one possible explanation for these phenomena.

More general comments can be found in fire science texts suggesting both that PPGC explosion events *do* occur and that they *do not* occur. The *Ignition Handbook* is one example, with the original volume suggesting how and why

such gasoline container explosions can happen while *a Corrigenda* to the original volume provided by the author on the internet states otherwise [6]. However, no references are provided to any significant testing or analysis for either condition, and as such, neither claim can be considered persuasive.

Drysdale also considers such incidents, but does not provide specific references or data as to their occurrence [7].

Federal agencies, including the U.S. Consumer Product Safety Commission (CPSC), the National Bureau of Standards (NBS) [predecessor to the National Institute of Standards and Technology (NIST)], and the NIST Building and Fire Research Lab (BFRL), have issued reports stating that explosions with PPGCs have been noted to occur. The former agency has also commented in its reporting that the use of flame arresters in the spout can prevent such explosions [8].

These reports were prepared in the 1970s addressing portable gasoline can safety by researchers at NBS, now NIST, which included input from research staff members at the Center for Fire Research, now the Building and Fire Research Labs. These include "Gasoline and Gasoline Container Fire Incidents," NBS Technical Note 850 by E. Tyrell and "Standards for Gasoline and Kerosene Cans," NBSIR 78-1414(CPSC) by Jones [9].

Consideration of such explosions in anecdotal forums is common. For example, the publication *Consumer Reports* has commented on this subject on two occasions citing leakage from available PPGCs as a potential cause of explosions [10, 11]. Likewise, newspaper and television reports are known to quote witnesses describing an explosion occurring. In at least one case, a plastic gasoline can was documented in a news video which had experienced an explosion—as opposed to high-temperature melting—based on evidence of the plastic material tearing behavior shown in Fig. 1 [12]. Documentation of similar occurrences, observed in the testing of PPGCs under laboratory conditions are presented in this article.

Gasoline Aging

Aging of gasoline, the loss of lighter weight gasoline fractions sometimes referred to as "light ends," is a relevant and important process in these discussions. This is because the so-called fresh gasoline has distinctly different make-up from the gasoline which has been subjected to aging, i.e., exposure to ambient conditions whereby evaporation or diffusion can occur. Further, not unexpectedly, such aging causes changes in the vapor pressure of gasoline as it ages, leading in turn to changes in hydrocarbon vapor concentrations in a given container as that aging continues.

While not characterized through use of an accepted standard method, aging is a phenomenon known to the fire investigation community as well as fire scientists involved with changes in gasoline properties during storage [13]. In that case, losses of the light ends by evaporation have led to measures of weathering based on fractional weight losses observed. This approach is common in characterizing accelerants taken from fire scenes [14].

Overall, characterization of weathering of any standard gasoline sample is a difficult task given the diversity and range of components present in the commercial products. In large part, this is because—even at a specific octane rating—gasoline blends sold vary both seasonally and regionally in terms of the specific hydrocarbon types they contain as well as included additives. However, "weathering" of gasoline as well as diesel blends has been the subject of articles in the fire science and combustion science literature recently [15, 16]. These "weathering"/aging processes are a function of gasoline's tendency to evaporate when exposed to ambient conditions such as when a PPGC is left open.

The individual constituent components of gasoline blends range from lighter through heavier hydrocarbon molecules, typically composed of between 4 and 12 carbon atoms per molecule [17]. Evaporation rates of these gasoline constituents are an inverse function of their molecular weight with the so-called lighter ends the lower molecular

Fig. 1 A PPGC shown in news footage following a fire incident. Damage demonstrates fractures consistent with explosion and rupture having occurred

weight fractions, evaporating preferentially from a hypothetical open container. As such, their loss results in the resulting gasoline blend of hydrocarbon developing a lower vapor pressure with time. This specifically is the process we refer to here as "aging." It is also essentially the same process referred to as "weathering" in fire investigation literature relating to accelerants, whereby lighter hydrocarbon fractions evaporate differentially from the hydrocarbon blends leaving heavier fractions only [18].

It has also been noted, as evidenced from research related to air pollution considerations, that component fractions of gasoline will diffuse across the walls of generic plastic gas cans differentially. In such cases, the rate of this diffusion is inversely proportional to the molecular weight of the hydrocarbon fraction involved, and directly proportional to the flux gradient of any given fraction [19]. However, it also must be borne in mind that such mass loss phenomena based on diffusion have rates that are 1–2 orders of magnitude lower than mass loss rates by direct evaporation. Thus, diffusion-based losses, while considering important regional perspectives in terms of impact on air quality given the number of plastic containers in use are secondary, when such diffusion-related aging losses from PPGCs are considered if containers are open to the air.

As noted above, aging of gasoline is related to evaporation, and evaporation rates for a given liquid are invariably linked to temperatures of any process. Consistent with this, it is well known that gasoline volatility decreases as temperature decreases. It is also known that it is important to maintain hydrocarbon fractions above the upper flammable limit (UFL) in a PPGC headspace if ignitions are to be precluded. Thus, the quantification of the relationships between the behaviors of different volumes of gasoline stored at similar temperatures within identically sized containers is important to characterize the properties of such systems.

In the explosion incidents initially investigated by the authors, subject PPGCs have been left standing open with either their nozzles removed or kept un-capped for weeks or months before incidents. Thus, these conditions provided initial baselines for evaluation of the conditions underlying the explosions which occurred.

As noted above, there are no standard methods to age gasoline blends, and so the authors used two generalized techniques to produce reproducible aging and approximate the relevant conditions of consumer use.

It is well known that gasoline volatility decreases with temperature. It is also known that it is important to maintain hydrocarbon fractions above the UFL in a container headspace if ignitions are to be precluded. Thus, quantification of the behavior of different volumes of gasoline stored at similar temperatures in the same volume of container is important. The process by which this relationship was developed follows.

For the initial explosion testing carried out in this program, accelerated aging of gasoline used was accomplished by exposing small amounts of gasoline to ambient outdoor conditions in large mouthed open containers similar to a common metal bucket.

Subsequently, a more systematic approach was developed. This involved ASTM-compliant PPGCs of a single size (5-gallon/18.93 L) purchased locally, utilized as a single-sized volumetric chamber which related directly to the incidents in question in which gasoline aging could be conveniently conducted. To induce aging, 10 of these containers were filled with various amounts of commercially purchased, 87 octane gasoline with their nozzles extended and open for exposure to ambient conditions. The exposures took place in a ventilated safety shed and average range, and mean daily temperatures recorded during the aging exposures were 10 and 8 °C, respectively.

In this case, differing amounts of gasoline were exposed to ambient summertime conditions in Berkeley, California in ten 5-gallon/18.93-L PPGCs. Weathered samples were developed from initial amounts 100; 200; 300; 600; 900; 1200; 1500; 3000; 6000 and 10,000 ML of gasoline. Nozzle openings were on the order of 0.75″/19 mm. Within 30 days, the smaller amounts of gasoline had evaporated completely. Monitoring of Vapor Pressures of Oxygen in the headspace of each separate container was conducted daily at a similar reference temperature.

In the ambient exposure environment utilized, the partially filled containers were subjected to daily changes in temperature with attendant pumping caused by changes in evaporation rates related to diurnal cycling. This created interchanges of hydrocarbon vapor and ambient air on a daily basis. The accelerated aging in both of these cases was due to the same mechanism, evaporation, and no heating or agitation was used.

Results for changes in gasoline vapor concentrations for various quantities of gasoline aged under ambient conditions in identical containers are plotted in Fig. 2.

These data are quite similar to data published recently by the Japanese researchers in the *Fire Safety Journal* [15]. They are also demonstrative of the light ends of the gasoline blend evaporating significantly more quickly than the heavier ends, and the associated headspace hydrocarbon vapor pressure and volumetric percent hydrocarbon dropping over time.

As shown in Fig. 3 below, the partial pressure of gasoline becomes lower with decreasing temperature as well as with decreasing amounts of gasoline exposed in an open container over time. As an example, for 1.5 L of gasoline stored in an open 5-gallon (18.93-L) can at an average temperature of 10 °C, the percent hydrocarbon in the vapor headspace falls into the explosive range in less than 20 days.

Fig. 2 Aging results for commercially obtained 87-octane gasoline outdoors with a 10 °C (50 °F) average mean temperatures in a 5-gallon (18.93 L) PPGCs complying with ASTM F-839 and F-852. Starting volumes ranged from 100 mL to 10 L
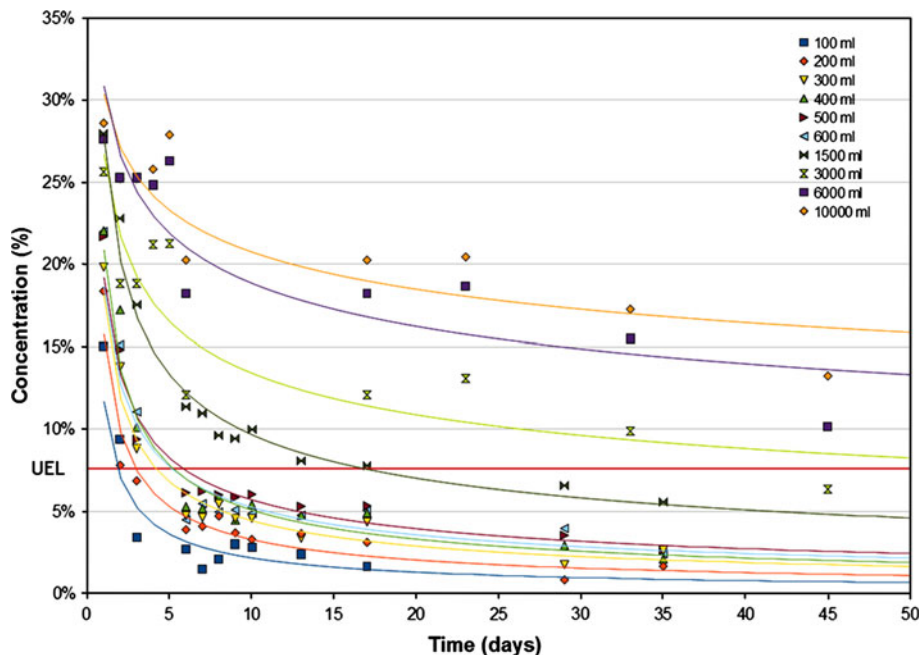
Fig. 3 Hydrocarbon vapor concentration in a 5-gallon (18.93-L) gasoline can for fresh and lightly aged, commercially purchased gasoline (120 h, outdoors, at 10 °C/50 °F average mean temperature)
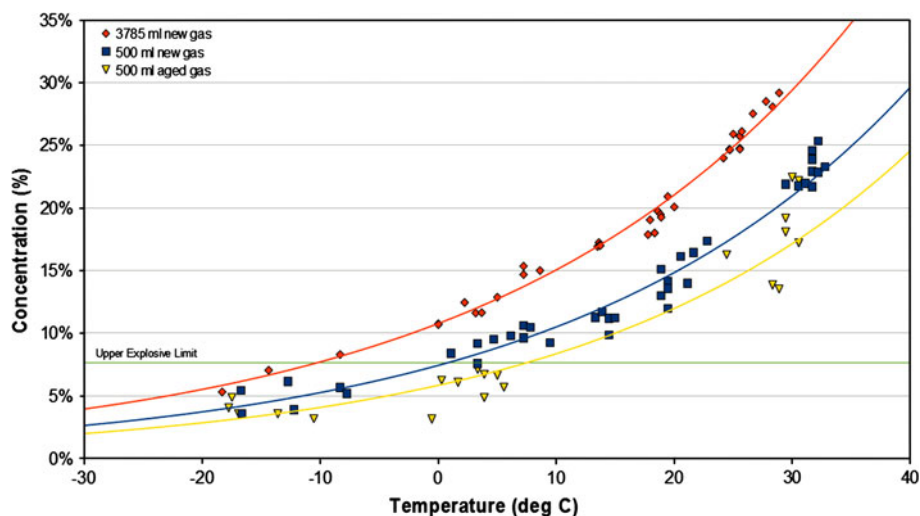
Measurement of Hydrocarbon Vapor Concentrations

In situ measurement of hydrocarbon vapor pressures as aging occurred presented interesting challenges. Methods such as ASTM F2714-08 [Standard Test Method for Oxygen Headspace Analysis of Packages Using Fluorescent Decay] or ASTM D6378-07e1 [Standard Test Method for Determination of Vapor Pressure (VPX) of Petroleum Products, Hydrocarbons, and Hydrocarbon-Oxygenate Mixtures] are available, but are not readily applicable for on-site testing with rapid data turnaround. For this reason, it was decided to use a methodology whereby an oxygen sensor-based system could be used in situ.

Such a system has been described by Shirvill and co-workers in applications to measure volumetric percent hydrocarbon in a vapor mixture consistent with a container headspace [20]. Their approach utilized an inexpensive oxygen sensor which was also readily applicable for direct, in situ use in a laboratory environment where it produced reproducible results in measuring headspace hydrocarbon concentrations [21].

Specifically, concentrations of gasoline vapors were obtained by recording pairs of 0–10 V readings from the meter which directly corresponded to 0–30% oxygen levels. The same method described by Shirvill and co-workers allowed in our study hydrocarbon concentrations in PPGC headspace to be directly measured in the laboratory.

To accomplish this, the following procedure was followed with pairs of recorded measurements to obtain concentrations of hydrocarbons in headspaces: Partial pressure of oxygen, V_{air}, was first measured in air. Next, partial pressure in the mouth of the gasoline can, V_{gas}, was obtained. Concentrations were then calculated using the relationship $(V_{air} - V_{gas})/V_{air}$. Sensor values were recorded upon reaching equilibrium.

Use of the gasoline aging protocol described above in conjunction with the direct measurement technique using the oxygen sensor allowed hydrocarbon concentrations in the headspace to be directly measured in the gasoline cans. Example measurements illustrative of fresh gas and lightly aged gas (equivalent of 5 days in an open gasoline container) are shown in Fig. 3. These results illustrate the interrelationship among aging, temperature, and amount stored in a given volume, as well as the relationship of these variables to the commonly accepted upper explosion limit (UEL) for common gasoline blends.

The results illustrate that the relationship between percent hydrocarbon in a gasoline can and its propensity to explode is a function of aging, temperature, and quantity of hydrocarbon. The data also show that the hydrocarbon vapor concentration of lightly aged gasoline (equivalent to 5 days in a gasoline can with an open spout at an average ambient temperature of 10 °C in Berkeley, CA) can readily fall below the UEL for lower temperatures and smaller amounts of liquid fuel in the can.

Changes in hydrocarbon vapor pressure caused by gradually warming and cooling of replicate individual gasoline samples were observed as shown in Fig. 3. Measurements of vapor pressures were made using the oxygen sensor technology described by Shirvill and co-workers to be discussed later in this report. Sample vapor pressures obtained were observed to be independent of the specific warming or cooling history of a sample to a particular temperature. Additional verification of the sensing method used in this study is provided later. The occurrence of explosions were accurately predicted by determinations of conditions existing either between the UEL and lower explosion limit (LEL) as well as outside the explosive range.
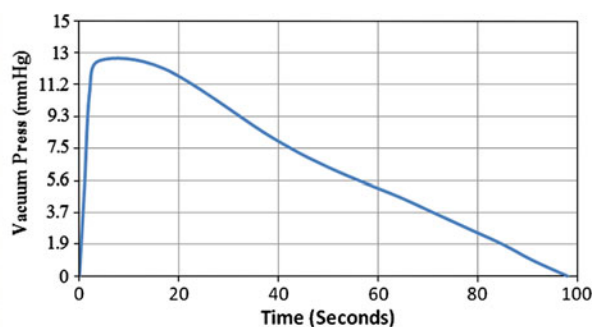
Air Entrainment in PPGC Use

It was theorized by Hasselbring that air entrainment during pouring might be responsible for the vapor headspace dropping below the UEL and thereby creating an explosive hydrocarbon/air mixture. In order to test this potential contributing factor, simple pour tests were conducted to directly measure vacuum produced when gasoline is poured from a PPGC and to confirm the displacement volumes in question.

The apparatus for the manometer testing and the results are shown in Fig. 4. The data produced illustrate the substantial reduction in internal pressure below atmospheric pressure which develops in a gasoline can being poured. These are in the range of 6–7 in. of water column (0.22–0.25 psi/1.5-1.7 kPa), and depend on the degree to which the can is tilted during pouring. This depression is adequate to cause an air inflow into a can contemporaneously with pouring of gasoline.

Subsequent investigations by the authors of specific fire and explosion incidents have revealed that the amount of gasoline involved in a gasoline can explosion event is typically small, i.e., less than 1 L, and the user typically tries to pour only a small amount. Thus, air entrainment is unlikely to be a significant factor in such a gasoline can explosion. For this reason, it was hypothesized that other mechanisms, such as aging of gasoline, ambient temperature, and amount of gasoline in the container, were primary variables of importance.

Explosion Testing

Field evidence, aging tests, and calculations indicate that explosions involving PPGCs can and do occur under foreseeable conditions when their concentration is within the flammable range which is consistent with published data, suggesting a LEL of 1.4% gasoline vapors in air through an UEL of 7.6% [22]. However, given the lack of documentation of such incidents under laboratory conditions in the literature, it was decided to conduct explosion

Fig. 4 Gas can monitored by monometer (left) during pouring from a 5-gallon (18.93-L) PPGC. A typical plot of time vs. vacuum pressure measured is plotted at the right side

testing to verify the reported events under reproducible conditions.

In these tests, measured amounts of gasoline samples were added to the container, and the container was inverted as in pouring, which mimics the most common scenario for incidents reported from the field. For safety purposes, inversion of the can was accomplished using a test jig inside a reinforced test cell. The open spout, sited near an ignition port in the test cell, was then exposed to a [2-cm-long] butane diffusion flame which was passed near the container spout as shown in Fig. 5.

Replicate explosion tests were initially conducted using a range of commercial ASTM compliant 5-gallon (18.93-L) gasoline cans. Commercial gasoline samples utilized in this testing were aged to various extents, and volumes added to the containers ranged from 20 to 1750 mL. Similar replicate explosion tests were also conducted with 2-gallon (7.85-L) containers.

For purposes of personnel and property safety, most testing was conducted with cans modified with a plastic plug to provide explosion relief, as shown in Figs. 5 and 6 (below). Use of these plugs prevented the excessively violent explosions which occurred in some of the cases

studied, where the can ruptures as illustrated in Fig. 7 took place.

The tests shown in Figs. 5 and 6 were ignited using a commercial butane lighter producing a diffusion flame 2 cm high as an ignition source.

Confirming the need for the explosion relief ports used, tests were also performed with gasoline cans in the as-is state, *without* the pressure relief port. In one such case, a can was launched by the jet coming out the spout, while more typically, the cans ruptured from the overpressure as shown in Fig. 7.

The ignition process leading to these overpressure conditions in the PPGCs that ruptured was documented using a high-speed video. In one such case, the travel of a flame front can be observed traveling up the plastic spout of a 2-gallon (7.85-L) can. Photos are shown in Fig. 8 taken from frames of high speed video.

Fifty-eight trials with similar PPGCs were conducted in the study presented here. Primary variables studied included (1) percent hydrocarbon vapor in the headspace, (2) amount of gasoline relative to headspace volume/container size, (3) ambient temperature, and (4) whether or not gasoline samples were aged or new/fresh.

**Fig. 5** Gasoline cans tested w/o flame arresters (6-19-08: tests 5 and 6)
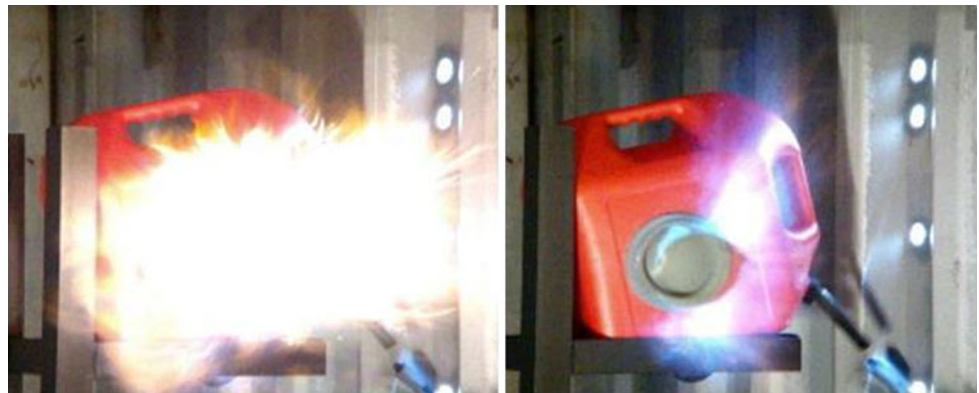
Fig. 6 Gasoline cans tested w/o flame arresters (6-19-08: tests 7 and 8)

Fig. 7 Five-gallon can (left) and two-gallon can (right) from unmodified gasoline can explosion tests

Fig. 8 Stills from a high-speed video of a 2-gallon (7.85-L) can test showing the flame traveling up the translucent plastic spout and confirming a flame speed of approximately 0.4 m/s
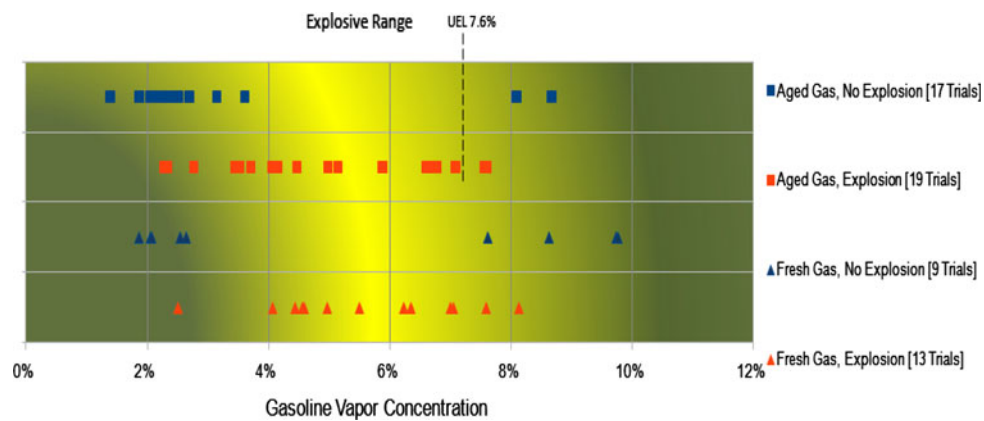
Fig. 9 Explosion occurrence as a function of percent hydrocarbon concentration for aged and fresh gasoline. Red points indicate that an explosion occurred in a separate trial. Cooling of samples was utilized to create ignitions with fresh gasoline. Other testing was done at ambient

Groupings of test data, plotted relative to the percent hydrocarbon in the vapor space, confirm published explosive limits for commercial gasoline blends. See Fig. 9.

The test results summarized in Fig. 9 include a small number of "non explosive" data points which were above the observed LEL of commercial gasoline. Referring to

462

J Fail. Anal. and Preven. (2011) 11:455–465

such cases, it should be noted that vapor concentrations were measured a few minutes before the time of ignition before the spout being present on the PPGC. As such, during these low vapor concentration tests, the gasoline vapor in the spout at the time of ignition may have been somewhat lower at the time of test than the measured value.

When gasoline vapor concentrations are low in such cases, the diffusion and gross motion of the gasoline vapor/air mix from the can to the spout will be slower than for testing at high vapor concentrations. This can lead to a situation where the actual gasoline vapor concentration in the spout is leaner than the LEL, while the measured value is richer.

The results developed and presented here confirm and are consistent with the published data on UELs for common commercial gasoline samples. While a significant error band was observed around the LEL, from operational or safety perspectives, this is of minor concern since it is difficult and/or unlikely for a gasoline can user to age gasoline in a PPGC near the lower limit.

Flame Arrester Technology

Flame arresters have been used industrially for almost 200 years. Sir Humphrey Davy first developed a flame arrester for coal miner helmets in 1815 [23]. Patents were issued for flame arresters in the 1880s for both chemical processes and flammable liquid containers [24]. During the early 1930s, R.J. Anschicks, developed and patented a tank fitting that incorporated a flame arrester [25]. All gasoline containers currently manufactured by the patent assignee continue to have perforated metal flash arresters positioned at container openings.

A flame arrester works by removing heat from a flame and keeping the temperature of the fuel on the other side of the arrester below its ignition point. The flame arrester mesh breaks the flame into many flamelets, and the heat of these flamelets is transferred to the walls of the mesh. There are two criteria for successful operation: the holes in the mesh must be less than the critical diameter, and the mesh must have a critical velocity higher than the flame speed.

The critical diameter d_{cr} from Mendozza et al. [26] and Gossel [25] is given by

$$d_{cr} < N_{pe,cr} \acute{\alpha} S_u \qquad \text{(Eq 1)}$$

where $N_{pe,cr}$ is the Peclet number with a value of 65 as recommended by those authors, $\acute{\alpha}$ is the thermal diffusivity in air (m^2/s), and S_u is the fundamental burning velocity (0.4 m/s for gasoline). The critical velocity (V) is also given by Gossel as shown below:

$$V = (38ay)/d^2 \qquad \text{(Eq 2)}$$

where a is the fractional-free area of the arrester surface, y is the thickness (width) of the arrester elements (m), and d is the diameter of the apertures (m).

The flame speed for the aged California gasoline containing ethanol in a standard, translucent gasoline can spout was measured optically with a high-speed video camera during testing and determined to be 0.4 m/s. This is the same value as the fundamental burning velocity for 100 octane gasoline reported in the literature.

Equation 2 is more conservative than 1 and includes application of a safety factor of 2.5 to the flame velocity to account for possible experimental error.

In this study, the criteria addressed in the equations above were considered in conducting tests of flame arrestors installed in three commercially available gas cans. The results of these tests are shown in Table 1.

For each arrester design, the mesh hole sizes were significantly less than the critical diameter, and the calculated critical velocity (with a 2.5 safety factor applied) is larger than the measured flame speed for gasoline in a gasoline can spout. All of these flame arresters have been successfully tested in ASTM compliant gas can designs.

While some manufactures state that such screens are installed to act as a filter, we have determined that such screens also act as effective flame arresters. A designated flame arrester from a commercial can is shown in Fig. 10.

Fifteen tests were conducted with flame arresters with the same aged gasoline and under the same conditions as the tests that produced explosions, without any explosions occurring. When measured during testing, temperature of the flame arrester was consistently found to be elevated and in the range of 100 °C. In these cases, the flame had reached the arrester assembly, but in no case passed through it. As a result of limited fuel supply, occurrence of burn back is ruled out as is observed in pipelines or large tanking systems where continuous supplies of combustible vapor may be present.

Explosion tests of PPGCs equipped with flame arresters were uneventful as shown in still photos taken from video, see Fig. 11. The test flame at the end of the spout is to be noted.

Discussion and Conclusions

The extensive testing and analysis performed in this study demonstrate that explosions of gasoline stored in commercially available PPGCs can and do occur. Control of such incidents continues to be important and their frequency can be expected to increase with increased use of oxygenated fuels. The latter is derived from ethanol, which

Table 1 A comparison of flame arrestor geometry and dimensions for cans from six different manufacturers

Manufacturer	Can material	d, mesh hole size, mm	Critical diameter, mm Equation 1	y, wire thickness, mm	Flame speed, m/s Equation 2	Fundamental burning velocity for gasoline, m/s
A: Commercial Cylindrical flame arrestor	Metal	0.584	3	0.25	1.374	0.4
B: Commercial Cylindrical flame arrestor	Plastic	1.43	3	0.48	0.503	0.4
C: Commercial Screen disk flame arrestor	Metal	0.3	3	0.20	3.04	0.4
D: Consumer (with plastic flame arrestor)	Plastic	1.2	3	0.75 (plastic)	0.74	0.4
E: Consumer Cylindrical flame arrestor by authors	Plastic	1	3	0.4	0.84	0.4
F: Consumer Screen disk flame arrestor	Plastic	1	3	0.3	0.72	0.4

One consumer manufacturer (F) utilizes a screen that acts as a flame arrestor. Authors developed and installed the flame arrestor in can (E)

Fig. 10 Photos of a screen-based flame arrestor used in a currently available commercial can (Manufacturer B). The screen arrestor is cylindrical, roughly 45 mm deep and 35 mm in diameter. Flame arrestor assembly fits into the gas can at the spout base
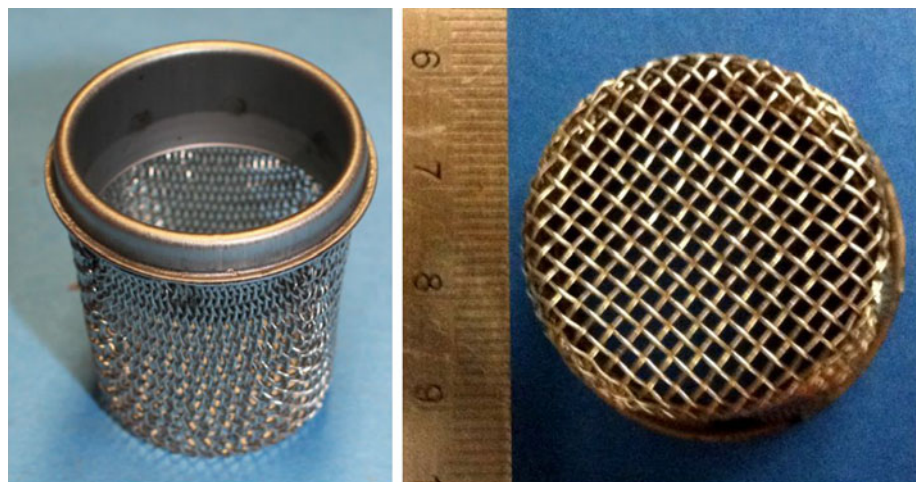
Fig. 11 Gasoline cans tested with flame arresters exhibited no explosion in spite of flame travel up nozzle

has lower vapor pressures intrinsically than the hydrocarbon-based analogs making them more susceptible to headspace explosions at ambient than current gasoline blends not containing oxygenates. Examples of research concerning these materials are found in the literature [27, 28].

Preconditions for such events are (1) the presence of an open flame or static ignition source and (2) the presence of

Fig. 12 Child-resistant, automatically closing nozzle jammed in open position

a vapor space where the percent hydrocarbon concentration is within the explosive range between the accepted UELs and LELs for commercial gasoline blends. Combinations of conditions leading to the vapor space being in the explosive range include aging of gasoline, low ambient temperature, and/or a small amount of gasoline remaining in the can.

The testing and analysis also demonstrate that an inexpensive screen flame arrester can prevent these types of event from occurring.

Potential drawbacks in the use of such flame arrestors with PPGCs occasionally cited include plugging due to sludge development or the presence of impurities. Removal of flame-arresting screens by end users is also cited. However, such devices have been on the market without incident for decades in military and NFPA 30-compliant commercial safety cans. These cans often have mesh sizes at an order of magnitude smaller than necessary for flame arresting [29, 30].

Spout designs for PPCGs have recently been modified to account for both the recent CPSC activity related to childproof dispensing features and changes by EPA to reduce vapor releases from PPGCs as sources of air pollution [31]. On the other hand, it has been suggested that these changes eliminate the potential need for flame arrestors in PPGCs since the new designs reduce possibilities for aging to occur. However, it is the authors' observation that inclusion of flame arrestors remains important. First, incidents of new spout designs jamming in the open position have been observed (see Fig. 12). Second, the recent studies by researchers at Worcester Polytechnic Institute in a project administered by the ASTM F-15 Committee have found that fresh, unaged, gasoline vapors in the headspaces of PPGCs are still in the explosive range with small amounts being present in the cans [32, 33].

Finally, fuels for future use modified and developed to reduce emissions—such as oxygenated blends—result in

more explosive mixtures developing in gasoline containers [28]. It should also be noted that spill-resistant cans currently on the market which contain flame arrestors have been tested by the authors, and it has been found that they will not explode from an external ignition source irrespective of internal vapor conditions.

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