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TECHNICAL ARTICLE—PEER-REVIEWED

Root Cause Analysis of an Oil-Burning Tabletop Torch Explosion

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Abstract Recent severe burn injuries and at least one death have been attributed to the sudden explosion of a particular type of tabletop fuel oil-burning torch when moved by or somehow affected by the user while lit. An investigation was performed to determine the variables involved in the design and operation of the subject torch that provided the necessary and sufficient conditions for the occurrence of the above explosions. The investigation findings strongly suggest that the explosions were caused by a faulty design of the tabletop torch that failed to separate the fire (ignition source) from a fuel that had too low of a flashpoint.

Keywords Catastrophic failure · Explosion · Failure analysis · Forensic analysis

Background

In 2013, a healthy male was having a small gathering on the outside deck of his newly purchased residence. At the gathering, he lit, for the first time, a decorative glass mosaic tabletop fuel oil-burning torch, see Fig. 1, that he had recently purchased. The lit torch began to smoke after a time period of no more than 5 min according to the witnesses at the gathering. He approached the lit torch in order to move it away from the immediate sitting area. After picking up the torch from the deck and while he was moving the torch, it violently exploded in his hands, separating the upper and lower portions of the torch, igniting his clothes on fire as well as sending fuel oil and glass mosaic fragments flying in all directions. He was transported to a medical center where he was treated for severe burns over 40% of his body. Due to the extent of his burn injuries, he passed away 3 months following this incident.

A number of other severe but non-fatal explosions resulting in burn injuries have also been reported while using the same tabletop torch design, which led to the US Consumer Products Safety Commission recalling the tabletop torch [1]. The commonality among such incidents was that the torch exploded after the user attempted to blow out the flame or move the lit torch from one place to another. All incident torches were filled with the same brand of Citronella torch fuel oil.

Investigation

The failure mode responsible for the reported explosions was the sudden and violent separation of the upper and lower halves of the tabletop torch due to the generation of an internal pressure force exceeding the mechanical seam strength at the interface of the upper and lower sections of the torch that kept the two sections of it together.

The mechanism for the development of the internal force was a pressure rise caused by the combustion of fuel vapor in the headspace of the torch. For combustion to occur, the simultaneous presence of three conditions was required, namely accumulation of fuel vapor, appropriate fuel-to-air ratio and an ignition source. When the above conditions occurred simultaneously, the accumulated vapor ignited resulting in a large pressure increase of the product gases in the confined headspace volume of the tabletop torch that resulted in a force that caused the vessel to fail. The absence of any of the above conditions would have

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Fig. 1 Photograph of decorative glass mosaic tabletop fuel oil-burning torch accessed from https://www.cpsc.gov/Recalls/2013/big-lots-recalls-tabletop-torches# on May 22, 2014

Fig. 2 Tabletop torch cap showing the 2 mm vent hole and torsional spring clip that is used to hold the wick

prevented the occurrence of the sudden torch failure. Therefore, our investigation focused on understanding the circumstances surrounding the event in order to answer the following questions: How did volatile vapor accumulate in the torch? How was the ignition source introduced to the accumulated vapor? Was the resulting internal force sufficient to cause the tabletop torch to fail?

Results and Discussion

Four approaches were used to answer the above questions. First was to determine the engineered features of the torch. Second, a chemical analysis utilizing gas chromatography and mass spectrometry (GC–MS) of the fuel oil was performed. Third, experiments were performed on an exemplar torch and torch fuel in order to determine whether vaporized fuel was present in the headspace of the torch that would have been necessary for the reported torch failure. Finally, a theoretical analysis was performed to determine whether enough pressure force could be generated by the reaction of the chemicals found in the headspace to separate the torch sections causing failure.

Mechanical Analysis of the Tabletop Torch

The tabletop torch was manufactured in two pieces that were joined together by mechanically folding the upper section to the lower section creating a circular seam around the periphery of the torch. The nominal diameter at the seam was 25.4 cm (10 in.). Glass mosaic tiles on a dark grout base were attached to the torch for decorative purposes. The screw-top cap to the torch contained two holes—one large opening through which the wick passed that required a torsional spring clip to hold the wick in place and a second small opening through hole approximately 2 mm in diameter. Figure 2 shows a close-up of the screw-top cap and the wick retaining clip.

We performed a hydrotest on an exemplar tabletop torch to safely measure the quasi-static internal pressure required to separate the top and bottom sections of the torch. A replacement cap was made that contained a sealed water supply line and a pressure gage. The test consisted of slowly opening a water supply line so that the pressure increased quasi-statically. At 30 ± 2 psig internal pressure, the mechanical seal connecting the top and bottom halves failed causing partial separation of the two sections. This quasi-static test provided a value for the internal gage pressure required for mechanical failure of the seam (30 psig). Given the 25.4 cm diameter of the torch, for every 1 psig increase in the internal pressure of the torch, its top and bottom pieces are subjected to a 78.5 lb_f pulling the tabletop torch pieces apart. At 30 psig internal pressure, the separating force on the torch seam is just over 2356 ± 157 lb_f.

Chemical Analysis of the Tabletop Fuel

Gas chromatography–mass spectrometry (GC–MS) chemical analyses of the subject torch fuel oil sample (obtained from the original fuel oil container used to fill the subject torch) and an exemplar sample from an unopened container of the same torch fuel brand were performed by Armstrong Forensic Laboratory (AFL) [2] in order to determine the chemical components present in each fuel sample. Flash points of both torch fuel oil samples were determined utilizing Cleveland open cup (ASTM D92) and Pensky–Martens closed cup (ASTM D93) test procedures. The measured flash points of both fuel samples were similar (subject fuel: open cup test 104 °F, closed cup test 102 °F; exemplar fuel: open cup test 102 °F, closed cup test 102 °F). As can be expected with different batches of fuel oil, the composition of the fuels was different with the subject fuel containing more branched chain alkanes and the exemplar fuel containing more normal alkanes.

We were interested to understand the chemical composition of other Citronella fuel oils that are available at local home improvement stores, so we purchased two additional torch fuels that contained "Citronella" in the product name and performed a second set of GC–MS (Hewlett Packard Agilent 5973) tests. All three fuel oils were diluted in acetone and injected in the GC–MS in order to profile the hydrocarbons present in each sample. Figure 3 shows a comparison of the total ion chromatograms of the fuel oils. Qualitative library matching with a NIST ChemStation library [3] indicates that fuel oil (3a), the exemplar subject torch fuel oil, contained lighter normal and branched chain alkanes similar to the exemplar sample components determined by AFL. It should be noted that the peak at 3.6 in all the chromatograms is diacetone alcohol, a contaminant in the acetone solvent that was used in the analysis and possibly a part of the citronella fragrance.

Understanding the components in the fuel oil is important, but what is more significant is to identify whether hydrocarbons are present in the headspace after the tabletop torch burned for the period of time for which the accident occurred. To that end, experiments were performed to determine what, if any, hydrocarbons existed in the headspace after burning the tabletop torch for a similar period of time as the deceased, reportedly approximately five minutes. An exemplar tabletop torch was instrumented with two 24-gage, type K thermocouples, one of which was located in the liquid fuel and the other was located in the vapor region above the liquid interface (headspace). Two ports had been previously created for a different experiment, but were not used in this experiment and were sealed with aluminum tape. In order to control the initial temperature of the fuel, the torch was placed in a constant temperature bath (86 ± 1.8 °F), the approximate ambient temperature at the time of subject incident. The instrumented tabletop torch situated in the constant temperature bath is shown in Fig. 4. Note that it is possible for the fuel temperature to be greater than the ambient temperature if the torch were subjected to incident solar radiation on a warm day.

For each test, the tabletop torch and pouring beaker were triple washed in acetone before each experiment. New vials and gastight syringes were used. 750 ml of a fuel oil was added to the tabletop torch, the amount the decedent reportedly used. For each fuel oil test, a new wick and different cap were used. Once the tabletop torch was assembled, the wick was soaked in the fuel for 15 min. The wick was lit when the temperature of the liquid fuel in the tabletop torch stabilized to the set point temperature. The torch burned for 5 min at which time the flame was extinguished. The wick and cap were immediately removed, and a 5-ml gas sample of the headspace was obtained from a centered location approximately 2 in. below the top of the tabletop torch using an 8-in. gastight syringe. The gas sample was slowly bubbled through a vial containing 1 ml of LC–MS grade acetone and then analyzed in the GC–MS where the compounds were separated and library matching was done to determine the components in the headspace. Figure 5 shows chromatograms from the headspace samples from the three fuel oils after 5 min of burning. NIST ChemStation mass spec standard library was used to match the compounds in the sample. The exemplar fuel oil chromatogram (5a) showed several compounds present in the sample, excluding the diacetone alcohol solvent: 3.8 min: 2,4-dimethylheptane; 3.86 min: 3-methyl-octane; 4.0 min: 1-ethyl, 2-methyl-cyclooctane; 4.07 min: nonane; 4.8 min: decane. In contrast, the headspace from the other two fuel oils showed only traced amounts of undecane (5.483 min) present.

It is clear that volatile organic carbon (VOC) compounds from the exemplar fuel oil were present in the headspace of the tabletop torch, which provided conditions required for an explosion. However, even when hydrocarbons are present in a ratio suitable for a chemical reaction, an ignition source is still required, and this is where the design flaws in the cap become important. The purpose of the cap is to keep the flame isolated from the fuel oil such that no path exists for the flame to propagate back into the interior of the torch. In a functional cap, this is accomplished by ensuring that there is no opening between the flame (an ignition source) and the fuel oil larger than a quenching length through which a flame cannot propagate. For the cap used in the subject tabletop torch, there are two lengths (gaps) to consider—the diameter of the vent hole in the cap and the gap created between the wick and the hole through which it passes.

Quenching diameters have been reported for a limited number of hydrocarbons [4, 5], among which include quenching gaps for octane ~ 1.04 mm and decane ~ 1.02 mm. Barnett and Hibbard [6] state the quenching gap is between 1.25 and 1.5 times smaller than the quenching diameter, which would yield quenching diameters between 1.3 and 1.6 mm, less than the 2 mm vent hole diameter present in the cap. An approximation for the quenching diameter for many hydrocarbons is given in Eq 1, which indicates the quenching diameter to be inversely related to temperature and pressure (where d_q [mm], T [K], P [kPa] [6]):

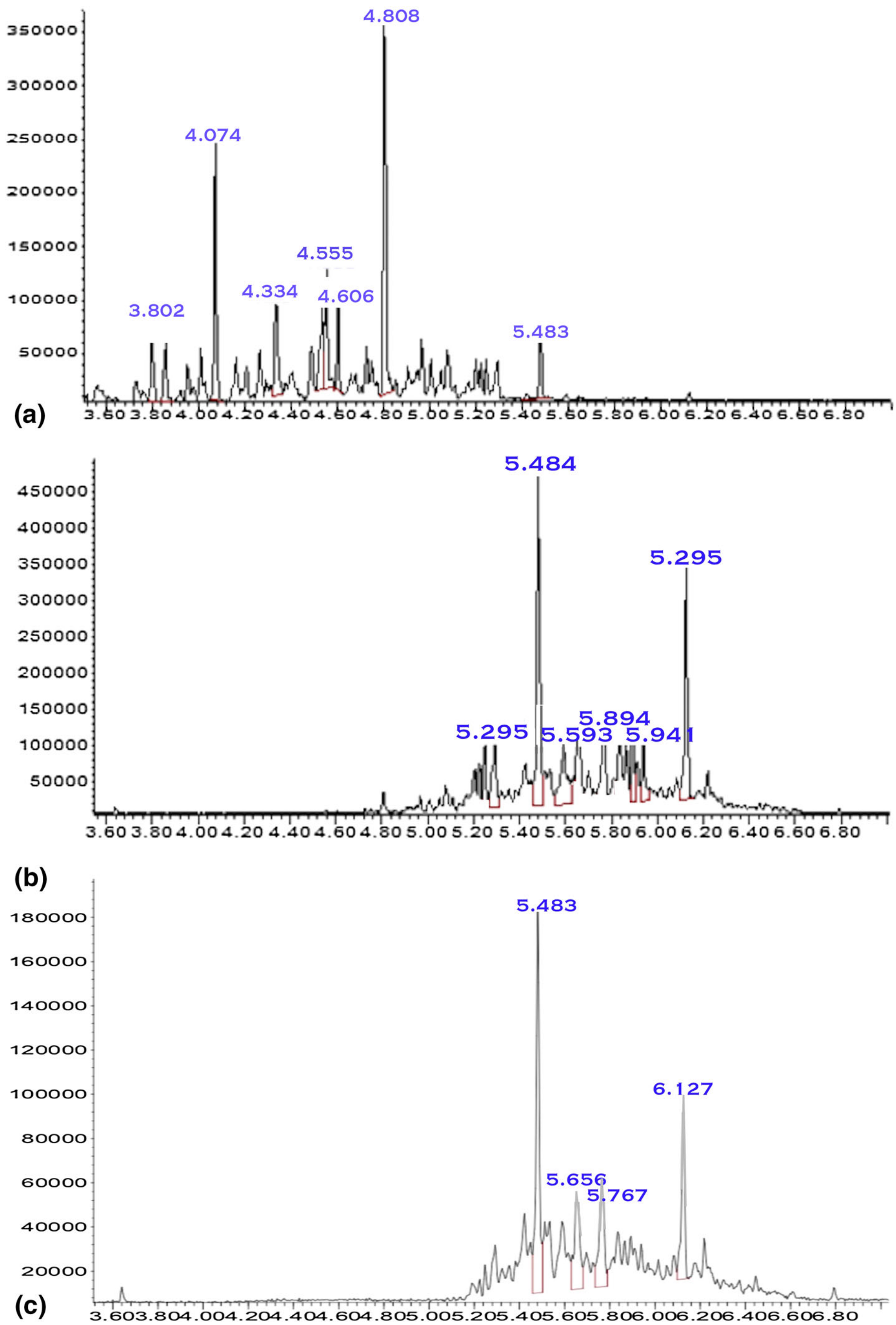

Fig. 3 Total ion chromatograms of direct injection of diluted fuel oils: (**a**) exemplar fuel oil, (**b**) and (**c**) other fuel oils that contain "Citronella" in the name

$$d_q = 2.54\left(\frac{289}{T}\right)^{0.5}\left(\frac{101.3}{P}\right)^{0.5} \quad \text{(Eq 1)}$$

In normal operation, the tabletop torch burns under atmospheric pressure; thus, a quenching diameter of 2 mm corresponds to a temperature of approximately 466 K, several times less than the combustion temperature of the flame.

The second area of concern was the gaps in the cap and wick assembly. A test was performed using a tabletop torch cap and wick assembly with exemplar fuel oil to investigate whether or not the gaps identified between the wick and cap were small enough to quench a flame and keep it from propagating to the interior of the torch. In this test, the cap and wick assembly was suspended above an open container of the exemplar fuel oil. The wick was lit, and after approximately four and a half minutes, the flame propagated through the cap as shown in Fig. 6.

With the presence of VOC compounds in the headspace identified and two possible ignition paths identified, we

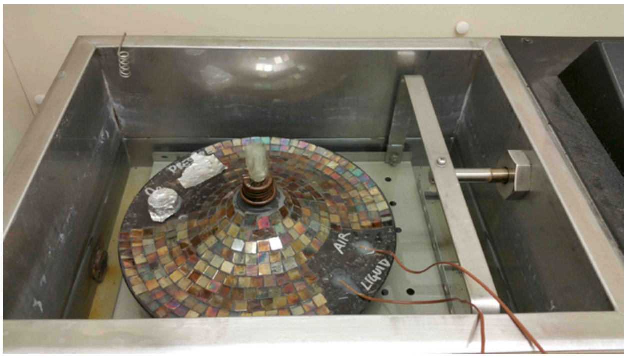

Fig. 4 Exemplar tabletop torch in a constant temperature bath instrumented with two thermocouples

now estimate the internal deflagration pressure developed as a result of combustion of a fuel vapor mixture within the tabletop torch headspace. This analysis neglects the complex reflections of the pressure waves within the tabletop torch and product gases that escape from the two mm vent hole or wick gaps. Further it is assumed that the reaction goes to completion with no dissociation. At the lower flammability limit (LFL), the products include oxygen, while at the upper flammability limit (UFL) the products include unburned fuel. The product gases behave ideally with constant properties, and there is no work or heat transferred during the reaction.

There were many hydrocarbon components identified in the headspace, but for simplicity we consider only nonane and decane vapors in the chemical reaction analysis for mixture ratios of 100–0%, 50–50% and 0–100% nonane–decane, respectively. The volume of the tabletop torch is 2.75 L—750 ml of liquid fuel in the torch (the approximate amount of fuel in the torch on the day of the accident), leaving a volume of 2 L for the fuel vapor and air in the headspace, which is considered a closed volume. The ambient pressure and temperature at the time of the accident were 100.2 kPa (14.5 psi) and 303.7 K (87 °F), respectively.

To estimate the internal pressure rise from the product gases, an energy balance is performed on the fuel vapor and air in the headspace region to determine the temperature of the product gases (carbon dioxide, water vapor, oxygen (fuel lean), unburned fuel (fuel rich) and nitrogen):

$$\sum N_{\mathrm{P}}\left[\Delta\bar{h}_{\mathrm{f}}^{\circ}+(\bar{h}-\bar{h}^{\circ})-P\bar{v}\right]_{\mathrm{P}} = \sum N_{\mathrm{R}}\left[\Delta\bar{h}_{\mathrm{f}}^{\circ}+(\bar{h}-\bar{h}^{\circ})-P\bar{v}\right]_{\mathrm{R}} \quad \text{(Eq 2)}$$

where the subscripts P and R refer to products and reactants, respectively.

An iterative solution technique is used to determine the final temperature of the product gases that satisfies Eq 2 from which the ideal gas equation is used to estimate the resulting internal pressure. Thermochemical properties were taken from [7–9]. The LFL and UFL by volume for nonane and decane are given in Fig. 1 (Table 1). The solution to Eq 2 yields the temperature of the product gases that ranged from about 1470 K (100% nonane at the LFL) to about 2300 K (100% stoichiometric decane), which corresponds to internal pressures ranging from about 64 to 100 psig, just over two to three times the hydrostatic pressure ($\sim$ 30 psig) required to separate the two sections of the tabletop torch. The maximum pressures calculated compare well with values from [11], which range from 80 to 100 psig. In the actual explosion, the neglected branched hydrocarbon elements would have increased the energy release and some product gas would have escaped through the 2 mm vent hole and the opening for the wick.

As mentioned earlier, in a quasi-static hydrostatic test performed on exemplar torches, where the internal water pressure in the torch was slowly increased, the seam connecting the two halves of the torch split apart at approximately 30 psi. In an actual explosion, where the internal pressurization due to the deflagration occurs suddenly and in a dynamic fashion, the required dynamic pressure for overcoming the seam strength of the torch would be much lower than the 30 psi threshold obtained through quasi-static tests. This can be explained by the fact that splitting of the steel seam between two halves of the torch involves both deformation and sliding of the seam material along both sides of the seam line. When the torch seam is subjected to high-strain-rate loading caused by the deflagration event, the seam material's (steel) strength for resisting deformation is decreased due to the lower strength of steel at high strain rates, while simultaneously, the friction forces that resist sliding of material along the seam line are decreased due to the dynamic coefficient of friction being less than the static coefficient of friction.

The death and other injuries that occurred could have been avoided. It took the confluence of design and fuel circumstances to result in the explosions of the tabletop torch. The tabletop torch design should have included a cap design with no vent hole and an extended tubular wick

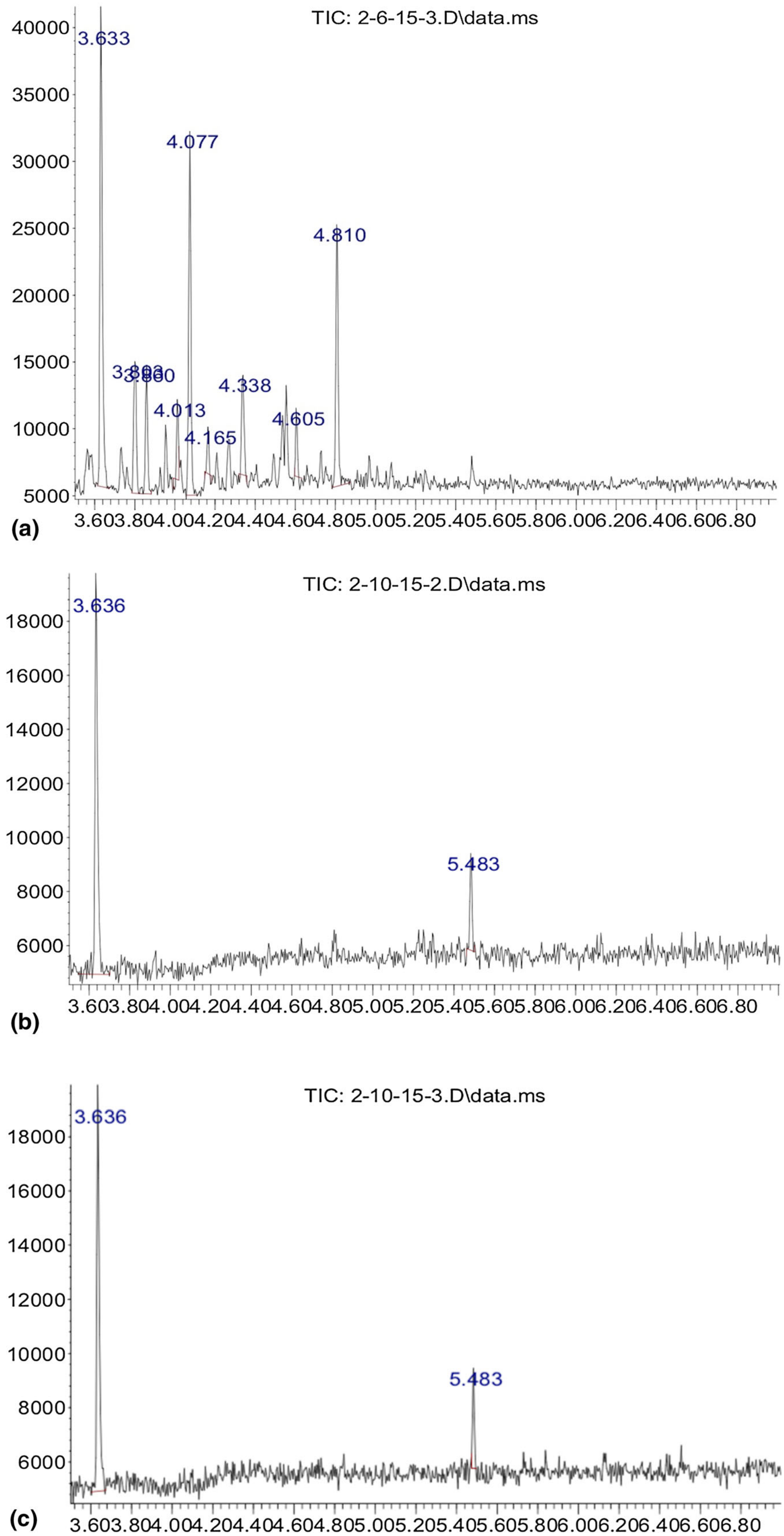

Fig. 5 Total ion chromatograms taken from the headspace after 5 min of burning: (**a**) exemplar fuel oil, (**b**) and (**c**) other fuel oils that contain "Citronella" in the name

Fig. 6 Flame propagating through the tabletop torch cap and wick assembly

Table 1 Flammability limits of two VOC compounds present in the headspace after the 5-min burning experiment [8]. Flammability limits for the mixture determined using Le Chatelier's mixing rule [10]. In comparison, MSDS (SDS) from various companies selling Citronella fuel oil indicates LFL and UFL ranging from 0.6 to 1% and 6 to 7%, respectively

	Lower flammability limit (vol.%)	Upper flammability limit (vol.%)
n-Nonane	0.8	2.9
n-Decane	0.8	5.4
50–50 mix	0.8	3.8

holder section that tightly held the wick in order to quench any flame propagation into the interior headspace.

Conclusions

Several tabletop torches, similar in design and manufacture to the subject torch investigated in this case, exploded, while the users were attempting to either move the torch while lit, or while attempting to distinguish the flame, one ultimately resulting in a fatality due to the extent of the sustained burn injuries. An investigation identified the tabletop torch explosions were caused by

- The defective design of its screw-top cap that provided multiple propagation paths for the exterior flame to ignite the combustible mixture in the interior of the tabletop torch and also provided a path for the outside air to mix with the accumulated vapor inside the torch to bring the air-to-fuel ratio within the necessary ignition range.
- The use of a fuel oil that would generate VOC compounds due to its low flash point temperature (∼ 102 °F) (1) during normal tabletop torch use and (2) during nonuse when ambient temperatures exceeded the fuel flashpoint as a result of ambient solar radiation and convection.

Had either a high-flash-point fuel (> 140 °F) or a cap with a flame extinguisher been used, the death and injuries could have been avoided.

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