Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org
ISSN: 2379-3252

Vol. 36 No. 1 June 2019

Forensic Engineering Investigation into Factors Contributing to Explosion of Consumer-Grade Tabletop Torch

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Abstract

In early 2013, approximately 3,500 consumer-grade tabletop torches, designed for use with citronella oil to ward off insects, were sold by a retailer. Within six months of their debut, 22 of these products experienced sudden explosions, resulting in one fatality and 21 severe burn injuries to consumers. The author was retained as an expert in the fatal explosion case to determine the root cause(s) that led to these explosions. This paper will describe the detailed, experimental-based investigation that was carried out to reveal design, manufacturing, and marketing defects for which the designer of the torch, the manufacturer of the fuel, and the retailer of the final product were responsible. It was determined that the explosions occurred as a result of a "perfect storm" scenario that involved defective product design, defective marketing of the product through the sale of incompatible fuel by the retailer, and deficient warning instructions by the manufacturer.

Keywords

Tabletop torch, explosion, fire, forensic engineering, flash point, consumer product, product defect, design defect, marketing defect, defective warning

Overview

The explosion that is the subject of this analysis, for which the author was retained as an expert, happened shortly after the tabletop torch had been lit. It reportedly began to smoke, and was picked up in an attempt to move it to an alternate location. The subject torch then exploded in the hands of the person moving it, spraying him with liquid torch fuel, which subsequently ignited. This resulted in severe burn injuries. The man was treated for his burns, but later passed away due to the extent of his injuries. The tabletop torches have since been recalled.

An extensive search of literature on design and manufacturing safety standards of tabletop torches did not reveal any mandatory safety standards or regulations adopted or publicized by the federal government or related private industry/agencies that were applicable to the subject mosaic tabletop torch at the time of its manufacture.

The purpose of this investigation was to determine the root-cause mechanism(s) responsible for the explosions of the tabletop torches in question. This included assessments of the torch design features as well as the properties of the citronella torch fuel that was used in the incident. Additional considerations included the appropriateness of the testing and marketing of the product.

Observations

The subject torch and four other similar model torches from other similar incidents that involved sudden explosion of the torch were inspected and carefully examined in an attempt to document common features in their design characteristics and mechanical failure characteristics as well as similarities in circumstances surrounding their explosions. Based on inspection and examination of the affected torches, as well as review of incident reports and statements by witnesses at the scenes of other torch explosions, the following features/circumstances were observed to be common across each of the explosion incidents investigated.

1. All exploded torches were lit and burning at the time of explosion.

2. All exploded torches were 10-inch diameter tabletop torches manufactured by the same company.

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Figure 1
Upper section of the subject torch exhibiting bulging as a result of the explosion.

3. All exploded torches were subjected to an internal pressurization generated by a combustion event. Note: Some explosions, including the subject event, resulted in a sudden and violent complete separation of the upper and lower sections of the torch, with the upper section showing clear signs of outward bulging due to a sudden internal pressure event, as shown in **Figure 1**. Other less severe explosions resulted in sudden, forceful ejection of the wick and/or the screw-top cap, thereby depressurizing the torch and avoiding catastrophic explosion of the torch vessel.

4. All exploded torches were charged with citronella torch fuel manufactured by the same company.

5. All explosions occurred at the instant a volume of air was pushed toward the flame — either while the user was attempting to extinguish the flame by blowing it out or when the user was moving the torch from one place to another.

Hypotheses

Observation 3, listed in the previous section, indicates that the failure mode (sudden and forceful separation of the upper and lower halves of the torch vessel) could only occur as a result of sudden generation of an internal pressure-pulse due to ignition of accumulating internal fuel vapor. The sudden increase in pressure exceeded the strength of the mechanical seam between the upper and lower sections of the torch that keeps the two sections of the vessel together.

The mechanism for the development of such a dynamic and overwhelming pressure-pulse in a closed container containing flammable fuel requires the simultaneous presence of three conditions — accumulation of fuel vapor, appropriate fuel-to-air ratio, and an ignition source. The simultaneous occurrence of the above three conditions would cause an explosion of the fuel vapor, resulting in a large pressure-pulse, while the absence of any one of the above conditions would prevent the occurrence of an explosion. Therefore, understanding how each of the three necessary conditions came to occur is integral to determining the root-cause mechanism of these explosions. The leading hypotheses on how each of these conditions developed were:

- The torch fuel began to vaporize at a normal operating temperature of the torch, causing the buildup of volatile vapor inside the torch;

- The screw-top cap on the subject torch was inappropriately designed, as it allowed excess air to enter the torch body;

- The screw-top cap was also inappropriately designed in that it inadequately separated the fuel/air mixture inside the torch from the flame on the top of the cap.

The following section describes the testing and analysis conducted in an attempt to determine the validity of the aforementioned hypotheses and ultimately the root cause mechanism(s) of the tabletop torch explosions.

Preliminary Analyses

Hydro-Pressure Leak Test

In an attempt to safely measure the static internal pressure required to separate the top and bottom halves of the torches as occurred in the explosion of the subject torch, the torch cap was outfitted with a sealed water supply-line instrumented with a pressure gauge. The water pressure entering the torch was then slowly increased until obvious signs of bulging of the top surface appeared as the mosaic tiles began to pop off. It should be noted that the subject incident involved a sudden pressurization as a result of an internal explosion.

This test, which employs a slow pressure increase, was not intended to replicate the actual explosion — but rather the separation strength of an exemplar torch vessel. At about 30 psi of internal pressure, the mechanical seal connecting the top and bottom halves failed, causing separation of the two parts. This resulted in water leakage and depressurization of the torch (**Figure 2**).

This was the first test performed, indicating the amount of pressure build-up required during an explosion event

Figure 2
Hydro pressure testing to failure of exemplar tabletop torch.
The vessel failed catastrophically at ~30 psi of internal pressure.

that would result in failure of the mechanical joint designed to keep the top and bottom halves of the torch together. Given the 10-in. diameter of the torch, the effective surface area on which the pressure acts was approximately 78 square inches. This means that for every 1-psi pressure build-up inside the torch, the top and bottom halves of the torch were subjected to a 78-pound force that was pulling them apart from each other. At 30 psi internal pressure, the force pulling the top and bottom sections of the torch apart was approximately equal to 2,340 pounds — or more than a ton. This separation explains why the users got soaked with liquid fuel during torch explosions. The force of the explosion pushed the upper and lower halves of the torch (containing liquid fuel) away from each other, and, upon separation, the liquid fuel in the torch was expelled outward, covering the surrounding area.

Torch Fuel Analysis

Samples obtained from the actual fuel used in the subject torch on the day of the incident, as well as samples from an exemplar bottle of the same type of torch fuel, were analyzed by Attenuated Total Reflectance — Fourier Transform Infrared Spectroscopy (ATR-FTIR) and Gas Chromatography/Mass Spectrometry (GC/MS) for identification of their constituents and quantification of flash point via both ASTM-D92 Cleveland Open-Cup and ASTM-D93 Pensky Martin Closed-Cup procedures. According to the test results, both the actual subject torch fuel and the exemplar torch fuel exhibited a flash point temperature in the range of 102°F to 104°F. From this point on, all tested torch fuel of the same type as the fuel used in the subject incident will be referred to as "subject" torch fuel.

It should be noted that a flammable liquid cannot ignite on its own unless it is in a vapor phase. The flash point of a flammable liquid is the temperature at which a liquid will produce sufficient vapors at the surface to allow ignition from a pilot flame source. The subject torch fuel, marketed and sold for use with the subject torch, has a flash point of 102°F to 104°F. This means that the fuel starts to transform into an ignitable vapor once the temperature of the torch fuel reaches ~104°F. Such a relatively low temperature can be easily reached during normal torch operation, especially when the ambient air temperature is in the 80°F to 90°F range (maximum temperature on the date of the subject incident was 87°F) or if the torch is subjected to solar radiative heating.

The subject torch fuel was then compared to an alternative fuel, namely citronella oil. Information on citronella oil was gathered from a material safety data sheet (MSDS) report available online, with the two properties of interest in this case being the flash point and vapor pressure of the fuel types. Since there was not an MSDS report available for the subject torch fuel, the flash point was determined as discussed previously, while the vapor pressure was determined from an MSDS report for a fuel with similar constituents formulation, namely Tiki Torch Fuel. The values for both fuel types are listed in **Figure 3**.

	Citronella Oil	Subject Citronella Torch Fuel
Flash Point	177.8 °F	102-104°F
Vapor Pressure (@68°F)	0.000098 mmHG	0.1-0.9 mmHG

Figure 3
Fuel properties of citronella oil vs. subject torch fuel.

The different fuel properties show that the subject torch fuel not only exhibits a lower flash point, but also likely produces a greater vapor pressure than citronella oil. This is significant when considering the mass of vapor that will accumulate during operation of the torch. The lower flash point of the subject torch fuel means that more fuel vapor is generated at a given temperature within the range of normal operating conditions. This issue is further accentuated by using a fuel with a greater vapor pressure. The violence of an explosion depends on the amount of fuel vapor within the torch. As such, with the subject citronella torch fuel (having a vapor pressure that is greater by several orders of magnitude than that of regular citronella oil), the user is at a greater risk of being subjected to a more violent explosion if ignition occurs.

Torch Explosion Recreation

Experimental Setup and Instrumentation

An exemplar tabletop torch was instrumented for data acquisition by removing small sections of mosaic tiles and creating small openings on the top surface of the torch for a pressure transducer, an oxygen sensor, and two thermocouples for monitoring the temperature of both the liquid and vapor phases of the fuel. Threaded nubs were manufactured and epoxied over each hole, into which a pressure transducer and an oxygen sensor were placed. Additionally, the two smaller holes were used to route the two thermocouples into the torch. Each thermocouple hole was then epoxied to create a “water-tight” (sealed) region, as shown in **Figure 4**.

The instrumented torch was then placed in a constant temperature, recirculating water bath. The height of the water bath was approximately 1 inch below the “lid” of the torch (location where the top and bottom of the torch are mechanically joined). The torch and water bath were then placed inside an enclosure designed to contain fuel and fire emission in the event of a torch explosion, as shown in **Figure 5**. The following instruments were used in this experimentation:

Figure 4
Exemplar torch instrumented with pressure gauge, oxygen sensor, and thermocouples to monitor pressure and temperature of vapor during operation of torch.

Figure 5
Instrumented exemplar torch placed inside a safety cage designed to guard against potential explosions during testing.

a) Thermocouples (2): Type K, 24 gauge (Omega.com) — one thermocouple was mounted such that it remained in the vapor space while the second was mounted such that it was always located in the liquid fuel.

b) Pressure Transducer (1): PX409-050-G5V fast-response (sub millisecond) sensor (Omega Engineering) — the pressure transducer was mounted such that its sensing face slightly protruded through the top surface of the torch.

c) Oxygen Sensor (1): SO-220 (ApogeeInstruments.com) — the oxygen sensor was mounted such that its sensing face slightly protruded through the top surface of the torch.

d) Data was obtained using a LabVIEW communicating with a National Instruments (ni.com) CompactDAQ chassis with analog input (NI 9201) and thermocouple input (NI 9213) modules. The recorded data points were then displayed to the monitor, and at the appropriate times were manually saved to a file. The data acquisition rate was set to record data at 1,000 Hz (1,000 data points per second).

Testing Procedure

At the beginning of each test, the instrumented exemplar torch was filled with 1,200 ml of subject torch fuel (the fill level indicated in the manufacturer's instructions) and placed in the constant temperature fluid bath. The bath temperature was kept constant during any given test at approximately 110°F to represent a typical hot summer day in south Texas and to represent vapor accumulation within the torch. After waiting about 15 to 30 minutes in the bath to ensure temperature stabilization, the wick was lit while the data acquisition system monitored the liquid and vapor fuel temperatures. An additional amount of time (ranging from 15 minutes to 1 hour) was required for both the vapor and liquid thermocouple outputs to reach steady-state condition (no change with time). Air from a laboratory supply line was directed at the flame in a pulsed manner to simulate a user blowing out a candle or moving the torch, resulting in air movement around the wick. This process was repeated in short pulses of air until either the flame was extinguished, or an explosive event occurred.

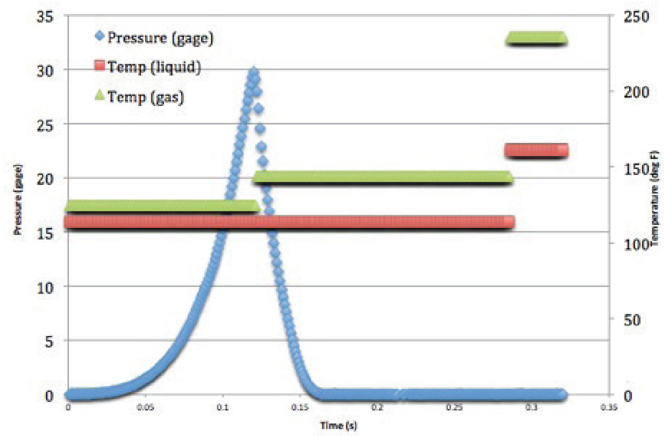

Figure 7
Pressure pulse (blue diamond data points) created within the torch as a result of an explosive event. Vapor fuel temperature (green triangle data points) and liquid fuel temperature (red square data points) are also shown in the graph for before and after the explosive event.

Results

The temperature data was analyzed in an attempt to discover how the temperatures of both the liquid and vapor phases of the fuel inside the torch changed as a function of time after the torch was lit. The results, as depicted in the temperature-time plot of **Figure 6**, show that the flash point temperature of the fuel was exceeded within 3 minutes of lighting the torch. Repeated experiments showed that the vapor temperature would exceed 105°F within two to three minutes of operation, and within 20 minutes the temperature would stabilize at around 120°F. This demonstrates that the fuel vapor within the torch is capable of reaching its ignitable flash point of 104°F after only a short period of operation. This explains how, as it did in the subject incident, an explosion could happen within minutes of lighting the torch when the ambient temperature is near 90°F and accumulation of radiant heating can cause the fuel temperature to reach the fuel's flash point within minutes. Therefore, the results clearly indicate that explosions can occur within normal operating conditions of this torch, as it did in the subject event.

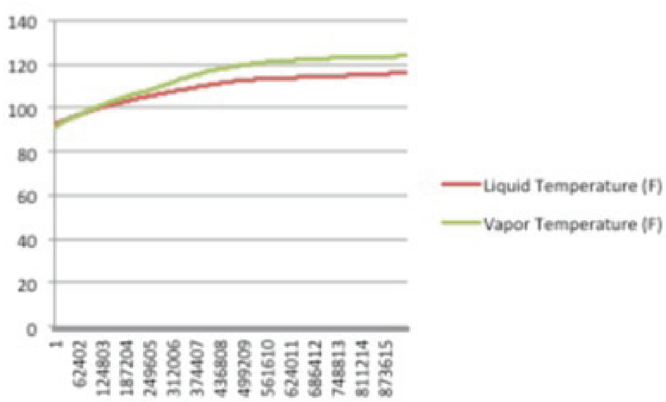

Figure 6
Internal liquid and vapor fuel temperature rise with elapsed time post lighting of torch — liquid fuel (bottom, red curve), vapor fuel (top, green curve).

In two separate instances, the above test procedure resulted in the sudden generation of a pressure-pulse that blew the wick off of the torch, indicating an internal explosion. In the first attempt to recreate the explosion, after 20 minutes of uninterrupted burn time (and with the introduction of air from the air supply line), an internal explosion occurred that blew the wick out of the torch cap. In the second attempt at recreating the explosion, after roughly 2 hours of burn time (but within 20 minutes of continuous burn time) while toggling the air hose between low and off positions, yet another internal explosion within the torch occurred that blew the wick out of the cap. During the above tests and throughout the explosion events, the internal pressure and temperatures of liquid and vapor fuel phases were recorded, and one of the events is displayed graphically in **Figure 7**.

This illustration depicts the internal pressure buildup as well as the internal temperature of both liquid and vapor fuel phases. Upon explosion, the pressure gauge indicated a pressure spike of 30 pounds per square inch above atmospheric pressure. This pressure spike corresponds to an internal force spike of approximately 2,340 pounds (30 psi acting on a surface area of ~ 78 square inches) that spreads the top and bottom halves of the torch apart from each other during an explosion event. The temperature readings from the two thermocouples within the vapor fuel (green

Figure 8
A screw-top cap (a) from a smaller torch model with an appropriate section for tightly holding the wick and disallowing the air and/or flame to be pushed into the interior vapor. As-designed subject torch cap (b), lacking proper sealing mechanism to keep the air and ignition source from entering the torch.

data) and liquid fuel (red data) show an expected time lag following the explosion that occurs due to the finite time constant of the 24 gauge thermocouples. As depicted in **Figure 6**, following the explosion, the gas/vapor temperature reached above 236°F, while the liquid fuel temperature reached ~161°F. The results of the testing show that the air/fuel ratio within the torch, which is normally fuel rich and above the upper explosive limit (UEL), can be bought into the explosive range and ignited by the introduction of air into and around the torch cap.

Features Contributing to Explosive Conditions

Cap and Wick Holder

Figures 8 and **9** show a comparison of the design features of the screw-top cap on a small tabletop torch model, 8(a), and the cap on the subject torch, 8(b) and 9(b), both of which were designed by the same company (based on information obtained through discovery). Comparing these two wick holder designs reveals that the smaller model utilizes a tubular wick holder section that is absent in the subject model. With a tubular wick holder, the cap conforms tightly to the wick and remains in tight contact with it over a length of wick measuring about 0.75 inches. The wick in the subject model, however, simply passes through an open hole in the thin top of the cap.

The purpose of the wick holder, aside from simply keeping the wick in place, is to restrict the ignition source from reaching the fuel-bearing chamber of the torch and igniting the oil within. A tubular section, such as the one found in the smaller model torch and shown in **Figure 8a**, accomplishes this by tightly securing the wick and providing protection against instances where the flame could travel down the wick into the fuel chamber. In the subject model, shown in **Figure 8b** and **Figure 9**, the wick is free to move and only restricted from falling down into the fuel

Figure 9
Subject tabletop torch (a) and close-up of the design of its screw-top cap (b). Note: Lack of a section to hold and contain the wick in order to separate the flame from the flammable vapors below the cap.

chamber by a small metal clasp. The open space between the cap orifice and the wick itself allows the flame access to the fuel vapor in the torch.

Alternative Design Comparisons

By comparing the design of the subject torch with that of similar torches designed by the same company, it is apparent that the omission of a tubular wick holder was exclusively found in the subject model. Additionally, torches designed by different companies were examined to gain industry-wide insight into torch design, specifically the wick holder, which in all such designs serves the function of a "flame arrestor," by providing a barrier between the flame and the fuel vapor.

Figures 10 through **13** illustrate the incorporation of

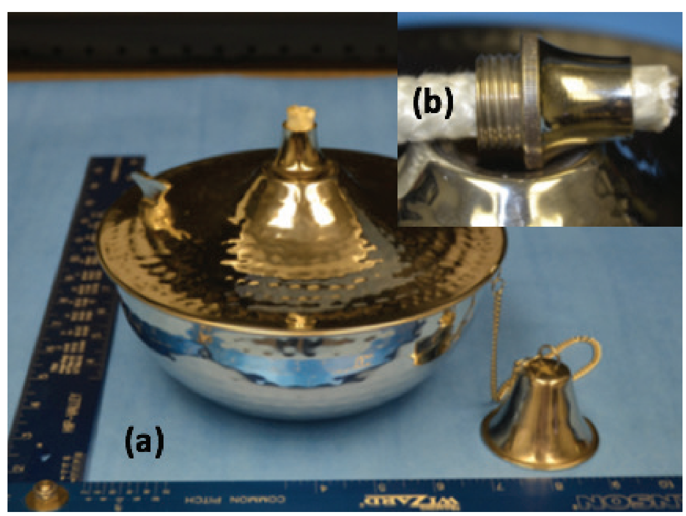

Figure 10
Alternative design of an exemplar tabletop torch (a) showing appropriate length of wick holder section to hold and contain the wick (b) to separate the flame from volatile fuel vapors below the cap.

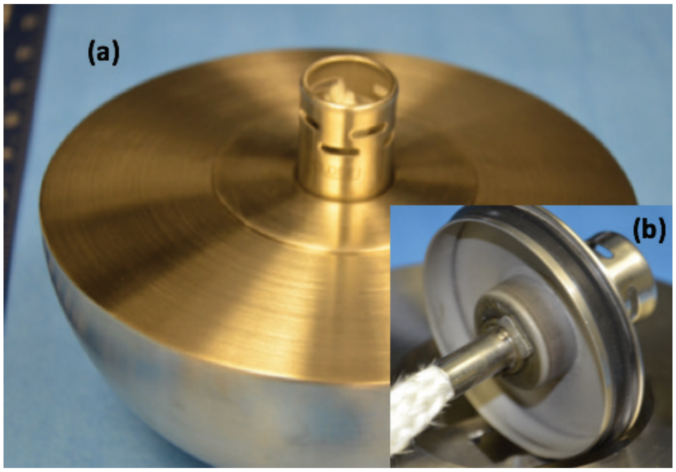

Figure 11
Alternative design of an exemplar tabletop torch (a) showing appropriate length of wick holder section to hold and contain the wick (b) in order to separate the flame from volatile fuel vapors below the cap.

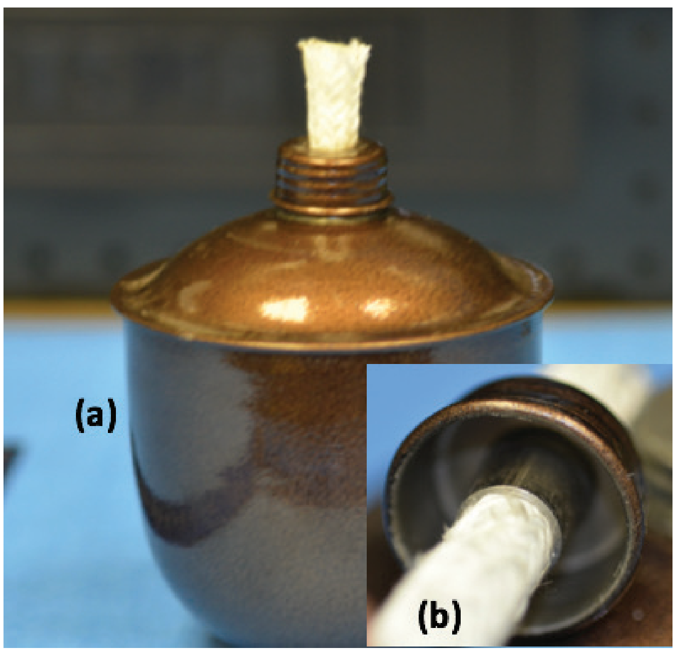

Figure 12
Alternative design of an exemplar tabletop torch (a) showing appropriate length of wick holder section to hold and contain the wick (b) to separate the flame from volatile fuel vapors below the cap.

this crucial component, a proper wick holder, throughout products in this industry that are similar to the subject model torch. This demonstrates a common knowledge amongst designers and manufacturers of torches that when designing a product that is to function as a torch including a wick, incorporation of a tubular wick holder section, to serve as both a heat sink, as well as a 'flame arrestor" for prevention of flame travel into the torch's interior space, is a necessary feature of the design. The lack of such a feature, as seen in the subject torch and shown in **Figure 9**, would render

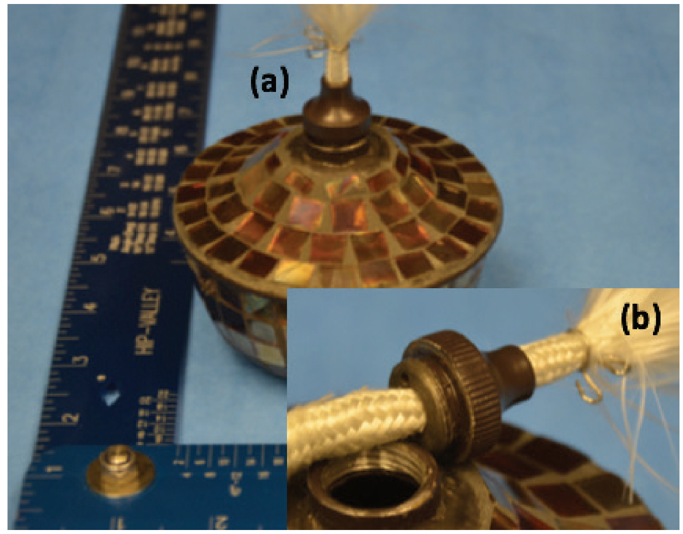

Figure 13
Alternative earlier model torch (a) designed and manufactured by the same designer involved in the design of the subject torch, showing appropriate length of wick holder section (b) to hold and contain the wick to separate the flame from volatile fuel vapors below the cap.

the torch unreasonably dangerous and susceptible to sudden catastrophic explosion during normal and anticipated usage by the consumers.

Comparison of the different torch models in **Figures 10** through **13** reveals that each of the exemplar torches utilize a cap with a wick holder that conforms tightly to the wick for at least a centimeter before allowing it to be exposed through the opposite side, thereby preventing the flame from coming in contact with the fuel vapor below. However, there is no such wick holder present on the subject model torch as shown in **Figure 8**; the wick passes through an unrestricted cap opening that is no more than 1 mm in thickness, with excess space between the metal cap and the wick itself. This excess space provides the vapor a means of reaching the flame and igniting the rest of the fuel within the chamber below.

Lack of Flame Snuffer

As the subject tabletop torch burns, the fuel chamber will experience a rise in temperature, which releases flammable vapor from the fuel. As this happens, vapor pressure will rise and begins to push air out of the chamber. Without a flame snuffer, common users would be prompted to blow out the torch manually, or even move the torch while lit — as there is no ready manner in which to extinguish the flame. This presents a serious safety hazard. Displacing the flame in a direction that would force air into the accumulated fuel vapor — either by moving the torch or blowing on the flame (especially without a tubular wick holder present) — could result in the air and flame entering back into the torch body, mixing with the accumulated fuel vapor. This could result in an air/fuel mixture capable of being ignited as well as an ignition source. The presence of all the necessary components for combustion could, in turn, cause a sudden and catastrophic explosion of the torch, as observed in many consumer cases involving the subject torch as well as simulation tests conducted in the laboratory.

Inappropriate Marketing, Warnings, and Product Testing

Influence of Specific Fuel Marketed for Use with the Subject Torch

Through review of depositions with representatives from the subject torch retailer, it was discovered that the retail store "absolutely" intended for the subject fuel to be used with the subject style tabletop torches. They viewed the subject torch fuel as an interchangeable item that could be used with any type of torch. As such, the subject brand torch fuel was displayed throughout the store, including on a display with the subject style tabletop torches. This shows that the retailer marketed the subject torch fuel as being compatible with the subject torch.

Because the subject tabletop torches were marketed as being compatible with a generic type of torch fuel, common users could get the impression that the torches could be filled and used with any type of fuel. The only warnings regarding specific fuel instructions were in fine print on the underside of the torch. The instructions and safety label adhered to the bottom of the torch is shown in **Figure 14**.

On the manufacturer's instructions and safety label, the interchanging of the words "torch fuel," "fuel," "citronella oil," and "oil" is misleading because there are several products that these descriptions could be referring to. The torch should only be used with fuels that have a flash point well above ambient operating temperature (~125°F), namely citronella oil with a high (much greater than 125°F) flash point, as intended by the manufacturer. Considering that the subject torch is only supposed to be filled with citronella oil — and not "torch fuel," which typically has a lower flash point — the obscurity becomes all the more problematic. The instructions, as worded, are not clear enough for the average user to be able to determine precisely what type of torch fuel should be used in the torch and what types (those with low flash points) should be avoided.

Figure 14
Instructions and safety label located on the bottom of the subject style tabletop torches.

Relative Effects of Overfilling Fuel

Based on the information presented in this case, there is no evidence that suggests there was overfilling of fuel involved. As such, any associated effects were not analyzed as part of this investigation. The instructions and safety label on the underside of the subject torch specify that the torch is not to be filled with a volume of fuel exceeding 1,200 ml. There are two separate points to be made regarding the potential issue of overfilling the torch with fuel:

- Unless users are expected to pour fuel into a measurement device prior to filling the torch, there is no practical way for a common user to know exactly how much 1,200 ml is. There are no markings, gauges, or any other type of fluid volume indicators located on the surface of the subject torch.

- The plausible danger associated with overfilling the torch was disregarded for this analysis as the amount of flammable fuel vapor within the fuel chamber is inversely related to the amount of liquid fuel present at any given time (i.e., the more liquid fuel in the chamber, the less flammable vapor escaping). The smaller volume of vapor reduces the amount of fuel available for an explosion and reduces the energy released. Due to the high-energy nature of the subject explosion, it was therefore concluded that over-filling of the torch was not consistent with the facts of the subject event. If that were the case, the explosion event would have been much smaller in magnitude due to smaller volume of available fuel vapor.

Inadequacy of Testing Protocol

Another factor contributing to the occurrence of these tabletop torch explosions stems from the inadequacy of the product testing that was performed. The testing agency that was hired to analyze the subject tabletop torch had chosen to perform several tests on only a sample group of torch models instead of all models. According to the discovery documents, the testing lab was in charge of establishing appropriate test protocol. The model family that the subject tabletop torch belonged to had four different torch models in it that, although they were similar in appearance, had differing design features such as overall size and cap/wick holder design.

While some testing was done on a torch model that came from within the same model family as the subject torch, no tests were ever performed on the subject torch model itself. It appears that the testing agency assumed that because the smaller, similar models within the same group functioned as anticipated, the testing of the larger subject model was not necessary. Even though the four models in the testing group were somewhat similar in terms of their appearance, making the assumption that a similar looking, larger product would perform in the same manner despite differences in size and design of the cap/wick holder constitutes negligence in prudent application of accepted engineering and testing principles.

The tests that were performed on products in the test group focused primarily on surface temperature changes, lead content, fuel consumption, surface defects — and whether or not any part of the solid material shell heated up after burning for a given amount of time. There was an evaluation listed on the testing report marked as "actual use — functionality — not covered by other tests," but it was marked as N/A (not applicable). The criteria for that evaluation read as follows: "Shall function as intended (Set wick — above the flame guard and burn continuously for 6 hours under normal use conditions)." First, it is questionable as to why this test would "not apply" to this group of samples. Second, such a test would not have constituted a true "actual use" test because it fails to take real-world variables into consideration such as the torch being moved while lit (either intentionally or not) or various torch extinguishing methods.

The tests conducted per the test protocol also failed to cover the appropriateness and safety performance of a fill cap that did not conform with the standard and customary design of the cap/wick holder. Additionally, none of the test protocols appeared to have addressed the appropriate type of fuel to be used (or not to be used) with the subject torch. As such, none of the tests performed were effective in determining whether the subject torch would be safe for consumer use in its as-designed and as-marketed condition.

Conclusions

Combustion occurs when all three of the necessary requirements are met: fuel, oxygen, and an ignition source. When theses subject style torches are filled with the subject type torch fuel and then lit, the temperature within the torch can exceed the flash point of the fuel. This, in turn, results in the production of a sufficient quantity of vaporized fuel (which is heavier than air). The oxygen component comes from the air surrounding the torch. When there is an event that forces air to move around the cap of the torch, such as blowing out the flame or moving the torch while lit, oxygen can be forced into the torch body through openings in the cap. The air can then mix with the accumulated fuel vapor inside of the torch, resulting in a fuel/air mixture ratio that falls within the flammability limits. The third and final component, the ignition source, comes from the torch flame. The flame can enter the torch body through either the vent hole in the cap or the space between the wick and the opening in the cap it passes through.

If all of these components necessary for combustion are in place, then an explosive event will occur. While explosive events involving the subject style torch are fairly rare, even under the right environmental conditions, they can occur under the torch's normal operating conditions. The environmental conditions that can contribute to an increased likelihood of an explosive event include: a warm day or exposure to direct sunlight (can increase the internal torch temperature), the use of subject type torch fuel (has a low flash point), and the movement of air around the flame (can introduce air and flame into the body of the torch).

The factors that contributed to the creation of the conditions necessary for the subject explosive event (and other similar events) to occur include:

- Use of a torch fuel with a low flash point;
- The design of the wick holder/cap;
- The lack of a flame snuffer;
- Inappropriate marketing of both the subject torch and fuel;
- Inappropriate product labeling and warnings;
- Ineffective product testing.

It follows that solutions to avoid such explosive conditions include:

- Keeping the temperature of the fuel used in the torch below its flashpoint for all operationally possible conditions;
- Redesigning the cap/wick holder assembly to make it a more effective flame arrestor by enclosing around the wick tighter and over a greater length;
- Including a flame snuffer with the torch;
- Marketing the product to be used with only compatible fuels;
- Using clearer verbiage on the product labels to ensure understanding of important safety information.