J. of Fire Prot. Engr., 6 (1), 1994, pp 1–10

FIRE TESTS INVOLVING STORAGE OF FLAMMABLE AND COMBUSTIBLE LIQUIDS IN SMALL CONTAINERS

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SUMMARY

The storage of containerized flammable and combustible liquids has been the subject of fire testing to determine the mitigating effects of a sprinkler system during a fire situation. This paper reviews the results of 85 sprinklered fire tests that have been made available and includes small, intermediate and large scale storage test configurations.[1] The storage configurations tested include solid pile/palletized, rack and shelf arrays that are found in warehouse and retail facilities. The flammable and combustible liquids used as test commodities were Class IB, IC, II, IIIA, and IIIB liquids. Steel, plastic and glass containers were used to contain these liquids. Several major variables have been found to determine the rate of fire growth and affect the ability of a sprinkler system to successfully control or suppress the reviewed fires. These include liquid properties, container design and size, packaging material, ignition scenario, storage arrangement and sprinkler system design parameters.

The most critical variable affecting fire control or suppression with "worst-case" liquids in their class was container design. The sprinkler system design parameters played a key role in the growth rate, magnitude and control of many of the fires. However, a number of fires using plastic containers could not be controlled regardless of the sprinkler system design. Steel containers have been proven to be more fire resistant than plastic containers. Sprinkler systems have been shown to be effective in controlling and suppressing fires using "worst-case" flammable liquids in steel containers. The occurrence of Boiling Liquid Expanding Vapor Explosions (BLEVE's) was eliminated with steel containers prone to this type of failure mode when equipped with plastic spouts and nozzles. These plastic spouts and nozzles functioned as "pressure relieving devices." The data base on glass and fiber containers was not sufficient to conduct a complete assessment of these container types.

REVIEW OF TEST RESULTS

A review of 85 small-, intermediate- and full-scale sprinklered fire tests involving containerized storage of flammable and combustible liquids has been conducted. The available data base is extensive, involves numerous reports published by different organizations on specific tests/programs, and includes a complex matrix of many different variables. The intent of this study is to evaluate these data and summarize the results in a condensed form.

The reviewed fire tests were performed at either Southwest Research Institute (SwRI), Underwriters Laboratories (UL), or the Factory Mutual (FM) fire test facility. The fire tests referenced in this paper were sponsored by the National Fire Protection Research Foundation, The Sherwin-Williams Company, The Factory Mutual System, Cigna Property and Casualty Companies, Distilled Spirits Institute, Inc./Distilled Spirits Council, Allendale Mutual Insurance, Factory Insurance Association (Industrial Risk Insurers), The 3M Company, Merck and Co., and the American Iron and Steel Institute. This paper was written under contract with the American

[1] A compilation of test data for these 85 fire tests can be found in a publication entitled *Directory of Fire Tests Involving Storage of Flammable and Combustible Liquids in Small Containers*. The directory also includes illustrations showing various container types. This publication is available from the Society of Fire Protection Engineers, Boston, MA.

Iron and Steel Institute to provide an objective review of the data. The reviewed reports have been made available and were compiled after a comprehensive literature search. The purpose for conducting these sprinklered fire tests was to assess the mitigating effects of a sprinkler system during a fire situation. Various sprinkler system designs were tested for effectiveness in controlling or suppressing fires. All of the sprinkler systems used were wet pipe and discharged either water or Aqueous Film-Forming Foam (AFFF). The sprinkler system discharge density, sprinkler orifice size, temperature rating and response time index (RTI) were varied in a number of the test programs to determine their effect. Additionally, the effectiveness of in-rack sprinklers was examined.

The flammable and combustible liquids used as test liquids are classified as either Class IB, IC, II, IIIA or IIIB as defined in NFPA 321, *Basic Classification of Flammable and Combustible Liquids*. This NFPA system is based upon a liquid's flash point and, in some instances, its boiling point. The materials used for the containers were steel, plastic or glass. When the type of plastic was stated it was either high density polyethylene (HDPE), high density polyethylene coextruded with nylon, or polyethylene terephthalate (PET). The container volume ranged between 8 oz. (237 ml) to 5 gal. (18.9 l) for the plastic containers and 32 oz. (950 ml) to 55 gal. (208 l) for the steel containers. The volume of the glass containers was 0.2 gal. (0.76 l).

Plastic pour spouts and plastic threaded nozzles were fitted onto steel containers in a number of fire tests. The plastic pour spouts were used on 5 gal. (18.9 l) tighthead containers, and the plastic threaded nozzles were used on 1 gal. (3.8 l) F-style containers. These plastic spouts and nozzles were evaluated for their effectiveness in relieving pressure and preventing Boiling Liquid Expanding Vapor Explosions (BLEVE's).

The containers that were less than 5 gal. (18.9 l) in volume were packaged in either ordinary corrugated cardboard, paraffin wax coated corrugated cardboard or fire retardant cardboard cartons with the exception of the two shelf storage array tests where the containers were uncartoned. A number of double row rack arrays used display shelving within the array. Some of the cartoned commodity was display cut in these arrays. The storage height ranged from 1 ft. 4 in. (0.4 m) to 24 ft. 2 in. (7.4 m). The ignitors used in the fire tests consisted of either cellucotton rolls soaked in gasoline or heptane "pool fire" ignitors ranging from 2 gal. (7.6 l) to 10 gal. (38 l). The storage arrays investigated included 45 solid pile/palletized, 30 double row rack, eight multiple row rack and two shelf storage arrays. The ceiling heights at the test centers were located between 18 ft. (5.5 m) and 30 ft. (9.1 m).

The test results included an accounting of the number of operating sprinklers and their operating times, ceiling gas and, when available, steel temperatures, fire travel throughout the test array, and a damage assessment of the test and target commodity. Not all of the pass/fail criteria were determined through quantitative means, as a subjective visual examination was also required.

Fire tests based on unprotected free-burns and data gathered from fire products collector (calorimetry) tests have provided useful information. This includes failure times and failure modes of various containers as well as the combustion properties of the released liquids. However, data generated in this manner have not always been a reliable index of the outcome involving larger-scale sprinklered fire tests. This is due to the larger array configuration and the use of an actual sprinkler system. Therefore, fire tests based on unprotected free-burns and data gathered from products of combustion collector fire tests are not included in this paper.

Based upon this review, the following have been identified as the major variables which determine the rate of fire growth and affect the ability of a sprinkler system to successfully control or suppress the reviewed fires:

Liquid Properties

Physical and combustion properties of the flammable and combustible liquids used as test commodities played a role in the severity of the fires. This includes flash point, boiling point, burning rate, water solubility and specific gravity.

The most severe fires resulted with low flash point hydrocarbon fuels such as heptane, a Class I B flammable liquid, and mineral spirits, a Class II combustible liquid. These two liquids are considered "worst-case" in their class as they have relatively high burning rates, are not water miscible and have a specific gravity less than 1. Although low flash point liquids are more easily ignited than high flash point liquids, fires involving low flash point liquids were not always the most severe. Fires using 40 percent and 50 percent mixtures of ethyl alcohol and water, a Class IC flammable liquid, were controllable even when contained in plastic and glass containers and arranged in high pile arrays. These results can be attributed to the high water content of these mixtures.

A severe uncontrollable fire resulted with mineral oil, a water insoluble Class IIIB combustible liquid having a specific gravity less than 1 and contained in plastic containers. Motor oil, having similar properties as mineral oil but having a higher flash point, resulted in both controlled and uncontrolled fires when contained in plastic containers. The difference in controllability of the motor oil fires was a function of the higher flash point, the use of horizontal barriers and design of the sprinkler system. Corn oil, a water insoluble Class IIIB combustible liquid having a specific gravity less than 1 and having a higher flash point than motor oil was involved in a controlled fire. This liquid was contained in plastic containers and arranged in a small, low pile array.

The effect of water solubility on the fire severity was noticed only in the fire tests using 8 oz. (237 ml) plastic containers of water soluble alcohol. When contained within 0.66 gal. (2.5 l) and 1 gal. (3.8 l) plastic containers, fires involving water soluble alcohol were severe and uncontrolled. These results indicate that there is also a connection with controllability to plastic container size.

Container Design and Size

When subjected to fire exposure, steel containers have been shown to maintain their integrity longer than plastic or glass containers. The enhanced performance of steel containers resulted in a much lower incidence of container failure and resultant release of the flammable or combustible liquid contents.

When steel container failure did occur, it resulted in pool fires, jetting or Boiling Liquid Expanding Vapor Explosions (BLEVE's). Plastic pour spouts and nozzles functioned as "pressure relieving devices" in a number of fire tests using tighthead and F-style steel containers. These "pressure relieving devices" were effective in preventing ruptured containers or BLEVE's. Additionally, the solder joint on the nozzles of steel F-style containers melted in an unpredictable manner, when it occurred, resulting in pressure relief. The melting of the solder joints and the plastic pour spouts and nozzles did contribute to the fire intensity due to burning and jetting at the container opening. However, this burning is localized and in many fire tests was controlled by sprinkler system discharge. Steel containers using "friction lids" typically failed in less time than the tighthead and F-style containers. The "friction lids" lifted, due to internal pressure, resulting in a confined pool fire. In some instances, burning liquid was displaced by sprinkler system water resulting in moderate spill fires.

When plastic containers were subjected to a fire exposure, they have been shown to have a much higher liquid release rate than the steel containers of the same size. Plastic container failure resulted from a deformation and melting of the plastic. When ignited, the liquid emitted from plastic containers generated two-and three-dimensional spill fires. All of the fire tests that were conducted with "worst-case" flammable and combustible liquids in their class in plastic containers were severe and uncontrolled. A limited number of fire tests have been reviewed using glass containers of 50% ethyl alcohol in a palletized array. The failure mode of these glass containers involved a cracking and breaking of the glass also resulting in two-and three-dimensional spill fires.

Container size did effect fire severity with both steel and plastic containers. When not equipped with "pressure relieving devices," steel container BLEVE's occurred sooner with the 1 qt. (.95 l) containers than with the 1 gal. (3.8 l) containers due to less heat capacity associated with the smaller containers. Also, as previously discussed, controlled fires did occur with 8 oz. (237 ml) plastic containers of water soluble alcohol. When a similar alcohol was packaged in 0.66 gal. (2.5 l) and 1 gal. (3.8 l) plastic containers, the fire was severe and uncontrolled. The failure of the 8 oz. (237 l) plastic containers resulted in both lower liquid release rate and resultant fire severity. This allowed the sprinkler system to control the fire.

Virtually all of the steel container fire testing has involved "worst-case" liquids in their class. In contrast, all of the controlled plastic and glass container fire testing involved liquids which are not "worst-case" liquids in their class.

Packaging Material

Ordinary corrugated cardboard cartons used as packaging material provided additional fuel beyond the "pool fire" ignitor, when used, and any released burning liquid. In general, cartoned storage of steel containers resulted in more severe fires. Fire retardant cardboard inhibited burning and limited fire severity in tests using flammable and combustible liquids in plastic containers when exposed to the heat flux of gasoline soaked cellucotton roll ignitors. However, when exposed to a "pool fire" ignition scenario, fire retardant cardboard was ineffective. Fire did penetrate through the outer walls and innerliners of the fire retardant cardboard boxes. Additionally, the paper tape used to seal the flaps of the boxes burned through in a matter of seconds. This allowed some of the flaps to open and expose the plastic containers within.

Ignition Scenario

All of the steel container fire tests used a heptane "pool fire" ignitor with the exception of one small scale test that used gasoline soaked cellucotton rolls. Comparative testing has not been conducted between gasoline soaked cellucotton roll ignitors and heptane "pool fire" ignitors with steel containers. The "pool fire" ignitor was used with the more easily ignited Class I and Class II liquids where a pool fire ignition could be expected.

Comparative fire testing with heptane "pool fire" ignitors of different volumes has been performed with steel containers. The "pool fire" ignitors were 2 gal. (7.6 l), 5 gal. (18.9 l) or 10 gal. (38 l) in volume. Fire tests using steel containers and a 2 gal. (7.6 l) heptane "pool fire" ignitor allowed the fire to incubate and resulted in more fire involvement of the test commodity, prior to sprinkler system operation, than when a 5 gal. (18.9 l) or a 10 gal. (38 l) heptane "pool fire" ignitor was used.

Fire tests have been conducted using "worst-case" flammable and combustible liquids in plastic containers with either gasoline soaked cellucotton or heptane "pool fire" ignitors. As previously mentioned, the failure mode of plastic containers involves a deformation and melting of the plastic and resultant release of the liquid within. In fire tests using gasoline soaked cellucotton ignitors, due to the container failure mode, a pool fire resulted within seconds after ignition, indicating that ignitor size was not a factor.

As previously discussed, when fire retardant cardboard was used, the fire tests that used gasoline soaked cellucotton ignitors did not result in large uncontrollable fires. The fire retardant cardboard prevented the release of large quantities of liquids from the plastic containers by limiting the transfer of heat into the plastic containers. In contrast, when a 5 gal. (18.9 l) "pool fire" ignitor was used, fire retardant cardboard failed to protect the plastic containers, resulting in an uncontrollable fire.

Several fire tests have been conducted using flammable and combustible liquids in cartoned plastic containers that are not considered "worst-case" in their class with successful results. All of these fire tests used gasoline soaked cellucotton ignitors. Comparative fire testing using a "pool fire" ignition scenario has not been performed.

Storage Arrangement

Solid pile/palletized and rack storage arrangements have been investigated at various heights in small, medium and large scale arrays. Higher solid pile/palletized storage heights, as with other types of commodities, present a greater challenge to sprinkler systems in their ability to control or suppress fires. This is primarily a result of obstructed flue spaces from adjacent stacks leaning toward each other and higher upward gas and flame velocities within the flue space. These conditions inhibit the downward penetration of sprinkler system discharge.

The potential for a jetting-type fire has been shown to be greatest in rack and shelf storage arrays of 5 gal. (18.9 l) tighthead steel containers fitted with plastic pour spouts. This is due to the inherent stability of these arrays and the presence of horizontal surfaces over the top of the lowest tiers in the array where the jetting occurred. These horizontal surfaces consisted of shelves or the bottom surface of pallet loads in upper tiers of storage. The horizontal surfaces acted as reflective surfaces for heat and directing it back into containers with melted plastic pour spouts allowing for greater evolution of burning vapor. These horizontal surfaces also shielded the test commodity from sprinkler discharge.

Fire testing has been conducted with double row racks using shelving consisting of open wire mesh and 2 in. x 6 in. (50 mm x 150 mm) wood slats spaced 2 in. (50 mm) apart. The wood slat shelves were subject to collapse, due to heat induced expansion of the steel frame rack. This resulted in a more severe fire, due to spillage, than with open wire mesh shelves.

Sprinkler Systems

As would be expected, the design of the sprinkler systems as well as the height of a ceiling sprinkler system above both the floor of the test facility and the top of the storage array played a role in its ability to control fires. Significant design variables include discharge density and sprinkler orifice size, temperature rating and response time index. In fire tests using steel containers, quick-response in-rack and ceiling sprinklers have been shown to provide enhanced performance over standard response sprinklers. Quick-response sprinklers have only been tested successfully with steel containers where a large spill potential was not present. Additionally, in fire tests using steel containers extra-large orifice ceiling sprinklers have been shown to provide enhanced performance over large orifice sprinklers. In rack storage fire tests with steel containers, in-rack sprinklers were not necessary for control of all fire tests. This was limited to racks that were 5 ft. 4 in. (1.63 m) wide and 14 ft. 1 in. (4.3 m) high under an 18 ft. (5.5 m) ceiling. Fire tests involving motor oil in plastic containers have been successfully controlled using quick-response in-rack sprinkler protection in conjunction with horizontal barriers within the rack. In-rack sprinklers were not effective in the motor oil fire tests without horizontal barriers located within the rack.

Foam-water has been shown to be more effective than water against fires involving flammable and combustible liquids. However, the enhanced performance of foam-water over water was not as apparent against fires involving jet flames, three-dimensional spill and flowing pool fires.

The ignition scenarios used in the reviewed steel container fire tests have not allowed for a comparison between fire tests using water and foam-water in order to quantify the difference. All of the foam-water fire tests used a 10 gal. (38 l) heptane "pool fire" ignitor, which facilitated activation of the sprinkler system in less than one minute. Fire involvement of the steel container filled commodity was nominal as the foam-water quickly suppressed the fires in all but one test. Fire testing using a 2 gal. (7.6 l) heptane "pool fire" ignitor was done in fire tests discharging water only.

Due to the significant difference in container performance, the available fire test results are summarized for each container type as follows:

Steel Containers

The available fire test data includes numerous examples of controlled and suppressed palletized and rack array fires with "worst-case" fuels. Not all of these controlled fire tests utilized large scale arrays and a small "pool fire" ignitor. However, there were a number of successful rack storage array fire tests that were large scale and utilized "worst-case" fuels and a small "pool fire" ignitor. The occurrence of Boiling Liquid Expanding Vapor Explosions (BLEVE's) was eliminated with containers prone to this type of failure mode when equipped with plastic spouts and nozzles. These plastic spouts and nozzles functioned as "pressure relieving devices."

The test results regarding the performance of the plastic nozzles and spouts correlates with earlier tests. These earlier tests were conducted with steel 55 gal. (208 l) drums equipped with plastic bungs that were exposed to pool fires.

Fire tests have also been conducted using steel 55 gal. (208 l) drums that were water filled. The rack storage fire tests did meet the pass/fail criteria of the test series. However, despite the application of a relatively high sprinkler discharge density of 0.60 gpm/ft^2 (24.5 mm/min.) using 1% AFFF, the palletized fire tests did not meet the pass/fail criteria for the storage of drums two high and over.

The results of the water-filled drum fire tests that met the pass/fail criteria of the test series would not be expected to be indicative of fires under all scenarios. Flammable and combustible liquid filled drums can behave differently than water filled drums under fire exposure. Additionally, flammable liquids that are also monomers and subject to exothermic polymerization are more prone to container over-pressurization and failure.

Plastic Containers

Fires involving flammable and combustible liquids that are considered "worst-case" in their class and packaged in plastic containers were severe and developed rapidly. The sprinkler systems in the reviewed fire tests used average and above average design parameters and were unsuccessful in controlling any of the fires. These fires were considered "free burns" and, when available, required a backup foam-water deluge system for extinguishment. A number of the fires were extinguished only after all of the fuel had burned itself out. Based on the failure of all of these fire tests, it is not known how to control fires involving "worst-case" flammable and combustible liquids in plastic containers. Examples include cartoned 1 gal. (3.8 l) containers of isopropyl alcohol and mineral spirits as well as uncartoned

5 gal. (18.9 l) containers of heptane that were stored in palletized arrays. Additionally, uncartoned 1 gal. (3.8 l) containers of mineral spirits and cartoned 1 qt. (0.95 l) containers of mineral oil are examples of "worst-case" liquids in their class that were involved in uncontrolled fires in rack arrays.

Fire tests involving flammable and combustible liquids in plastic containers have revealed that controlled fires have only occurred with a limited number of flammable and combustible liquids. These liquids are not considered "worst-case" in their class. Examples include cartoned 8 oz. (237 ml) containers of water soluble alcohols, cartoned 0.46 gal. (1.75 l) containers of 40% ethyl alcohol solution and cartoned 1 gal. (3.8 l) containers of corn oil. It should be noted that plastic container size apparently plays a role in liquid release rate and subsequent controllability of water soluble alcohol fires.

Controlled fire tests using cartoned plastic containers occurred in rack storage arrays with 1 qt. (0.95 l) and 1 gal. (3.8 l) containers of motor oil when horizontal barriers were placed within the racks. These racks were also equipped with quick-response in-rack sprinklers.

Glass Containers

A limited number of fire tests using glass containers in palletized storage arrays have also been performed using 0.2 gal. (0.76 l) containers of a 50% ethyl alcohol solution. Controlled fires were reported; however, due to the limited number of tests, a complete comparison to plastic and steel cannot be made.

Conclusions

The fire test results were measured in terms of the number of operating sprinklers and their operating times, ceiling gas, and when available, steel temperature, fire travel throughout the test array, and a damage assessment of the test and target commodity. These results have revealed that there are a number of major variables that determine the rate of fire growth and affect the ability of a sprinkler system to successfully control or suppress the reviewed fires. These variables include liquid properties, container design and size, packaging material, ignition scenario, storage arrangement and sprinkler system design parameters.

In fire tests using "worst-case" flammable and combustible liquids in their class, container design was the most influential variable that affected the control or suppression of the reviewed fires. The sprinkler system design parameters played a key role in the growth rate, magnitude and control of many of the fires. However, a number of fires using plastic containers could not be controlled regardless of the sprinkler system design. Steel containers have been proven to be significantly more fire resistant than plastic containers since steel containers tend to retain their integrity during fire exposure. The data base on glass and fiber containers was not sufficient to conduct a complete assessment of these container types.

A large body of useful data has been generated as a result of the reviewed fire tests. The most thoroughly studied area has been with double-row rack storage of "worst-case" flammable and combustible liquids in steel containers. Additional fire test research using large scale configurations should focus on the following areas using realistic "worst-case" ignitors:

- Solid pile/palletized and multiple-row rack storage as well as retail display arrays with "worst-case" liquids in 5 gal. (18.9 l) and less steel containers with and without "pressure relieving devices."
- All storage arrays with "worst-case" liquids in steel, plastic and fiber drums (greater than 5 gal. [18.9 l]). The liquids should include self-reactive monomers that are also flammable liquids. The steel drums should be tested with and

without "pressure relieving devices." Given the significant difference in container performance and impact on controllability of a fire, it may not be possible to test "worst-case" liquids with plastic and fiber drums.

- All storage arrays with "worst-case" liquids in intermediate bulk containers (less than 793 gal. [3,000 l]). The materials of construction for the intermediate bulk containers should include wood, fiberboard, plastic, textile, paper-multiwall and metals, including steel and aluminum. The liquids should include self-reactivemonomers that are also flammable liquids. The metal intermediate bulk containers should be tested with and without "pressure relieving devices." Given the significant difference in container performance and impact on controllability of a fire, it may not be possible to test "worst-case" liquids in non-metal intermediate bulk containers.
- All storage arrays and, where appropriate, retail display arrays with "worst-case" and "non-worst-case" liquids in 5 gal. (18.9 l) and less glass and plastic containers.
- Quantifying the difference in performance between water and foam-water sprinkler protection.

Fire tests using container volumes that are 5 gal. (18.9 l) and less should utilize low temperature quick-response sprinklers. This should include extra-large orifice (ELO) and early-suppression fast-response type sprinklers. There are many variables that could be explored. The above areas are felt to be of most interest based upon the reviewed fire tests.

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