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Forensic Engineering Analysis of an Explosion Allegedly Caused by an Overfilled Propane Cylinder

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Abstract

Analyzing the origin and cause of fires or explosions for the purposes of legal proceedings requires the smooth integration of a reliable fire investigative methodology with sound engineering principles and practices. The origin of a building fire was first determined based on the methodology of NFPA 921 Guide for Fire and Explosion Investigations*. Engineering analysis was applied to witness observations, arc mapping, fire dynamics, and the evaluation of fire patterns. The fire cause was then evaluated considering NFPA 921 and integrated applied engineering analysis and calculations. The allegations of an overfilled propane cylinder as the cause of the fire were considered. Spoliation issues, poor investigation methodology, and the lack of sound engineering principles (resulting in unreliable opinions) are also contrasted and discussed.*

Keywords

NFPA 921, fire investigation, origin, pattern, arc mapping, cause, propane cylinder, overfilled, overpressure, regulator, relief valve, leak, heat transfer, fluid dynamics, propane, gas migration, dissipation, diffusion, spoliation, forensic engineering

Background

The property owner and eventual plaintiff, an elderly gentleman, was working inside his small detached office building adjacent to his residence when suddenly an explosion and fire occurred. Sometime during the incident, he sustained serious burn injuries that required hospitalization, substantial treatment, and rehabilitation. At some point after being discharged from the hospital, he collected and retained a 100-lb propane cylinder, a 12-foot section of copper tubing, and a wall-mounted space heater from the incident scene. An unburned 20-lb propane cylinder was also later collected and preserved by the owner. The owner concluded that the 100-lb propane cylinder must have been overfilled, leaked propane gas, and caused the explosion/fire incident. He then hired a plaintiff attorney to represent him.

Approximately one month after the incident, the plaintiff attorney hired an engineering firm to retain and evaluate the artifacts collected by the owner for causation purposes. At that point, the incident scene still existed; however, the engineering firm made no request nor any effort to examine, document, or process the scene. The engineering firm simply procured the artifacts from the owner, examined them, and then secured them at their facility.

Google Earth imagery indicated that the fire-damaged structure was still standing approximately eight months after the incident. Approximately 12 months after the incident, the propane company that allegedly filled the 100-lb cylinder was first placed on notice of the incident via a lawsuit filed against it. They had no prior notification of the incident. In addition, prior to the lawsuit filing, the fire scene and structure were substantially demolished and disposed of without any form of proper examination, documentation, or scene processing by a qualified party. The insurance company for the propane company retained a defense attorney, who subsequently retained this author to investigate the origin and cause of the explosion/fire.

Description of the Office

Figure 1 depicts a general plan view layout of the detached office building, which was derived from the remains of the foundation, flooring, fragments remaining at the scene, and a verbal description provided by the owner.

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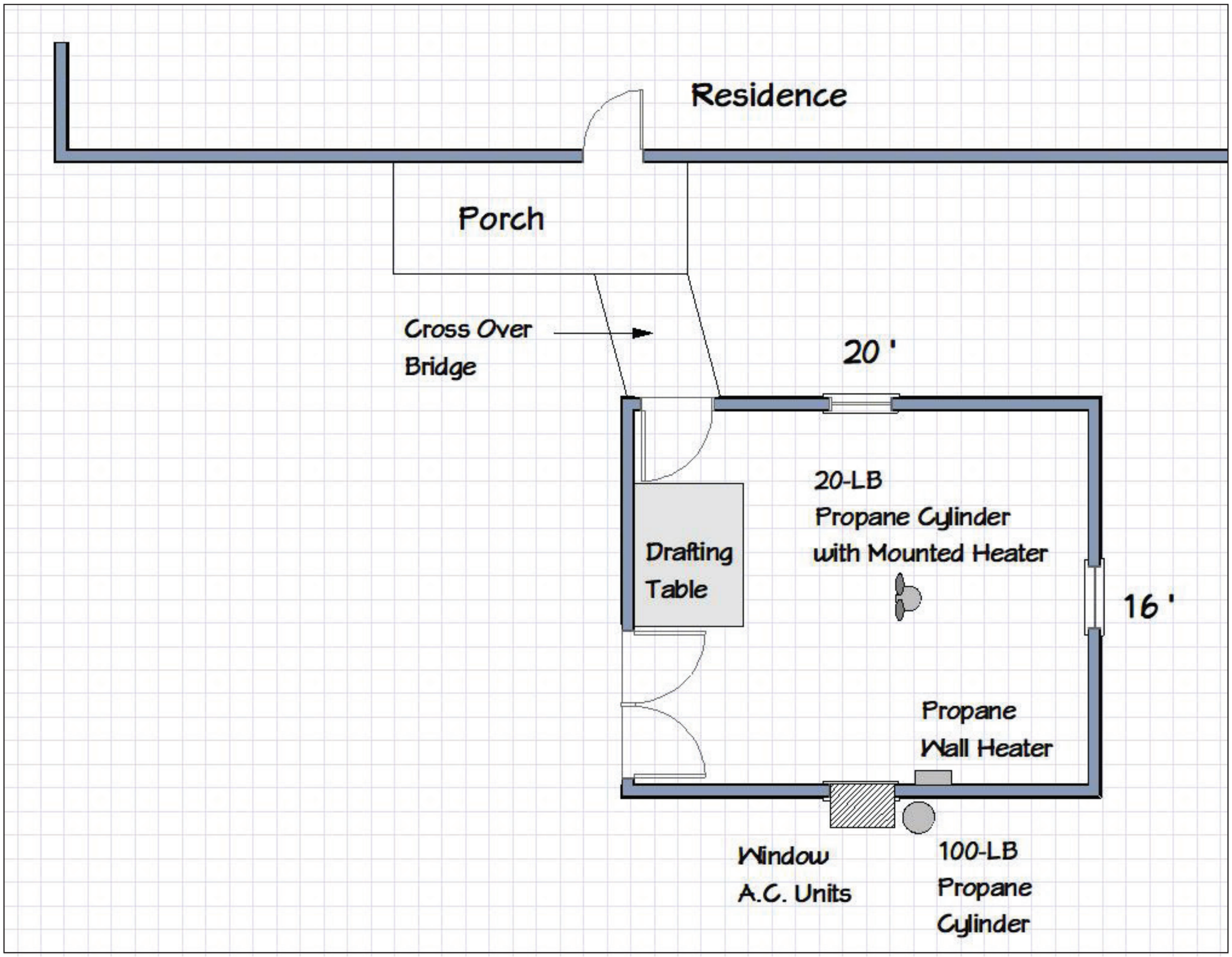

Figure 1
Office plan view layout with the approximate location of a 20-lb propane cylinder with top-mounted heater.

The incident building had been constructed by the owner approximately 16 years before the explosion/fire. The building had been a wood-framed structure, consisting of one open room that measured approximately 16 feet by 20 feet. The office had a plywood floor and was elevated above grade on concrete piers with an open crawl space and no skirting. The office was located approximately 12 feet from the owner's residence with an elevated plank walkway (cross-over bridge) connecting the covered porch of the residence to the entry door of the office building.

At the time of building construction, the owner purchased and installed an interior wall-mounted, unvented propane gas-fired heater, a 12-foot copper tubing gas supply line, and an exterior set 100-lb propane cylinder and regulator. The wall-mounted heater was installed on the interior south wall of the building. The 100-lb propane cylinder was set on patio bricks on the exterior of the south wall near two window air-conditioning units. One of the window air-conditioning units was installed in the window of the south wall. A second unit was installed through a cut-out opening in the south wall immediately below the window. According to the owner, the gaps in the wall openings around both air-conditioning units were sealed to prevent air exfiltration and infiltration.

The entry door of the office was in the north wall, which also contained a window. The west wall contained a pair of 3-foot doors located near the southwest corner, which were always closed and blocked closed by file cabinets. The east wall contained a window. The walls were insulated and sheathed with exterior wood panel T1-11 siding. The interior portions of the walls were sheathed with Oriented Strand Board (OSB). The ceiling was also sheathed with OSB and insulated above. The roof was wood-framed and covered with metal.

Figures 2 and **3** depict the remains of the scene over a year after the incident. **Figures 4** and **5** depict the artifacts collected by the owner after he was discharged from the hospital.

Owner's Description of the Incident

Around 3:30 p.m. on the day before the incident, the owner disconnected the copper gas supply line and regulator from his 100-lb propane cylinder. Then, with

Figure 2
View from the south side of the office adjacent to the residence looking north.

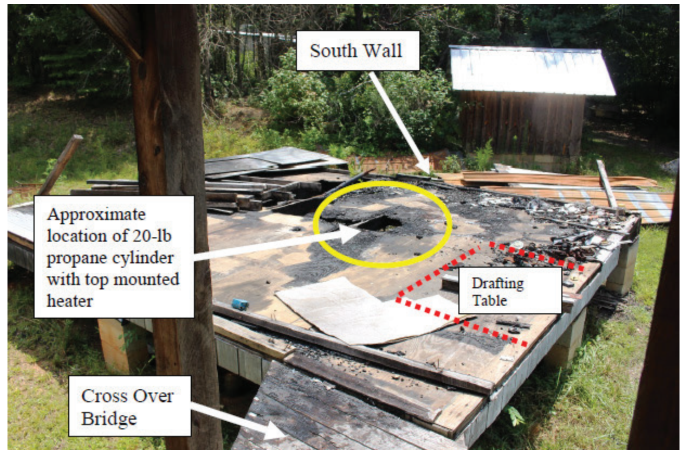

Figure 3
View from the northwest corner of the office looking from the residence porch, southeast over the elevated cross-over bridge.

Figure 4
View of the artifacts collected by the owner.

Figure 5
View of the 100-lb propane cylinder collected by the owner.

assistance from a friend, he reportedly took the cylinder to a propane refilling store and had it filled. He brought the cylinder home and reconnected the gas supply line and regulator around 4 p.m. After turning the gas on at the cylinder service valve, he indicated that he performed a soap bubble test to verify there were no leaks at the made connection points. He went inside the office, turned the gas "on" at the heater, and lit the pilot, after which time he retired for the evening to his residence. Reportedly, he never operated the heater, but only lit the pilot — and left the gas control in the pilot position the day before the explosion.

At approximately 2:30 p.m. the next day, he was in his office working at a drafting table and indicated that all of a sudden there was an explosion. He looked to his left, and realized "the whole (south) wall was burning." He went outside to turn off the gas and observed flames around the top of the 100-pound propane cylinder. The flames prevented him from turning the cylinder service valve off. He then went to retrieve a water hose and heard a second loud explosion. Upon returning with the water hose, he began trying to extinguish the fire when there was a third explosion that "tossed" him "20 feet." The fire department arrived, aided him, and extinguished the fire.

Plaintiff's Proffered Expert Opinions

The plaintiff's engineering expert did not prepare a written report, and his expert disclosures were without explanatory details or basis for his opinions. The plaintiff's engineering expert file was large, with seemingly scattered data, research, and various calculations. Part of the assignment of the author of this paper was to prepare engineering deposition questions for examination of the plaintiff's engineering expert to fully understand the opinions and the basis of the opinions intended to be offered at trial. To that end, extensive questions were prepared and implemented in the deposition. In summary, the plaintiff's engineering expert offered the following primary opinions:

1. The 100-lb propane cylinder was overfilled by the propane store.

2. At the time the cylinder was exposed to heat from the fire, it was near 96% liquid full.

3. The overfilled condition was conclusively determined based on the "vapor bubble" fire pattern remaining on the cylinder after the fire.

4. The temperature of the propane and cylinder at any given time is essentially the instantaneous ambient air temperature plus approximately 18°F for solar loading (radiant heat effect from the sun shining on the cylinder).

5. The gas leaking out of the regulator relief valve pre-incident wasn't caused by a failed regulator diaphragm.

6. Before the initial explosion and fire — and as a result of the overfilled condition — liquid propane had entered the regulator, rapidly expanded into a gas, and created a pressure of approximately 4,000 psi that destroyed the regulator diaphragm and leaked propane gas out.

7. The propane gas that leaked out of the regulator relief valve accumulated (outside and several feet above the ground) and then migrated through the wall, through the air-conditioners, into the office. It also migrated 7 to 8 feet up the exterior wall surface due to convection currents and then through the soffit into the concealed space above the ceiling.

8. The explosion ignited the accumulated propane gas that flashed back through the wall and the air conditioners to the leaking gas at the propane cylinder, igniting it and causing a continuous jet fire.

9. The propane cylinder became hot, and the relief valve on the cylinder service valve opened, discharging more gas into the fire.

10. One of the relief valve discharges and subsequent burning propane gases impacted and injured the plaintiff who had come outside to extinguish the fire with a water hose.

11. The propane cylinder, while remaining 96% full and connected to the copper tubing and regulator, was knocked over by one of the relief valve discharges and rolled away from the building. The cylinder came to rest on a slope with its foot elevated above its top. At that point, the 96% full cylinder was subjected to radiant heat impingement from the burning building that resulted in the "vapor bubble" fire pattern forming on the cylinder.

12. An investigation of the origin of the fire was not in the scope of the plaintiff expert's assignment. Note that there were no other investigators hired by the plaintiff's attorney.

13. The origin of the fire, however, became "self-revealing" and "self-apparent" after he concluded that the cause was an overfilled cylinder.

Fire Investigation Methodology

National Fire Protection Association (NFPA) 921 *Guide for Fire and Explosion Investigations* is well recognized in court systems as a peer-reviewed acceptable methodology for the investigation of fires and explosions. It provides comprehensive reliable scientific techniques in the fire investigative profession for analyzing the origin and cause of fires and explosions, including proper scene documentation, scene processing, scene data collection, evidence identification, collection and preservation, and analysis methods. Engineers performing fire investigative work must be familiar with and proficient in the application of NFPA 921; otherwise, they can expect serious court challenges to their opinions.

The subject case involved a multitude of blatant failures on the part of the plaintiff's attorney and his expert in properly investigating the incident. The extensive nature of the failures prohibits a detailed listing and discussion in the limited space available. However, some of the failures will be discussed in this paper to illustrate their significance.

In the 2014 edition[1] of NFPA 921, Chapter 4 *Basic Methodology* incorporates some of the following excerpted relevant provisions [emphasis added]:

4.1* *... The use of a systematic approach often will uncover new factual data for analysis, which may require previous conclusions to be reevaluated. With few exceptions, the proper methodology for a fire or explosion investigation is to first determine and establish the origin(s), then investigate the cause… .*

4.3 Relating Fire Investigation to the Scientific Method

4.3.3 Collect Data. *…The data collected is called empirical data because it is based on observation or experience and is capable of being verified or known to be true.*

4.4.3.3 *In any incident scene investigation, **it is necessary for at least one individual/organization to conduct an examination of the incident scene for the purpose of data collection and documentation**… . The use of previously collected data from a **properly documented scene** can be used successfully in an analysis of the incident to reach valid conclusions through the appropriate use of the scientific method… .*

4.4.3 Conducting the Investigation

4.4.3.1 *…The fundamental purpose of conducting an examination of any incident scene is to collect **all** of the available data and document the incident scene. … .*

4.4.3.4 … Improper scene documentation can impair the opportunity of other interested parties to obtain the same evidentiary value from the data. This potential impairment underscores the importance of performing comprehensive scene documentation and data collection.

4.6.3.1 *The methodologies used and the fire science relied on by an investigator are subject to peer review. For example, **NFPA 921 is a peer-reviewed document describing the methodologies and science associated with proper fire and explosion investigations**.*

Other relevant chapters of NFPA 921 (with provisions that were extensively referenced as part of the author's investigation into the incident and engineering report) included: 16 *Documentation of the Investigation*; 17 *Physical Evidence*; 18 *Origin Determination*; and 19 *Fire Cause Determination*.

Plaintiff's Expert Origin Analysis

The proper fire investigation sequence most commonly involves first determining the origin of the fire and then the cause of the fire. The plaintiff's expert testified in his deposition that he was not hired to perform an origin investigation or origin analysis, was not going to give an opinion as to the origin of the fire at trial, and therefore no scene examination, processing, or documentation was necessary for origin determination. Furthermore, no additional scene data or evidence was necessary to evaluate his opinions or test his hypothesis. In his opinion, the fire origin became "self-revealing" and "self-apparent" after he first determined the cause to be an overfilled cylinder. He began with a cause and then inferred an origin. He concluded the origin was at the side of the building where the 100-lb propane cylinder was located. The owner — the only witness interviewed by the plaintiff's expert — initially reported an overfilled cylinder as the cause, and the expert never bothered to examine the scene or interview other witnesses. As such, expectation bias is strongly implicated. NFPA 921, Chapter 4 *Basic Methodology* warns against such bias in Section 4.3.8 partially excerpted below:

4.3.8 Expectation Bias. *Expectation bias is a well-established phenomenon that occurs in scientific analysis when investigator(s) reach a premature conclusion without having examined or considered all of the relevant data. Instead of collecting and examining all of the data in a logical and unbiased manner to reach a scientifically reliable conclusion, the investigator(s) uses the premature determination to dictate investigative processes, analyses, and, ultimately conclusions, in a way that is not scientifically valid.* **….**

Origin Analysis Methodology

In origin area analysis, NFPA 921 incorporates information derived from one or more of the following: witness information, fire patterns, arc mapping, and fire dynamics. Fire dynamics, in part, involve analyzing the initiation, development, and spread of a fire in the context of, and consistent with, the data obtained from the first three elements — namely witnesses observations, fire patterns, and arc-mapping. Therefore, fire dynamics is properly integrated into and considered in the analysis and discussion of those three elements.

The plaintiff's engineering expert failed to interview any witnesses as part of his investigation other than the owner. He also failed to obtain a copy of the fire department incident report, which provided the response information and the conclusions of the municipal investigation. As part of an attempt to settle the case, the author did (with the permission of defense counsel) forward a copy of the procured incident report and provided a summary of the information received during interviews of fire department personnel to the plaintiff's engineering expert during the course of the litigation.

The first responding firefighter happened to be the owner's next-door neighbor and the assistant fire chief of the responding fire department — who ultimately completed the municipal investigation and the incident report. The assistant fire chief was at his home when he heard the initial explosion, observed smoke coming from the plaintiff's property, and immediately responded. Upon arrival, he observed the owner coming out of the office with burn injuries and inquired as to what happened. The assistant chief testified, consistent with his incident report and interview, that the owner told him he was attempting to light a propane heater installed on the top of a propane cylinder inside the office when the explosion and fire occurred.

As part of his investigation after the fire, the assistant chief observed a 20-lb propane cylinder with a portable heater mounted to the top, located in the approximate center of the office. He also observed that the windows of the office building had been blown out from an explosion occurring inside the structure. Some of the window glass was lodged into the side of the adjacent residence. In addition to the observations of the assistant chief, the first firefighter that made entry into the office to extinguish the fire also observed the 20-lb propane cylinder with heater mounted to the top of it in the approximate center of the room. In his deposition, the owner denied the presence of this propane cylinder and denied the account of the assistant fire chief as to the cause of the fire.

At the time of the incident, the assistant chief concluded that based on his observations and on what the owner reported to him, the explosion/fire originated when the owner attempted to light the space heater mounted to the top of the 20-lb propane cylinder in the room. He concluded that there was most likely an accidental release or leak of gas into the room at the cylinder or at the heater mounted on top of the cylinder. Upon the owner's attempt to ignite the heater, the accumulated gas exploded. Since the assistant chief determined the incident was accidental, there was no municipal documentation or processing of the scene.

Failing to interview all relevant witnesses is a significant error that is substantially compounded when there are very different accounts, and a proper fire scene examination is not performed. NFPA 921, for example, notes:

18.3.3.15 Witness Observations*. …Witness statements regarding the location of the origin create a need for the fire investigator to conduct as thorough an investigation as possible to collect data that can support or refute the witness statements.…*

Figure 1 depicts the plan view of the office with the location of a 20-lb propane cylinder with top-mounted heater as observed by both the assistant fire chief and the first-in firefighter. **Figure 3** is annotated to indicate the general location of where the 20-lb cylinder with top-mounted heater was located. **Figure 6** depicts an "exemplar" 20-lb propane cylinder with top-mounted heater of a similar configuration

Figure 6
"Exemplar" 20-lb propane cylinder with top-mounted heater of the general type observed by the assistant fire chief and first-in firefighter.

as observed by the assistant fire chief and first-in firefighter. Since neither the cylinder nor the top mounted heater were recovered, the manufacturers are unknown — yet the configuration and style were similar, according to the witnesses.

As previously noted, fire patterns are recognized as a primary tool in the investigation of a fire or explosion. The contents of the office building were removed and disposed of without systematic examination and documentation. The walls, ceiling, roof, windows, and doors of the building were similarly demolished. The gas system components were removed and not systematically excavated, reconstructed, or documented in any fashion relative to the fire scene or contents of the scene. There was no reconstruction of contents and building structure elements and therefore no means to evaluate any fire patterns in relation to available fuel loads and configurations. In fact, there were no documented fire patterns of the scene to evaluate particularly relative to the context of the site. The isolated and alleged "vapor bubble" fire pattern used by the plaintiff's expert to conclude the cause of the fire will be discussed later. All the fire patterns should have been comprehensively examined, documented, and analyzed during a proper joint scene examination, excavation, reconstruction, and processing. The plaintiff's attorney and expert failed to perform or allow such work to be performed.

As previously noted, arc mapping is recognized as a primary tool in the investigation of a fire or explosion and is potentially useful in aiding in the establishment of the origin of the fire, in evaluating the spread of the fire and potentially in evaluating the fire cause. The electrical system of the building was demolished and discarded; therefore, there was no opportunity to properly excavate, examine, and document the electrical system. Furthermore, the window air-conditioning units and all other electrical devices within the office building were discarded, and no opportunity to properly excavate, examine, and document these components was provided. Arc mapping should have been comprehensively performed, documented, and analyzed during a proper joint scene examination and processing. The plaintiff's attorney and expert failed to perform or allow such work to be performed.

Spoliation

Spoliation was a key issue in the subject case. There were no factors or conditions that prevented the plaintiff from following proper methodologies in this investigation. Included in the author's engineering report was a time line description of events related to the investigation and the known conditions of the scene based on discovery documents and research. The plaintiff and the plaintiff's expert became involved a few weeks after the incident when the scene was still intact. Google Earth imagery, depicted in **Figure 7** and dated eight months after the incident, indicated the burned structure was still standing. There was simply no reason that the defendants could not have been notified in a timely manner of the event by the plaintiff and given an opportunity to properly jointly investigate the scene.

NFPA 921 addresses numerous issues related to spoliation, and the reader is encouraged to review those provisions. Some of these were previously mentioned in the citations of Chapter 4 as they relate to the impairment of the opportunity of other interested parties to obtain

Figure 7
Google Earth image of incident site approximately eight months after the event.
Note: The south wall of the building is completely shaded beneath the trees.

evidentiary value from the scene and the need for performing comprehensive scene documentation and data collection. The definition of spoliation is found in NFPA 921 section 3.3.167. Other sections of interest include: 12.3.5.5 *Documentation Prior to Alteration*, 18.3.2.5 *Avoiding Spoliation*, and 29.3.1 *Notice to Interested Parties*.

In addition to citing specific proper investigative methodology infractions, it is often useful to provide a list of evidence items that may have been of interest. **Figure 8** is an example of such a list that was provided in the author's report in the subject case.

Alleged "Vapor Bubble" Fire Pattern

The plaintiff's expert determined the cause of the fire based on his interpretation of a single, isolated, alleged "vapor bubble" fire pattern on the surface of the 100-lb propane cylinder. The "vapor bubble" fire pattern is depicted in **Figure 9**. He opined that the fire pattern conclusively indicated the cylinder was overfilled. According to the plaintiff's expert, the propane cylinder at some point during the event was knocked over by one of the cylinder service valve pressure relief valve (PRV) discharges. The cylinder then rolled away from the building on the slightly sloped ground surface below the building and ended up with the foot being elevated above the top of the cylinder. In addition, he opined that the copper pipe and regulator remained attached to the cylinder and uncompromised at the point it came to rest. Radiant heat from the elevated burning office building then impinged on the cylinder lying on the ground below. Differential heat transfer in the liquid and vapor regions of the cylinder produced the demarcation lines ("vapor bubble" fire pattern) on the cylinder. After measuring the dimensions of the "vapor bubble" fire pattern (excluding the portion of the pattern extending across the open foot ring), the plaintiff's expert then back-calculated the amount of liquid propane that was in the cylinder. He concluded the cylinder had 96% liquid propane in it at the time it was lying on the ground and exposed to radiant heat from the fire (even after three relief valve discharges during the fire event). Over the course of falling to the ground and during the radiant heat exposure, the regulator housing, regulator diaphragm, and copper tubing remained intact and uncompromised, according to his interpretation.

1	20-lb propane cylinder observed inside the office building
2	Portable space heater mounted to the top of the 20-lb propane cylinder observed in the building
3	Remains of the regulator reportedly attached to the 100-lb propane cylinder
4	Any securing brackets or bracing potentially associated with the soft copper tubing routed between the 100-lb cylinder and the interior wall-mounted space heater inside the office building
5	Both window air-conditioning units installed in the south wall of the office and any components associate with them
6	Electrical wiring system for the structure including but not necessarily limited to the structural wiring, electrical outlets, switches, etc.
7	Electrical appliances including but not necessarily limited to, lights, lamps and electrical equipment inside the office
8	Fire pattern documentation of the structure, interior and exterior and potential artifacts of interest in-situ (prior to disturbing the scene or any artifacts) - photography and measurements
9	Documentation of a systematic progressive excavation and reconstruction of the fire scene; including exposed fire patterns related to the structure, contents and recovered artifacts-photography and measurements
10	Construction details, documentation and measurements related to the walls, ceiling, insulation, barriers, roof, windows and doors
11	Reconstruction and documentation of the gas system and gas system components; including but not necessarily limited to the location and positioning of all propane cylinders, piping and heaters and subsequent documentation of the same relative to any fire patterns
12	Reconstruction of the 100-lb propane cylinder, copper tubing, window AC units and roof, etc. with photographic and dimensional documentation of same
*** It is not possible to state all the relevant or potentially relevant evidence items or data that may have been recovered, simply because there is no way to know what may have been discovered during a properly conducted joint scene examination, scene processing and documentation when the scene and evidence were destroyed.	

Figure 8
Examples of evidence items of potential interest***.

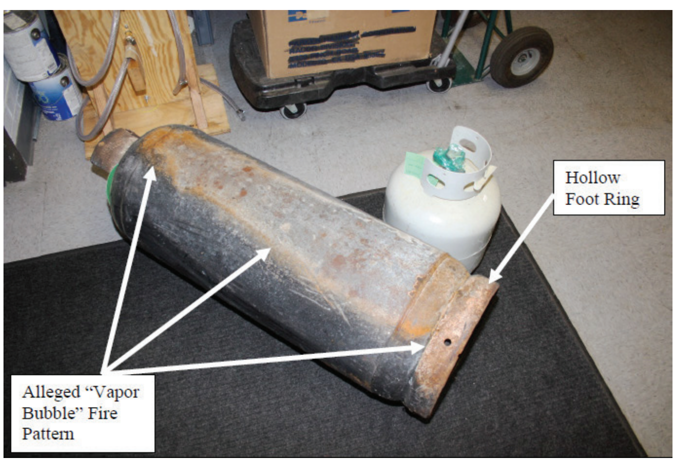

Figure 9
A view of the 100-lb propane cylinder and the alleged "vapor bubble" fire pattern. Note that the alleged fire pattern extends beyond the cylinder wall in contact with propane across and to the end of the hollow foot ring. Allegedly, the cylinder was lying on its side with the foot higher than the top, still connected to the regulator and line, 96% full, and the liquid/vapor bubble interface created the depicted pattern during radiant heat exposure from the burning building.

The interpretation of a single, isolated, alleged fire pattern, in particular relative to an undocumented and destroyed fire scene, does not constitute a proper and complete analysis of all or even most of the fire patterns of a fire scene and is not consistent with the requirements of NFPA 921. Such an evaluation is arbitrary and is similar to having a single piece of a puzzle without any other pieces to the puzzle, or even a photograph of what the completed puzzle looks like. As such, one can create any picture they want from that single puzzle piece. NFPA 921 contains a number of relevant provisions that should be reviewed related to proper scene excavation and reconstruction including consideration of the effects of various fuels on fire pattern production, including: 18.3.2 *Excavation and Reconstruction*, 18.3.2.3 *Excavation*, 18.3.2.8 and 18.3.2.8.2 *Contents*, 18.3.3.2 *Description of Fuels*, 18.3.3.9 *Fuel Gas Systems*, and 18.4.1.1 *Consideration of All Patterns*.

It was detailed in the author's engineering report that the history of the 100-lb propane cylinder and local environmental conditions post-fire were unknown. The 100-lb cylinder was not documented at the scene in any fashion after the explosion/fire event. There was no in-situ photographic documentation of the cylinder as it was found after the incident. There was no reconstruction documentation or photographs of the cylinder relative to the structure, fuels, and other elements that were present at the fire scene. Some significant questions to consider included, but are not limited to: Where was the cylinder located, and what was its geometric positioning relative to fuel loads, the structure immediately next to it, and other fire patterns present after the fire? What were the other fuel loads around the cylinder? What was the orientation of the cylinder and any alleged burn patterns on the cylinder in its as-found position? How long was the cylinder on the ground outside after the fire? What were the outdoor ambient and ground conditions over the time period it was there? Where is the documentation of the cylinder in each of the conditions it was originally located, moved, and stored in?

Metals exposed to elevated temperatures, such as very often happens in a fire, are subject to accelerated oxidation. When left exposed to the elements, various oxidation patterns can and do form post-incident on metals. For example, if the steel cylinder was lying on its side in the moist soil, fire debris or in a puddle of water for a period of time and later picked up, there can be an irregularly shaped oxidation pattern on the side of the cylinder reflecting where it was lying in the soil, debris, or water. The pattern depicted on the side of the cylinder could be just oxidation (rust) on a previously burned steel cylinder left out and exposed to the elements.

Furthermore, as implied above, another important question to consider is: What were the other fuels that were burning around the cylinder and their orientation relative to the alleged pattern on the cylinder? We know, for example, that the propane cylinder itself relieved gas through the relief valve multiple times as a normal consequence of the fire during the event. The regulator diaphragm (once quickly compromised by heat from the fire) would also have rapidly released gas into the fire. These events in themselves will create localized intense burning in close proximity to the propane cylinder. Flame impingement on the cylinder would be directionally dependent upon the sequence of events that occurred during the incident. In other words, localized intense burning can create patterns on one portion of the cylinder surface relative to the rest of the cylinder surface.

Compressor oil contained in the pressurized refrigerant lines of the air-conditioning units are another fuel source that can be released into the fire in close proximity to the cylinder and create areas of highly localized intense burning and the production of irregular patterns. Proper scene documentation, processing, and reconstruction as well as proper evidence identification, collection, documentation, and preservation would have allowed for a detailed and proper analysis of all the fire patterns and fuel loads in context with one another. Some additional relevant portions of NFPA 921 considered included [emphasis added]:

6.3.1.2.2. *The patterns seen by an investigator can represent much of the history of the fire. Each time another fuel package is ignited or the ventilation to the fire changes, the rate of energy production and heat distribution will change. <u>Any burning item can produce a plume and thus a fire pattern</u>… .*

6.3.1.2.1. *T**<u>he production of lines and areas of demarcation depends on a combination of variables</u>**: the material itself, the rate of heat release of the fire, fire suppression activities, temperature of the heat source, ventilation, and the amount of time that the material is exposed to the heat. ... The investigator should keep this concept in mind while analyzing the nature of fire patterns… .*

10.1.2.1. *During fire or explosion events, disrupted fuel gas systems can provide additional fuel and can greatly change or increase fire spread rates, or can spread fire to areas of the structure that would not normally be burned. The flames issuing from broken fuel gas lines (often called flares) can spread fire and burn through structural components.*

There was no reliable scientific basis for opining that the isolated alleged fire pattern on the 100-lb cylinder was conclusively caused by differential heat processes primarily involving the liquids and vapors inside the cylinder and heat exposure. Aside from the absence of the history of the cylinder post-incident as previously described — and the unknown nature of other fuel packages, locations, quantities, positions, and the fire patterns associated with them — the observations in the following paragraphs are also relevant.

The allegation includes that the "fire pattern" formed while the cylinder was exposed to heat from the fire, after it fell over, rolled away, and was lying on the ground on its side — all the while still in a near liquid filled state with the bottom of the cylinder elevated above the top of the cylinder. Such conditions are not justifiable. The cylinder was reportedly connected to a soft copper pipe and installed in a vertical position adjacent to the office south wall. The cylinder service valve was open to the connected aluminum regulator and copper piping. The windows were blown out by the interior explosion, and the vertically oriented cylinder would be subjected to convective and radiant heat from the fire venting from inside the structure out through the breached window. The venting fire would rapidly heat the cylinder, causing it to normally vent propane, as designed, through the pressure relief valve (PRV) to prevent overpressure and catastrophic failure of the cylinder.

At the same time, the heat and flames would rapidly compromise the rubber diaphragm and rubber orifice seat inside the regulator (attached to the top of the 100-lb propane cylinder at the open service valve), as well as the regulator aluminum housing, allowing high-pressure propane gas to rapidly free flow from the cylinder into the atmosphere through the regulator vent and housing. It is well known in the fire investigative industry that gas systems exposed to heat from fires are normally compromised and release their fuel contents into the fire, creating localized intense fire as a normal consequence. First responding witnesses also indicate there was no line or regulator attached to the cylinder service valve when they arrived at the scene. Evidence indicates that the regulator did, in fact, melt, and the connection to the cylinder failed. The rubber diaphragm would have failed sooner than the aluminum housing.

It is highly unlikely that the regulator diaphragm and housing were not compromised by the heat of the fire prior to the 100-lb propane cylinder falling over (resulting in the free flow of high pressure gas from the cylinder to the atmosphere). The cylinder was witnessed upright and venting through the PRV during the event, indicating that it was subjected to substantial heat before falling over. If the cylinder was subjected to high heat, so was the attached regulator at the top of the cylinder.

Furthermore, it is highly unlikely that the cylinder fell over with the cylinder top down and bottom sticking up without further compromising the heat damaged regulator and piping system, increasing the free flow of high-pressure propane to the atmosphere. Under such conditions, it is highly unlikely that the cylinder would still be in a state near liquid filled and exposed to fire while lying on the ground with a compromised attached piping and regulator system. Therefore, it would be unlikely to create an alleged "vapor bubble" fire pattern.

Finally and very significantly, the alleged "vapor bubble" fire pattern, purportedly formed by differential heating between the liquid filled regions and the vapor regions of the cylinder, extends into and across the foot ring. The foot ring is hollow and completely open to the atmosphere (i.e., is 100% air/vapor space and has no liquid in it), yet the pattern (with demarcation lines) continues completely across and to the bottom edge of the foot ring. By the plaintiff's expert hypothesis presented, there ought to be liquid propane present and contained in portions of the open to atmosphere foot ring, which is nonsensical.

Near the beginning of his deposition, the plaintiff's expert claimed he knew that the cylinder was overfilled because of the "vapor bubble" fire pattern and that the mere presence of the pattern precluded a pre-fire failure of the propane regulator rubber diaphragm. Had the diaphragm failed pre-fire, the contents of the cylinder would have been rapidly evacuated. Therefore, there would be no differential liquid/vapor space to create the observed pattern upon heat exposure. However, several hours later in his deposition, he contradicted himself when he opined that the regulator diaphragm failed pre-fire due to the introduction of liquid propane into the regulator chamber from the overfilled cylinder. In his opinion, when liquid propane entered the regulator chamber, it vaporized and produced a pressure of approximately 4,000 psi, which would have destroyed the rubber diaphragm and regulator.

Overfilled Cylinder Engineering Analysis Methodology

The plaintiff's expert examined the weather data for the day before the incident when the cylinder was allegedly filled as well as the weather data for the date of the incident. He concluded that the cylinder was filled at the refill station when the ambient temperature was 55°F; therefore, the propane in the 100-lb cylinder started at 55°F. He then concluded that at the time of the incident, the ambient temperature was 71°F; however, to account for solar radiation heating of the cylinder, an additional 18°F needed to be added. As a result, he opined that the temperature of the liquid propane in the cylinder (ending temperature) was at least 89°F at the time of the incident. Assuming a 100% liquid full cylinder, using a temperature differential of 34°F (i.e., 89°F to 55°F), multiplying that by a coefficient of thermal expansion interpolated from a rough graph, and then subtracting the gas volume consumed by the operating pilot on the heater, he concluded that the cylinder expelled a total of 0.91 gallons of liquid propane through the pressure relief valve of the regulator.

From this, he calculated that 0.91 gallons would convert to 28.2 ft^3 of pure propane gas and — when mixed with ambient air — form an explosive volume of between 294 ft^3 to 1,311 ft^3 outside and adjacent to the wall. He reasoned that this was more than sufficient volume to diffuse through the wall and be ignited inside. Although he estimated a discharge amount and calculated corresponding explosive concentration volumes, his analysis did not compute any rates of discharge, which as will be discussed later are a significant factor in determining the potential for an explosion and fire to occur.

The Google Earth image depicted in previously referenced **Figure 7** indicates that the south wall, including the 100-lb propane cylinder, is well shaded in the afternoon due to the nearby stand of trees. The propane tank at the refilling store where the cylinder was allegedly filled was not significantly shaded, but substantially exposed to direct sunlight most of the day. **Figure 10** depicts the refilling station. The cylinder was allegedly filled near the end of the day.

When the plaintiff's expert was asked in his deposition why he did not factor in any solar heating of the tank at the refill station to his calculations, as he had done with the 100-lb cylinder, he deflected the question and ultimately ended up stating that the starting temperature was really irrelevant to the problem. Obviously, that is not true in the calculation that he performed. See **Equation 1**.

Equation 1: $\Delta V = V_i\beta(T_f - T_i)$

Where ΔV = change in volume
V_i = initial volume
β = volumetric temperature expansion coefficient
T_f = final temperature
T_i = initial temperature

Clearly, the closer the initial and final temperatures are to each other, the less change in volume there will be — and correspondingly the less potential exists for expelling any propane due to an alleged overfill condition.

In addition to ignoring any solar heating on the filling supply tank at the refill station, the plaintiff's expert assumed that the temperature of the liquid propane in the 100-lb cylinder was essentially the instantaneous outdoor temperature plus 18°F for solar radiation heating at any given time. For example, as the outdoor thermometer ticked to 71°F, the propane inside the cylinder at that instant was 71°F + 18°F = 89°F. He reasoned that this was true because of the high thermal conductivity of the steel cylinder, which would, in his view, more or less instantly heat the liquid propane inside to the same temperature.

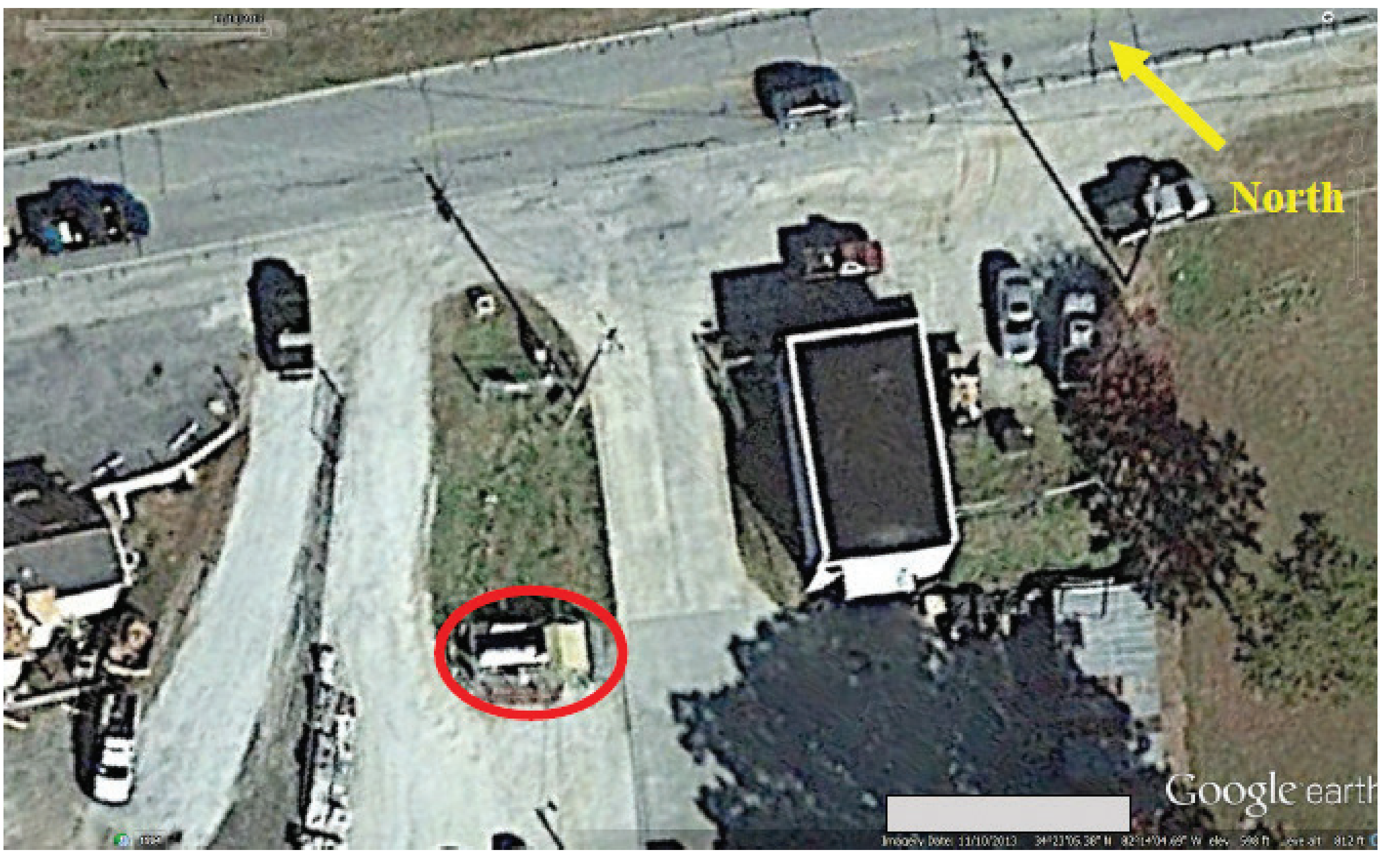

Figure 10
Refilling station and supply tank. The refilling tank and pump station is circled in red.
The pump station had a rain canopy. The vast majority of the tank is exposed.

It is well established that many engineering heat transfer problems are transient in nature and involve non-steady-state heating and cooling processes. For example, Holman[3] (page 139) notes the following:

…If a solid body is suddenly subjected to a change in environment, some time must elapse before an equilibrium temperature condition will prevail in the body…

In other words, objects do not generally heat up and cool down instantaneously, matching the immediate ambient environmental temperature into which they are placed. There is an initial temperature lag between the object and the environment it is placed in. The temperature difference will gradually approach zero over time as the object remains in the ambient environment and warms up or cools down to match the ambient temperature.

Transient heat transfer engineering problems associated specifically with propane cylinders have been studied and determined mathematically/experimentally to reliably follow and be predicted by the classical "Lumped Heat Capacity System"[4,5]. For example, Petersen[5] performed experimental testing and mathematical "Lumped Heat Capacity System" modeling calculations on propane cylinders placed in an outdoor environment with results indicating less than a 5 percent difference between the calculated and actual temperatures of the cylinder and the propane it contained.

Lumped Heat Capacity System engineering analysis addresses the transient heat transfer process and predicts resultant temperatures when placing a propane cylinder (including the liquid mass within) of a given temperature into an environment with variable ambient conditions (such as the outdoors). The analysis can include evaluating the diurnal cycle effects (i.e., evaluating the hourly ambient temperature, solar, and nocturnal radiation effects occurring during daylight and nighttime hours). These effects can include, if justified, the addition of degrees of temperature to the hourly ambient air temperature to model the overall complex heat transfer processes that occur at the air/surface and liquid/surface interface of the cylinder and mixing that goes on with the cylinder. The heat transfer and fluid mechanics occurring is more complex than simply looking at the thermal conductivity of the shell of the vessel. The general equation for Lumped Heat Capacity System analysis is expressed below. However, De Nevers[4] and Petersen[5] thoroughly cover the application to propane cylinders; therefore, the development and methodology will not be repeated.

Equation 2: $(T_o-T)/(T_o-T_1) = e^{(-hA/mc)t}$ **where:**

T_o = ambient temperature [°F]
T = temperature at the end of the time period [°F]
T_1 = initial temperature for the time period [°F]
h = heat transfer coefficient [Btu/(HR-°F-ft^2)]
A = container area, (exposed to liquid) [ft^2]
m = mass of propane and container [Lbm]
c = combined specific heat for propane and the container
t = time period, [Hr]

Mathematical Modeling Considerations for the Incident Case

Factors that may have impacted predicted temperatures of the cylinder and the mass of propane within the cylinder in question include the orientation and geometry of the 100-lb propane cylinder relative to the two window air-conditioners, roof overhang, and wall of the building, as well as the numerous surrounding trees. The dimensional measurements of the cylinder relative to the air-conditioning units, wall, and roof overhang of the building were not documented or preserved.

However, based on reported information, the 100-lb cylinder was located somewhere near the window units, which would likely provide some degree of shading effect for a period of time on the cylinder surface and reduce any potential overall solar heating effects. In addition to the air-conditioning units, the wall and roof overhang of the building also provide a shading effect from the sun for periods of time. Furthermore, there are considerable trees surrounding the area, which would also impact and substantially reduce any potential solar heating effects for periods of time (see **Figure 7**, depicting the trees and the corresponding shading of the building's south exterior wall where the cylinder was located).

The initial temperature of the propane in the 100-lb cylinder that would correspond to the temperature of the propane in the supply tank is also an important factor to consider as previously discussed. The temperature of propane in the supply tank is dependent upon several elements, including the quantity of propane in the tank, corresponding wetted surface area of the tank, the heat transfer coefficient, and diurnal cycling accounting for solar and nocturnal radiation before the 100-lb cylinder was filled. The amount of propane and temperature of the liquid propane that was in the supply tank at the time of the 100-lb cylinder filling is unknown. Commonly, such data is easily and reliably collected shortly after an incident by documenting the fill level gauge on the tank and obtaining the tank pressure. There was no opportunity to document the condition of the supply tank within the immediate time frame of the incident. Again, it was over a year after the incident before the propane store was placed on notice via a lawsuit.

Thermal Expansion Modeling and Rates of Discharge for the Incident Case

Since there was an absence of some important data, an attempt to model the precise conditions of the incident was not performed. However, demonstrative modeling using the "Lumped Capacity Heat System" can still provide some useful information for analysis and opinions.

The heat transfer process associated with a liquid propane mass warming and cooling inside a cylinder located in outdoor ambient conditions is slow and gradual; therefore, the thermal expansion and contraction rates of the liquid propane in the cylinder are also slow and gradual. The "Lumped Heat Capacity System" model previously described can be used to reliably demonstrate the slow nature of the temperature changes and the corresponding expansion and contraction rates of the liquid propane over a normal diurnal cycle. Two demonstrative models were utilized to aid in the subject incident.

For both demonstration calculations, properties of liquid propane were obtained from the National Institute of Science and Technology (NIST), Material Measurement Laboratory database. The database is available free online at the NIST website. In addition, the hourly outdoor ambient weather conditions, as reported by the U.S. Department of Commerce, National Oceanic & Atmospheric Administration (NOAA) at the nearest observation station, were used. Some of the hourly weather data for the incident case, on the date of the incident is shown in **Figure 11**. The day prior is not included here to preserve space.

For purposes of the first demonstration, variables were selected in such a manner as to attempt to produce a forced expansion of liquid propane in an assumed liquid-full cylinder; such that, roughly, the quantity of propane alleged by the plaintiff's expert to have been released (0.91 gallons) would be discharged into the atmosphere. However, instead of simply determining a total quantity of gas released over an undefined time, the model places the release in the context of time and therefore provides an estimated average release rate. As previously mentioned, release rates are one critical factor in determining whether flammable gases will create conditions that may produce an explosion or fire hazard. Release rates are discussed

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp		Wet Bulb Temp		Dew Point Temp		Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)
						(F)	(C)	(F)	(C)	(F)	(C)				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
15	0056	12	CLR	10.00		40	4.4	32	0.2	19	-7.2	43	3	290	
15	0156	12	CLR	10.00		35	1.7	30	-1.0	21	-6.1	57	0	000	
15	0256	12	CLR	10.00		33	0.6	29	-1.5	22	-5.6	64	0	000	
15	0356	12	CLR	10.00		31	-0.6	29	-1.9	24	-4.4	75	0	000	
15	0556	12	CLR	10.00		29	-1.7	27	-2.6	24	-4.4	82	0	000	
15	0656	12	CLR	10.00		30	-1.1	28	-2.2	24	-4.4	78	0	000	
15	0756	12	CLR	10.00		41	5.0	35	1.7	26	-3.3	55	3	180	
15	0856	12	CLR	10.00		48	8.9	39	3.7	25	-3.9	41	5	190	
15	0956	12	CLR	10.00		51	10.5	43	5.9	32	0.0	46	7	220	
15	1056	12	CLR	10.00		57	13.9	45	7.3	31	-0.6	37	10	230	16
15	1156	12	CLR	10.00		62	16.7	48	8.7	31	-0.6	31	8	250	20
15	1256	12	CLR	10.00		66	18.9	50	9.9	32	0.0	28	14	230	22
15	1356	12	CLR	10.00		68	20.0	51	10.7	34	1.1	29	15	250	22
15	1456	12	CLR	10.00		70	21.1	53	11.4	35	1.7	28	18	240	24
15	1556	12	CLR	10.00		71	21.7	53	11.8	36	2.2	28	16	230	29
15	1656	12	CLR	10.00		71	21.7	53	11.8	36	2.2	28	17	240	24
15	1756	12	CLR	10.00		69	20.6	53	11.6	37	2.8	31	13	220	22
15	1856	12	CLR	10.00		65	18.3	52	10.8	38	3.3	37	9	220	
15	1956	12	CLR	10.00		62	16.7	51	10.3	39	3.9	43	9	210	
15	2056	12	CLR	10.00		61	16.1	50	10.0	39	3.9	44	8	210	
15	2156	12	CLR	10.00		62	16.7	51	10.3	39	3.9	43	10	210	
15	2256	12	CLR	10.00		61	16.1	51	10.2	40	4.4	46	14	220	
15	2356	12	CLR	10.00		60	15.6	50	10.0	40	4.4	48	16	230	

Figure 11
Some of the hourly weather data for the incident case.

Time of Day (Clock)	Out Door Ambient |F| [With Applied Solar but No Nocturnal Radiation] |To|	Ending Temperature of the Propane and Cylinder |F| at the end of the time period	Total Volume of Liquid Propane in Cylinder |+ or -| Incremental Change in Volume	Liquid Propane (expansion or deficit) Beyond the Fixed Cylinder Volume = [Vcyl-Vf] in^3
4:00 to 5:00 PM	55	57.37	6594.6000	0.00
5:00 to 6:00 PM	53	56.44	6584.1274	-10.47
6:00 to 7:00 PM	53	55.72	6570.6106	-23.99
7:00 to 8:00 PM	49	54.30	6557.3080	-37.29
8:00 to 9:00 PM	45	52.34	6533.7613	-60.84
9:00 to 10:00 PM	41	49.94	6505.4156	-89.18
10:00 to 11:00 PM	45	48.90	6492.3363	-102.26
11:00 to 12:00 AM	45	48.08	6479.4705	-115.13
12:00 to 1:00 AM	44	47.22	6466.6094	-127.99
1:00 to 2:00 AM	40	45.69	6448.9535	-145.65
2:00 to 3:00 AM	35	43.44	6426.5073	-168.09
3:00 to 4:00 AM	33	41.23	6399.6925	-194.91
4:00 to 5:00 AM	31	39.07	6377.8899	-216.71
5:00 to 6:00 AM	30	37.16	6356.3045	-238.30
6:00 to 7:00 AM	29	35.44	6339.5160	-255.08
7:00 to 8:00 AM	48	38.09	6359.3551	-235.24
8:00 to 9:00 AM	59	42.50	6398.5248	-196.08
9:00 to 10:00 AM	66	47.46	6443.7028	-150.90
10:00 to 11:00 AM	69	52.01	6485.3257	-109.27
11:00 to 12:00 PM	75	56.86	6533.5734	-61.03
12:00 to 1:00 PM	80	61.75	6583.2502	-11.35
1:00 to 2:00 PM	84	66.44	6629.1678	34.57
2:00 to 3:00 PM (1/2 hr)	87	68.74	6619.4026	24.80
			Total in^3	59.37
			Gallons	0.26

Figure 12
Part of the spreadsheet calculations for the first demonstration.

along with other important factors later.

The manufacturer's fixed tare weight and water capacity data permanently engraved on the collar of the 100-lb cylinder were used to obtain the propane liquid volume of the cylinder, assuming 100% liquid filled, and the weight of the filled cylinder. The calculated combined **mc** term of **Equation 2** for the case in question was consistent with the calculated value for 100-lb propane cylinders referenced by De Nevers[4]. The calculated **hA** values of **Equation 2** were also likewise consistently comparable with De Nevers[4] and Petersen[5].

In the first demonstration calculations (**Figure 12**), for all daylight hours (beginning 30 minutes before sunup), an extremely unrealistic scenario, an assumed 18ºF solar effective temperature addition was added to the ambient hourly temperature. As a point of reference to the unrealistic nature of the assumption in the incident case, in one experimental test performed by Petersen[5] in Texarkana, Texas during the summertime, he added only 3 to 10 degrees for the incremental hours between 10 a.m. and 6 p.m. to adjust the model for solar loading gain to match the field experimental data. The case in question occurred during the winter time in South Carolina. Nevertheless, nocturnal radiative cooling was ignored, although likely significant, given the very cold (as low as 29°F) and clear night that had transpired. Shading was also ignored, although it was most likely a significant factor. A starting temperature of 58ºF was used for propane from the supply tank (3ºF above ambient), although it was substantially open and exposed to sunlight throughout the day.

Even with the extreme unrealistic conditions forced, the model calculates that only 0.26 gallons (as opposed to 0.91 gallons) would be released over a period of 1½ hours. **Figure 12** depicts a small part of the spreadsheet layout for the calculations performed. **Figure 13** depicts the model's predicted average vapor release rates and the total quantity of released gas vapor associated with the extreme unrealistic first demonstration. As can be seen, the discharge rates are extremely small, as is the total amount of gas discharged. **Figure 14** further illustrates and characterizes the extremely small quantities represented. Slow discharge rates provide substantial time for gas to disperse harmlessly, particularly in the outside open air. The propane cylinder regulator was several feet above grade. There was wind movement around the time of hypothetical gas venting. Furthermore, there was plenty of air cross flow in the absence of underpinning. These factors are discussed in further detail below.

For purposes of the second demonstration, a baseline model was produced. In the baseline model, both solar and nocturnal radiation (for the cold clear night) assumed gains and losses are ignored, and simply the ambient air conditions are utilized. The initial starting temperature of the propane is assumed to be 55ºF. Results of the baseline model indicated the predicted average vapor release rates associated with the demonstration calculations are zero. Beginning with an assumed liquid filled cylinder at 55ºF — and allowing it to pass through the diurnal ambient temperature cycle that occurred during the incident case — the cylinder will retain a vapor head space (0.33 gallons) and not release any gas to the outside. This demonstration (like the first) also includes the gas consumption of the pilot. An analysis of any assumed solar gain (and/or losses via nocturnal radiation) beyond the baseline model would necessitate field testing an actual propane cylinder and its propane mass contents at the site for precise validation purposes. However, it is noteworthy that the cold ambient temperatures alone that night would have substantially cooled the cylinder and its propane mass contents down.

Dispersion Rate Factors and Migration of Gases

As discussed above, discharge rates are only one of the important considerations in analyzing a hypothesis related to an alleged gas leak or release potentially causing a fire or explosion hazard. For example, in discussing gas leaks that occur **inside** of buildings, Kennedy[6] notes additional factors that must be considered [emphasis added]:

> ***Spread and Diffusion of Fuel Gases***
> *<u>When any fugitive fuel gas leaks</u> into a structure, it <u>will mix with the air by</u> one or more of <u>the following actions</u>: turbulent jet mixing, the natural buoyancy of the gas, the turbulent action of building ventilation, or molecular*

Unrealistic Demonstration #1: Average*** Exterior Vapor Gas Release Rates (assuming a continuous discharge) Associated with (unrealistic) Demonstration Calculations; and Total Quantity Released to the Outside Air		
Time Period	**Vapor Gas Discharge Rate CFH**	**Vapor Gas Discharge Rate CFM**
1200-1300	0	0
1300-1400	5.44	0.0907
1400-1430	7.81	0.1302
Total Quantity in Cubic Feet over 1.5 hrs (90 min.)	**9.345 CF**	**9.345 CF**
*** Any alleged releases through the internal relief of the regulator would most likely be intermittent as opposed to a continuous release, as thermal warming under ambient conditions is slow and subsequently the incremental expansions of the propane is also slow and gradual, not instantaneous nor massive.		

Figure 13
Vapor gas release rates.

Unrealistic Demonstration #1: Average*** Liquid Propane Inlet Rates into the Regulator and total quantity discharged.		
Time Period	**Liquid Propane Inlet Rate Milliliters per Minute (ml/min)**	**Liquid Propane Inlet Rate Milliliters per Second (ml/s)**
1200-1300	0	0
1300-1400	9.4	0.157
1400-1430	13.5	0.226
Total quantity flowed over the elapsed time period	**0.26 gallons over 1.5 hours**	**0.26 gallons over 1.5 hours**
*** Any alleged releases through the internal relief of the regulator would most likely be intermittent as opposed to a continuous release, as thermal warming under ambient conditions is slow and subsequently the incremental expansions of the propane is also slow and gradual, not instantaneous nor massive.		

Figure 14
Liquid propane inlet rates.

> *diffusion. Mixing by molecular diffusion is extremely slow when compared to the others.* ***All of the mixing actions dilute the gas with air*** *more and more the farther from the gas leak source.* ***Gases once mixed with air tend to remain mixed with air and not separate due to density differences. If the gas is escaping under pressure from a small source such as an*** *open pipe or* ***hole*** *in a pipe,* ***air will be entrained into the sides of the gas plume*** *created by the turbulent jet. …If the gas is heavier than air, the plume will be less buoyant than the surrounding air and tend to settle downward in a three-dimensional flattened fan shape… .*

In the incident case, the allegedly small gas leakage (from the regulator vent) is on the exterior of the structure occurring in the outside open air, and, as a result, dispersion and dilution of the gas with air can be expected to be rapid. The alleged small leak rates of propane gas into the open outside air will be subject to mixing with the outside air. Mixing occurs as the gas is discharged out of the vent opening of the regulator and immediately entrains air into the discharging plume, diluting the gas. The diluted gas/air-mixed plume is then subject to additional dilution in the outside open air via molecular diffusion, thermal diffusion, and natural convection air currents around the localized discharge area. Molecular diffusion involves the natural mixing of gas molecules due to different concentration gradients between the gases[3]. The gases will diffuse together until the concentration gradient comes to equilibrium. Thermal diffusion (e.g., due to temperature differences between the gases or thermal gradients) accelerates the mixing process. Natural convection currents are present even in assumed still air conditions. For example, thermal gradients on different objects can induce small localized air currents. These air currents will further act to dilute gases in the ambient.

The above processes exclude any mixing due to air movement related to air breezes (forced convection currents). The open crawl space with no underpinning provides a clear avenue for substantial cross flowing airways. The weather data indicates wind speeds of 8 mph with gusts of 20 mph around 12 p.m. out of the west/southwest; wind speeds of 14 mph with gusts of 22 mph around 1 p.m.; wind speeds of 15 mph with gusts of 22 mph around 2 p.m.; and wind speeds of 18 mph with gusts of 24 mph around 3 p.m.

Sophisticated Computational Fluid Dynamics (CFD) models (e.g. NIST Fire Dynamics Simulator [FDS][7] or FLACS[8]) have been developed, tested and validated for use in evaluating the complex nature of gas discharge, dispersion and migration problems. The alleged leak rates and quantities for the case in question, however, were very small. More importantly, they occurred in the outside open air; therefore, there is no justifiable mechanism by which to produce a flammable concentration of gas inside the building.

Pressure relief valves (PRVs) incorporated with cylinder service valves and relief valves built into gas regulators are designed by manufacturers to release propane in a controlled manner under overpressure conditions. With the exception of the window, which was closed and sealed, there were no openings in the wall. Window air-conditioning units are intentionally designed not to communicate unconditioned air from the outside of a building to the inside.

Window air-conditioning units are installed in a window or through a wall and sealed around the perimeter to prevent outdoor unconditioned air from infiltrating inside, or indoor conditioned air from exfiltration to the outdoors. The owner stated that his installed air-conditioning units were sealed, which is the appropriate, ordinary, and common method of installing and using these units. The units simply draw air from inside the room, circulate it through the evaporator heat exchanger coil, and then discharge it back into the room. No outside air is drawn into the evaporator heat exchanger coil. In fact, it is separated from the outside by an internally sealed air (gas) barrier to specifically prevent such an occurrence.

The exterior wall of the office was reportedly constructed of overlapping T1-11 siding with the inner cavities being insulated and the interior side covered with OSB. No windows were open, and no other wall openings were reported; nor were the wall or window air-conditioning units made available for examination or reconstruction. Exterior walls are intended design barriers to minimize the migration of air or other gases through the wall in either direction. The purpose behind ordinary construction is to keep unconditioned air (gas) outside and conditioned air inside. Air and propane vapors gas are gases, and both would likewise be substantially kept outside by ordinary construction barriers.

There was no scientific basis (including any mathematical modeling, CFD, or experimental testing) that was presented in the incident case by the engineering plaintiff's expert to support his opinions.

The regulator, or remnants of the regulator, were not available for examination, identification, or potential testing (i.e., of exemplars), and the make and model of the regulator was unknown. However, design standards[9] require that regulator relief vents operate in a manner such as to maintain the outlet pressures at or below approximately 2 psi, with start-to-discharge settings occurring when the pressure climbs to 19 to 33 inches water column (0.685 to 1.19 psi). For example, the Fisher Emerson Process Management *Bulletin LP-15*[10] regarding LP gas regulators provides:

…the regulator vent will exhaust LP-Gas when the internal relief valve opens. Every second stage domestic and light commercial LP-Gas regulator reducing pressure down to appliance pressure must have an internal relief valve. <u>An open internal relief valve can exhaust small bubbles of gas</u> or large volumes of gas depending upon the condition that caused the overpressure situation…

…UL 144, Standard for LP-Gas Regulators requires that the second stage regulator internal relief valve must open (begin-to-bubble) between 170% and 300% of the regulator outlet setting.

The regulator that was connected to the cylinder service valve outlet was designed to receive high inlet pressure propane — most have a maximum input pressure rating of 250 psi. Any alleged liquid propane dripping or "sputtering" into the piping connected to the regulator and into the regulator inlet would immediately convert to vapor in the regulator chamber and as soon as sufficient gas pressure had built up in the chamber, the internal relief vent would operate and discharge (or bubble out) the gas vapor to the open outside air. Once the internal regulator pressure dropped below the start to discharge setting, it would close until the pressure built-up again.

The average discharge rates previously presented in **Figure 13** were used to estimate and illustrate the average liquid propane inlet rate into the regulator, which are presented in **Figure 14**. As shown, the rates are very small. The volumetric flow rates are comparable to a children's medicine dropper or a small graduated medicine dosage cup.

Fire Origin and Cause Conclusions

A complete independent origin and cause investigation could not be completed by the author due to the destruction of the scene and gross absence of any scene examination, documentation, and processing. The assistant fire chief was the only municipal authority to make an examination of the fire scene prior to its destruction as well as directly witness portions of the event itself. In addition, the chief spoke directly with the owner regarding the circumstances of the incident at the time it was occurring. Furthermore, the chief and the first-in firefighter both observed the 20-lb propane cylinder with the top mounted heater in the office. This information was ignored and then claimed to be false by the plaintiff.

The 20-lb propane cylinder and top-mounted heater located within the enclosed room was a valid and substantial potential source of explosive fuel to consider in the investigation of this explosion and fire. Connections between a heater and cylinder can potentially leak (e.g., due to a loose connection, damaged threads or seals, broken or cracked fittings, etc.) Likewise, damaged or defective gas-carrying portions of the heater connected to the cylinder may have been leaking gas and resulted in an explosion. Neither the propane cylinder nor a heater was available for laboratory examination. The 20-lb propane cylinder and top-mounted heater that was located in the office could not be ruled out as a potential source of fuel and an ignition source for the explosion and fire, or as the point of origin of the fire. The heavily damaged unvented wall heater could also not be ruled out as an ignition source for the explosion.

The explosion originated in the one-room office. The correct cause of the explosion and fire for this case is undetermined; however, a detailed engineering analysis eliminated an overfilled cylinder as a potential cause of the incident.

References

1. NFPA 921-2014. Guide for fire and explosion investigations. Quincy, MA; National Fire Protection Association.
2. NFPA 58-2008. Liquefied Petroleum Gas Code. Quincy, MA; National Fire Protection Association.
3. Holman JP. Heat transfer, 7th edition. New York, NY: McGraw-Hill, Inc.; 1990.
4. De Nevers N. Ambient and solar heating of propane containers. Fire Technology.1997;22(3).

5. Petersen J. Forensic engineering techniques for testing and predicting LP-gas container relief venting. Journal of the National Academy of Forensic Engineers. 2004;21(2).

6. Kennedy P, Kennedy J. Explosion investigation and analysis: Kennedy on explosions. Chicago, IL: Investigations Institute; 1990.

7. Pape R, Mniszewski KR. The use of FDS for estimation of flammable gas/vapor concentrations. Presented at: Society of Fire Protection Engineers, 3rd Technical Symposium on Computer Applications in Fire Protection Engineering; Sep 12-13, 2001; Baltimore, MD.

8. Gavelli F, Davis SG, Hansen OR. A modern tool for the investigation of indoor flammable gas migration. Proceedings, International Symposium on Fire Investigation Science and Technology, Hyattsville, MD, 2010.

9. ANSI/UL 144-2014. Standard for LP-gas regulators. Northbrook, IL; Underwriters Laboratories, Inc.

10. Bulletin LP-15-2011. Give a regulator the attention it deserves. McKinney, TX; Fisher Emerson Process Management.