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Forensic Engineering Analysis of an Apartment Building Explosion Involving Flammable Refrigerant

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Abstract

On a Saturday afternoon in March of 2014, a low-order explosion occurred within a first-floor dwelling unit of a multi-tenant apartment building located in Georgia. Due to the explosion, the building sustained extensive damage, and the occupant of the unit of origin sustained serious burn injuries. This paper examines the origin and cause of the explosion.

Keywords

Explosion, propane, flammable, refrigerant, air-conditioning, heat pump, NFPA 921, forensic engineering

Description of the Structure

The apartment building, identified as "Building P," was an eight-unit, two-story wood-framed structure built on slab with an asphalt shingle roof and exterior vinyl-clad siding walls. For orientation purposes, the front of the building faced north. **Figures 1** and **2** depict the north and south sides of the building. Moving east to west, individual dwelling units (identified as P-1, P-2, P-3, and P-4) were located on the first floor (accessible from ground level). Dwelling units identified as P-5, P-6, P-7, and P-8 were located on the second floor (accessible from an exterior stairway located on the north side of the building). The dwelling units are labeled, and the explosion originated in unit P-3.

Figure 1
View from the front (north side) of Building P.

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Figure 2
View from the rear (south side) of Building P.

Building P was an all-electric utility service structure and had no natural or propane fuel gas utility services. Dwelling unit P-3, which was a single-story unit (approximately 1,056 square feet), featured two bedrooms, two bathrooms, a living room, and dining and kitchen areas. A floor plan of P-3 is shown in **Figure 3**.

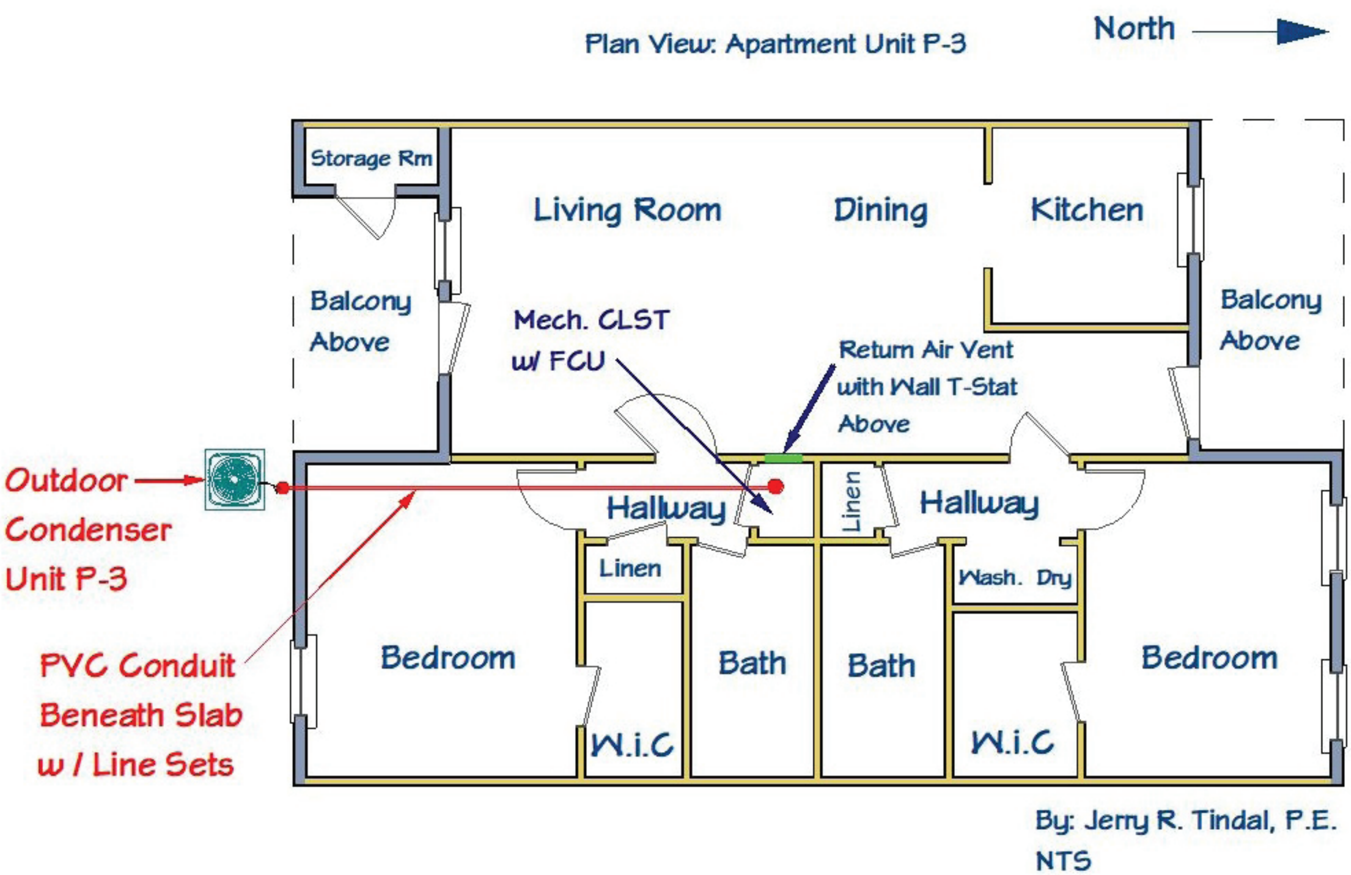

Figure 3
Floor plan of apartment unit P-3.

Description of the Incident

The single occupant of P-3 was in the south bedroom when he heard a hissing noise. Upon investigation, he determined the noise originated from the area around a wall-mounted thermostat located on the east wall of the living room/dining room. He detected no unusual odors. Believing there might be a problem with the air-conditioning system, he proceeded to switch the thermostat to the off position, at which time the explosion occurred. The occupant was facing the thermostat at the time and experienced a blast of pressure and flames coming from the direction of the thermostat.

The thermostat was mounted directly above a 16-inch by 25-inch non-ducted return air wall grille opening. The vent opening directly communicated the air space of P-3's mechanical closet to the air space area around the thermostat and the occupant. Responding firefighters used a fire extinguisher to put out a small fire in the mechanical closet. The involved occupant was transported to the hospital with burn injuries.

HVAC System Configuration

Heating, ventilation, and air-conditioning (HVAC) in P-3 was provided by a split system heat pump with an outdoor coil unit (located adjacent to the exterior south wall of P-3) and an indoor fan coil unit (FCU) located inside the mechanical closet. A copper tubing refrigerant pipe set, routed within and through a polyvinyl chloride (PVC) conduit installed beneath the slab of the building, connected the outdoor coil unit to the indoor FCU. **Figure 3** depicts the general location of the indoor and outdoor units and the under-slab PVC routing.

The south end of the PVC conduit was buried underground and originated between the south exterior wall and the outdoor coil. The refrigerant pipe set for P-3 was routed from the outdoor coil into the ground and then into the buried end of the PVC conduit. The PVC conduit ran north under the building slab, turned up, and terminated near the floor level inside the mechanical closet of P-3. The refrigerant pipe set continued up past the terminated PVC conduit and connected to the indoor FCU in the closet.

The pipe set was made up of two full runs of soft copper tubing, connecting the outdoor coil unit to the indoor FCU. Refrigerant circulated in a closed path circuit through the tubing between the outdoor coil unit and the indoor FCU. The two runs of tubing were of two different sizes. The larger insulated copper tubing is the vapor (gas) low pressure line, and the smaller copper tubing is the high-pressure liquid line. **Figures 4** through **7** depict the HVAC system of unit P-3.

Figure 4
Outdoor split system heat pump unit.

Figure 5
Excavated PVC conduit — the refrigerant pipe set from the outdoor unit entered the buried PVC conduit.

Figure 6
Excavated PVC conduit routed beneath slab and terminated at floor level of mechanical closet. Refrigerant line set continues up to the FCU located inside the closet.

Figure 7
East wall of living room/dining room area with wall thermostat and return air grille of the mechanical closet.

Explosion Characterization and Origin

Building wall structures and components were primarily intact although cracked, bulged, and displaced due to overpressure. Windows and doors were broken, dislodged, and displaced over short distances. The damages were consistent with low-order explosion damage, as characterized in NFPA 921 Section 23.3.1[1]. **Figures 8** through **13** depict typical overpressure damages observed to the building.

There was no seat (cratered area) remaining after the explosion. The absence of an explosion seat is characteristic of a diffuse (dispersed) fuel gas explosion, as described in NFPA 921 Section 23.7. In addition, only a relatively small amount of post-explosion burning in the structure occurred, which is consistent with a generally overall lean fuel mixture. The primary fire damage occurred within the mechanical closet, which was congested with equipment and piping. Accumulated gas in the congested and small volume of the mechanical closet created conditions favorable for localized fuel-rich pockets of gas to form

Figure 8
Exterior walls bulged. Window blown out.

Figure 9
Wall / ceiling joint separation.

and sustain burning after the explosion. The door of the mechanical closet was blown off its frame and down the hallway during the incident but sustained no burn damage. This was indicative of an explosion preceding the limited fire in the closet.

Explosion vector diagrams provide a useful tool for explosion dynamics analysis, origin identification, and illustration, as explained in NFPA 921 Section 23.15. An explosion vector diagram was constructed based on the blast patterns observed during scene examination. Blast patterns, fire patterns, and witness observations were consistent with an explosion originating in, or immediately adjacent to, the mechanical closet of P-3. **Figure 14** shows the explosion vector diagram.

Fuel Source

The source of the fuel for the explosion was determined to be a flammable refrigerant with a market name of "R22a," although the proper American Society of

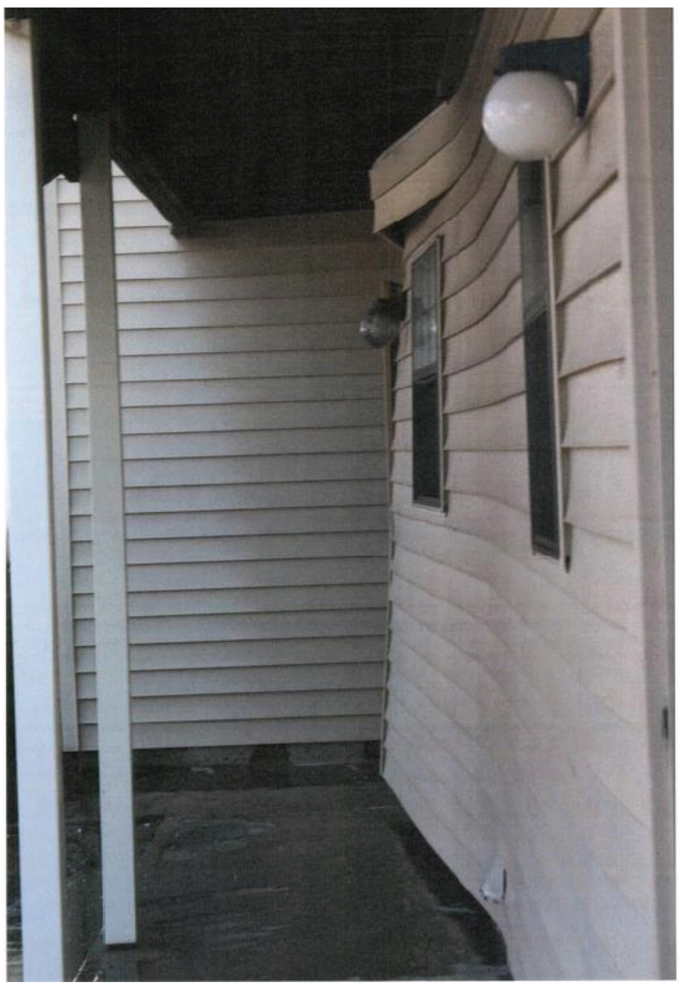

Figure 10
Exterior walls dislodged.

Figure 11
Exterior walls dislodged.

Figure 12
Interior and exterior walls separated from ceiling structures — windows intact.

Figure 13
HVAC vent deformation and dislodgement.

Heating Refrigeration and Air-Conditioning Engineers' (ASHRAE) designation is R-290 (i.e., propane). The propane refrigerant was intentionally substituted into the heat pump unit as a cost-savings replacement for non-flammable refrigerant R-22 by apartment complex maintenance personnel. The propane was not odorized with Ethyl Mercaptan or other approved recognized industry odorants (typically found in fuel-gas systems) as such odorants would be corrosive to the internal compressor components. Instead, the refrigerant manufacturer used a non-industry standard, unrecognized, and unapproved "fresh pine scent" odorant — similar to what you would smell with household cleaning agents. The tenants of the apartment unit never smelled any odors, and were never warned or otherwise informed to be cognizant of such odors as indicative of a potential fuel-gas explosion hazard. In addition, as noted earlier, the building had no fuel-gas utility services.

The refrigerant pipe set for P-3 was jointly examined and pressure tested with low-pressure air at the scene; first in situ and then after excavation and extraction. The field examination and testing indicated a failure and subsequent leak had occurred in the high-pressure liquid line piping associated with P-3.

During excavation and extraction of the refrigerant line set, a single failure point in the liquid line piping was located inside the PVC conduit a couple of feet north of the exterior south wall. The failure manifested in the form of a bulging split or rupture in the wall of the piping, running parallel to the pipe axis. There were no other leaks or points of damage observed in the liquid line other than the single rupture point. In addition, there was no observed evidence of kinking, twisting, or bending that could potentially have been caused by explosion forces.. The refrigerant lines were primarily located inside of a protective PVC conduit and below the building concrete slab. No evidence of any substantial movement of the FCU or the refrigerant lines by the explosion was observed. The failure in the pipe was

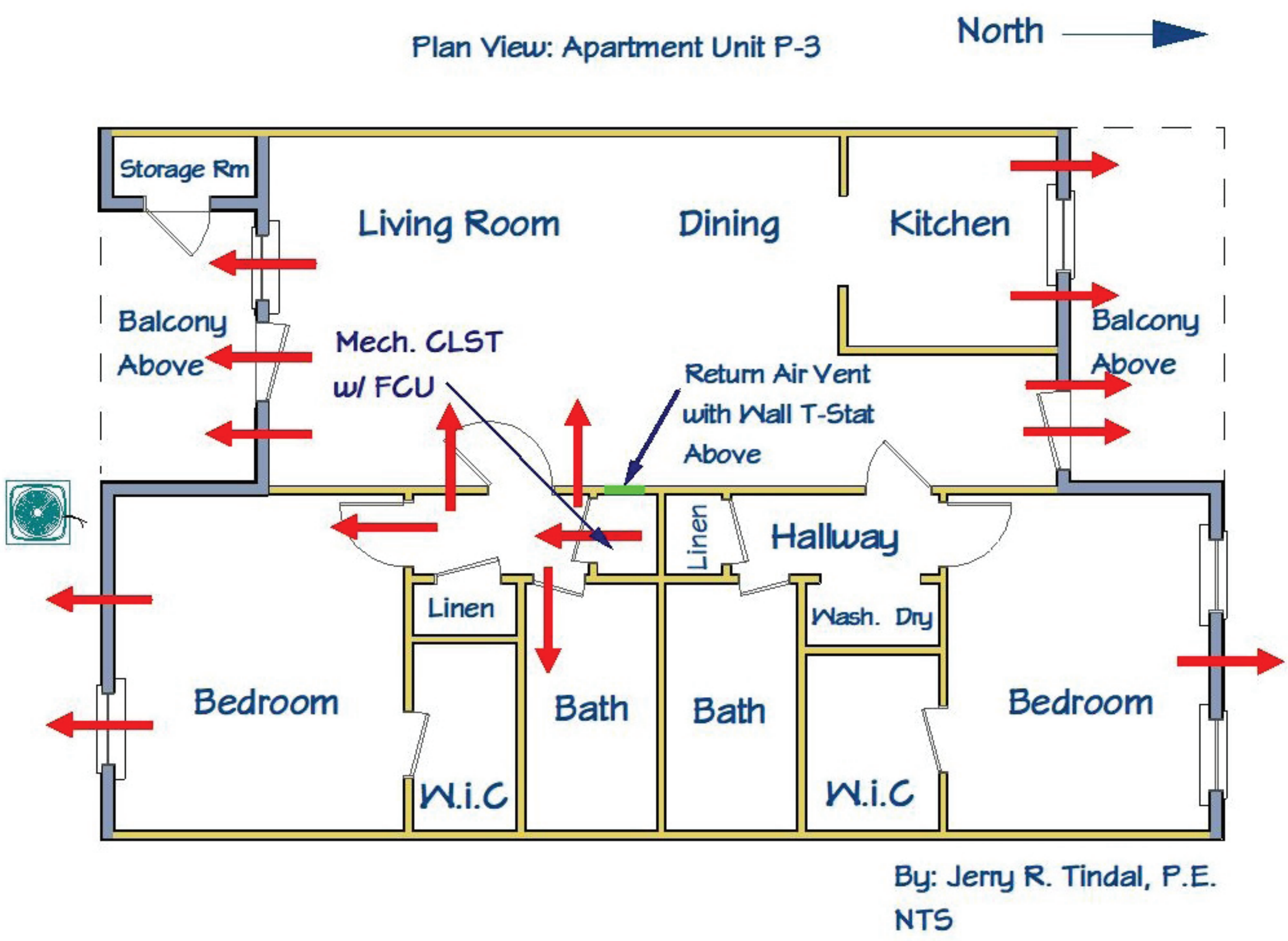

Figure 14
Explosion vector diagram.

not likely caused by explosion forces.

The bulge in the pipe wall opening indicated the refrigerant line was under internal pressure at the time of the pipe failure. The internal pressure created a localized bulge in the pipe wall as the pipe failed at that point, split open, and released the refrigerant. **Figures 15** and **16** depict images of the failure point. Extensive metallurgical testing was not completed to determine the exact cause of the failure; however, such failures in refrigerant piping are engineering-foreseeable occurrences. Mechanical systems, including HVAC systems and their components, are subject to wear, tear, corrosion, and therefore eventual failure. Components, including piping, routed in the ground or through open conduits in the ground are subject to water submersion, salts, lawn chemicals, and other chemical contaminants.

Pressurized liquid refrigerant (propane) was discharged through the rupture opening in the pipe, flash vaporized in the PVC conduit, and then flowed into the mechanical closet. The release of pressurized refrigerant into the PVC conduit and flowing of the refrigerant into the mechanical closet is consistent with the witness observations of a hissing noise — strongest in the area of the mechanical closet/thermostat. The south side of the PVC conduit was below ground, and the outlet was packed with soil, which would create a barrier to the free flow of gas on that end of the conduit.

Although there were leaks discovered in the heat exchanger component of the FCU located inside the mechanical closet, they were most likely caused by fire damage sustained after the explosion. Leaks in FCUs commonly occur because of heat impingement during fires and subsequent compromising of solder joints. As previously discussed, there was a fire burning in the mechanical closet after the explosion.

Fuel Quantities and Explosion Damage

Fuel gas discharge, dispersion, and migration problems are transient, and can be extremely complex. In many cases, proper analysis requires using sophisticated Computational Fluid Dynamics (CFD) models, such as the National Institute of Standards and Technology (NIST) Fire Dynamics Simulator[2] or GEXCON FLACS[3], which have been developed, tested, and validated for such purposes. The case in question, however, involved an incident where there was: (1) a simple fixed amount of available propane gas in the heat pump and no other explosive gases present; (2) that fixed amount of propane gas was actively being released into a fixed volume at the time of the ignition of the explosion; and (3) ignition occurred near the release point of the gas into the fixed volume. The primary engineering question presented focused on whether there was sufficient propane gas available to produce the explosion damages observed.

Worst-case scenario overpressures produced by near stoichiometric fuel-air mixtures can be determined for given quantities of explosive gases and fixed room volumes using the methodology outlined in the Society of Fire Protection Engineers' SFPE Handbook[4] *Section Three Hazard Calculations*, page 3-406 *Closed Vessel Deflagrations*. Some of the equations provided in the SFPE Handbook to determine overpressures developed are given in the forms:

(1) $P_m / P_o = n_b T_b / n_o T_o$

(2) $(P-P_o / P_m-P_o) = m_b/m_o$

Where

P_m = pressure developed at the completion of a closed vessel deflagration

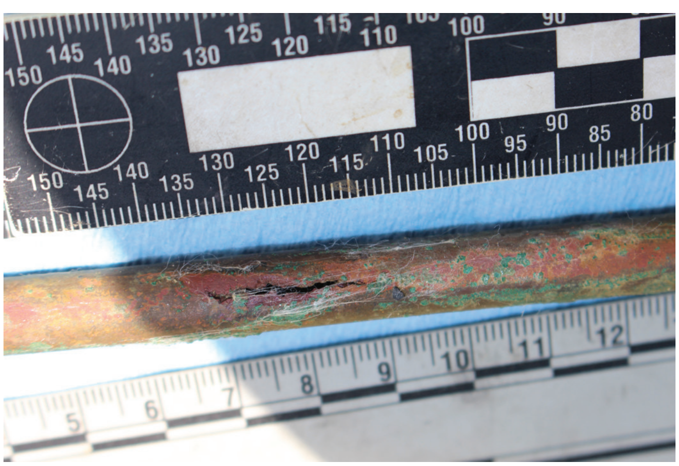

Figure 15
Failure point in liquid line.

Figure 16
X-ray image of failure point bulge.

P_o = initial pressure in the enclosure

P = deflagration pressure at time t

n_b = number of moles of burned gas at the completion of the deflagration

n_o = number of moles of gas-air mixture initially in the enclosure

T_b = temperature of the burned gas at the completion of the deflagration

T_o = initial temperature of the gas-air mixture

m_b = mass of burned (propane) gas in the enclosure at time t

m_o = total mass in the enclosure

The entire room volume need not have a fuel-air mixture within the flammable concentration range for an explosion to occur. A portion of the room volume within the flammable concentration range and the introduction of a competent ignition source into that region is sufficient to cause a damaging explosion. Worst-case overpressure scenarios with fixed available fuel quantities involve stoichiometric (optimum) fuel-air mixtures — whether the mixture occurs in only a portion of the room or throughout the entire room.

In considering a limited amount of fuel-gas discharged into a large fixed volume space, the fuel mass available from the discharge for a stochiometric mixture to occur in *part* of the space is compared to the total mass necessary for the entire room to reach stochiometric mixture conditions. The problem is essentially identical to the *Example 3* problem involving a small butane gas release into a fixed volume room presented in the SFPE Handbook *Section Three Hazard Calculations*, page 3-410 — except the current problem involves propane. Properties for propane and air relevant to the calculations can be found in Table C.1 of the SPFE Handbook. The enclosure volume of the interconnected rooms for the case in question was 3,394 ft^3 (96 m^3).

Following *Example 3* given in the SFPE Handbook, the room mixture (air and propane) molecular weight, M_{mix} is calculated (see Equation 3 below) based on the stoichiometric concentration of propane (4.02 volume percent).

(3) $M_{mix} = x_{propane}M_{propane} + (1\text{-}x_{propane})M_{air}$

Therefore, M_{mix} = (0.0402)(44.1) + (1-0.0402)(28.8) = 29.4

From this, the mixture density, ρ_o is calculated as:

$\rho_o = M_{mix}P_o / RT_o$ where R is the ideal gas constant.

Therefore, ρ_o = (29.4)(101 x 103 Pa) / (8314 J/kmol-K)(298 K) = 1.2 kg/m^3

The SFPE Handbook then calculates m_o as follows:

(4) mo = $[(x_{propane})(M_{propane})/(M_{mix})]\rho_o V$, where V equals the room enclosure volume

Therefore, for the case in question, m_o = [(0.0402)(44.1)/(29.4)](1.2 kg)(96) = 6.95 kg

One cup of liquid propane is approximately 0.2625 lbm or 0.119 kg. Assuming approximately 1 cup of liquid propane flash vaporizes, disperses into the air of the enclosure, and forms a localized stoichiometric mixture, Equation 2 can be used to determine the overpressure as:

$P\text{-}P_o = (m_b/m_o)\ (P_m\text{-}P_o)$

The quantity P_m - P_o (or P_{max}) can be obtained from the SFPE Handbook Table 3-16.3 for propane.

Therefore $P\text{-}P_o$ = (0.119 kg / 6.95 kg)(7.9 bar) = 0.1353 bar g (2 psig)

Doubling the quantity of gas discharged and dispersed (i.e., 2 cups or 0.5250 lbm) to a stochiometric mixture produces an overpressure of 4 psig.

Based on the size of the heat pump unit and the R-22 refrigerant charge specifications, the heat pump and piping would hold an equivalent propane charge exceeding approximately 2.5 pounds.

In regard to damaging overpressures, NFPA 921 Section 23.14.4.1.6 and Table 23.14.4.1.5 (b) provide (in part) that:

> *...Generally, one can expect peak overpressure of 7 kPa to 14 kPa (1 psi to 2 psi) to cause the failure of most light structural assemblies....*

The table further indicates that "minor structural damage" occurs at an overpressure of just 0.4 psi; the "shattering of glass windows" between 0.5 to 1.0 psi; the "partial demolition of houses" at 1.0 psi; and the "partial collapse of walls and roofs of houses" at 2.0 psi.

As can be seen, the available quantity of propane in the heat pump unit was more than capable of producing the explosion overpressure damages observed to the building. In fact, only a fractional amount of the available gas in the heat pump needed to be released and mixed locally around the return air grille and thermostat at the time of the ignition to cause the observed damage.

Source of Ignition

The source of ignition of the fugitive propane gas that accumulated in the building (specifically around the thermostat and the occupant) was determined to most likely be a parting arc generated when the thermostat was switched to the off position. Evidence of melt damage due to typical parting arc activity was observed on the contact pads inside the thermostat. Furthermore, the explosion occurred at the moment the thermostat was switched by the occupant.

NFPA 921 provides useful information related to parting arcs as an ignition source. See, for example, NFPA 921 Sections 9.9.4 Arcs and 9.9.4.4 Parting Arcs. In addition, NFPA 921 Section 26.5.3.1.1 further discusses switches creating parting arcs.

Underwriters Laboratories, Inc., in an extensive whitepaper[5] entitled "Revisiting Flammable Refrigerants" provides a useful discussion related to potential ignition sources of flammable refrigerants within HVAC equipment and appliances, including hot surfaces and parting arcs occurring at contacts, switches, temperature, and humidity controls.

Occupant Burn Injuries

Another question presented for partial (non-medical) evaluation involved the sufficiency of the briefly ignited propane fuel gas to cause occupant burn injuries. The explosion overpressure damage and origin (vector diagram analysis), witness observations (pressure and flame front directions), and burn injuries to the occupant indicated the occupant was standing in a cloud of propane gas and impacted by a flame front. The occupant was wearing only pajama pants with no shirt and no shoes or socks. Therefore, he had substantial exposed skin, and sustained primarily first and second degree burn injuries with some limited third-degree burn injuries to approximately 40% of his body. A combustion explosion such as this results in the burning of accumulated fuel gases via a propagating flame front, subjecting persons in the path of the flame front (although briefly) to the potential for burn injuries. The injuries the occupant sustained were consistent with those outlined and described in NFPA 921 Section 25.2.10.3 *Thermal Injuries*, for the conditions and low-order explosion that occurred.

The flame front produced in the subject low-order explosion incident was similar to that of a flash fire as defined in NFPA 921 Section 3.3.81, except there was sufficient fuel present to cause damaging overpressure to the structure. Flash fires are well-recognized events in which exposed persons can be subjected to serious burn injuries or death. For example, Neal and Lovasic[6] report that:

> *In spite of significant progress in reducing industrial flash fire hazards, thousands of second and third degree burn injury cases occur in the workplace each year in North America (1). These injuries result from the exposure of workers to the intense radiant and convective energy resulting from a flash fire incident. Flash fire exposures are usually of sufficient intensity and duration to ignite conventional work clothing and burn unprotected (bare) skin.*

The occupant's burn injuries were consistent with the circumstances of the incident.

Regulations, Codes, and Standards Violations

Propane is an ASHRAE Safety Group A-3 refrigerant; therefore, it is subject to substantial restrictions and limited use. Use of propane as a refrigerant in split system heat pumps in apartment complexes, such as the one in question, is prohibited by the Environmental Protection Agency (EPA) and violates provisions of the International Fire Code (IFC) and the International Mechanical Code (IMC). Therefore, it also violated provisions of the Georgia State Minimum Fire Safety Standards. In addition, the use of propane as a refrigerant in the HVAC system and the building occupancy group in the subject case violated established reasonable industry safety standards.

EPA

At least eight months prior to the explosion, the United States Environmental Protection Agency had issued warnings[7] regarding the use of unapproved flammable refrigerants. Excerpts of the release are as follows [underlined emphasis added]:

> ***EPA Warns Against Use of Refrigerant Substitutes That Pose Fire and Explosion Risk. Release Date: 07/01/2013***
>
> ***WASHINGTON*** *– The U.S. Environmental Protection Agency (EPA) is warning homeowners, propane manufacturers and sellers, home improvement contractors and air conditioning technicians of potential safety hazards related to the use of propane or other unapproved refrigerants in home air conditioning systems.*
>
> *At this time, EPA has not approved the use of propane refrigerant or other hydrocarbon refrigerants in any type of air conditioner....*

Georgia State Minimum Fire Safety Standards

At the time of the accident as well as many years prior to the explosion, the state of Georgia had directly adopted minimum fire safety standards[8] that specifically addressed the use of flammable refrigerants. These standards prohibited the use of such refrigerants in systems such as the one in question. A primary purpose of the Georgia State Minimum Fire Safety Standards is: *to establish the state minimum fire safety standards and requirements for the prevention of loss of life and property from fire, panic from fear of fire, explosions or related hazards in all buildings, structures and facilities….[120-3-3-.01(2)]*

IFC, IMC and ASHRAE

As part of accomplishing that purpose, *The Georgia State Minimum Fire Safety Standards* directly adopts the International Fire Code (IFC)[9] and the International Mechanical Code (IMC)[10] with Georgia modifications. The IMC, in turn, references and incorporates provisions of the American Society of Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) Standards 15 (2010) *Safety Standard for Refrigeration Systems*[11] and 34 (2010) *Designation and Safety Classification of Refrigerants*[12].

Among other topics, the IFC provisions address existing conditions, operational and maintenance provisions of properties and equipment (including apartment complexes), and HVAC systems at those facilities. The IFC provides specific definitions related to occupancy classifications, mechanical systems (including HVAC systems), and refrigerants. Of particular interest is the IFC provision related to changing the refrigerant type in an existing system, which states [underlined emphasis added]:

> *606.4 Change in refrigerant type. A change in the type of refrigerant in a refrigeration system shall be in accordance with the International Mechanical Code.*

As previously noted, the IFC applies to existing buildings, existing systems, and operations — and the maintenance of systems within buildings, including HVAC systems. IFC 606.4 specifically stipulates that a change in the type of refrigerant be in accordance with the IMC, which provides extensive provisions related to the use of refrigerants and particularly flammable refrigerants. Additional useful insight into the code provisions are often found in the commentary associated with the code. Some of the relevant excerpts of the IMC, as modified by the state of Georgia along with the associated code commentary, are provided below [underlined emphasis added]:

> ***SCOPE:***
> *The provisions of the Georgia State Minimum Standard Mechanical Code shall regulate the design, installation, maintenance, alteration and inspection of mechanical systems*
>
> [Code Commentary] *Chapter 11 Refrigeration:*
>
> *General Comments*
> *The purpose of this chapter is to regulate the use of refrigerants and protect refrigeration systems, property and life from the hazards associated with the refrigerants and their related equipment. The hazards include,… flammable and decomposing effects of refrigerants.*
>
> *Refrigerants create a hazard because they are liquefied gas under pressure in a mechanical system and many refrigerant vapors cannot be seen, tasted or smelled, so there is no natural warning of a hazard occurring.*
>
> *Building damage includes, but is not limited to, fires, explosions and loss of property… .*
>
> *Some refrigerants, when combined with air at atmospheric pressure, ignite causing a flame and possibly an explosion (flammable).*

IMC Chapter 11 Section 1101.7 and associated commentary provide:

> *1101.7 Maintenance. Mechanical refrigeration systems shall be maintained in proper operating condition, free from…leaks.*

> [Code Commentary] *Periodic maintenance is essential for the proper operation of mechanical refrigeration equipment…. In essence, if the refrigerant stays contained in the refrigeration system, the hazards to occupants and the environment are greatly reduced; the hazards increase when the refrigerant becomes exposed outside of the system, often quickly and unexpectedly.*

As previously mentioned, refrigerant line failures are engineering-foreseeable events, and the codes recognize the hazards associated with the rapid release of refrigerants, particularly flammable refrigerants. IMC Section 1102.2 stipulates the refrigerant that is placed into equipment be that which the equipment was designed for — or that the equipment be properly converted to use another refrigerant. The HVAC unit in question was manufactured and designed for use with R-22, and there was no acceptable or approved method for converting it to use with R-290 (propane) or any other flammable refrigerant.

The IMC Section 1103.1 requires that refrigerants be classified in accordance with ASHRAE 34. The IMC commentary for Section 1103.1 provides:

> *Because the classification of refrigeration systems is a necessary step in the application of Section 1104, the code addresses the hazards of refrigeration systems to building occupants by considering three things: the type of refrigerant, the type of system (Section 1103.3) and the type of building occupancy (Section 1103.2). Certain systems are more hazardous in terms of possible exposure to escaping refrigerants (see commentary, Section 1103.3). Certain occupancies are more hazardous in terms of the number of people who could be exposed or who are, for various reasons, particularly susceptible to injury because of disability, detention or incapacity (see commentary, Section 1103.2).*

Section 1103.2 of the IMC provides occupancy classification definitions and descriptions. The occupancy of the subject case is a multiunit apartment. Section 1103.3 of the IMC provides system classifications as it relates to the type of HVAC or refrigeration system. The code commentary for 1103.3 provides additional insight into the hazard considerations for the various types of systems. Section 1103.3 and the associated commentary provide [underlined emphasis added]:

> *1103.3 System classification. Refrigeration systems shall be classified according to the degree of probability that refrigerant leaked from a failed connection, seal or component could enter an occupied area. The distinction is based on the basic design or location of the components.*

> [Code Commentary] *Direct systems have coils containing primary refrigerant over which the room air passes. A leak in the heat exchanger could place refrigerant directly in the occupied space. Such systems are high-probability systems… .*

> *1103.3.2 High-probability systems. Direct systems… shall be classified as high- probability systems.*

> [Code Commentary] *In a high-probability system, chances are good that system leakage would expose building occupants to a refrigerant…*

> *…The typical split system heat pump; DX coil in an air handler, furnace or split system air conditioner; package terminal units and window air conditioning units are all high-probability systems.*

As noted in the code and code commentary above, the system in question would be classified as a high-probability system because the chances are good that system leakage would expose building occupants to refrigerant. Although not a leak in the coil, the effect is the same in that a leak in the PVC-encased refrigerant lines resulted in a direct discharge of propane refrigerant into a location with multiple sources of ignition.

IMC Section 1104.3 identifies restrictions on types and quantities of refrigerants allowed in various system types and occupancy types specifically for the purpose of limiting risk of fires and explosions. The permissible quantities are based on the safety group classifications located in ASHRAE 34. For the case in question, Section 1104.3.2 and its associated commentary are of interest [underlined emphasis added]:

> *1104.3.2 Nonindustrial occupancies. Group A2 and B2 refrigerants shall not be used in high-probability systems where the quantity of refrigerant in any independent refrigerant circuit exceeds the amount shown in Table 1104.3.2. Group A3 and B3 refrigerants shall not be used except where approved.*

> [Code Commentary] *This section applies to all occupancies other than industrial occupancies….Group A3 and B3 refrigerants are the most flammable and therefore can be used only in industrial occupancies and where specifically approved by the code official.*

As previously mentioned, propane is a Group A3 refrigerant; therefore, it is not permitted to be installed except where approved. The equipment manufacturer in question did not approve propane refrigerant for the equipment in question. In addition, neither the federal, state, or local authorities having jurisdiction (code officials) specifically approved propane for use in the equipment in question. The provisions of ASHRAE Standards 15 and 34 detail similar provisions regarding the use of flammable refrigerants and the associated hazards.

Underwriters Laboratories, Inc.

As previously referenced, in 2011, Underwriters Laboratories, Inc. issued a comprehensive whitepaper, *Revisiting Flammable Refrigerants*, addressing historical as well as important hazard issues associated with flammable refrigerants. The paper examines fire and explosion hazards as well as codes and standards issues as they relate to flammable refrigerants. A section entitled "The Challenges Posed By Flammable Refrigerants" notes that historically:

> *…Because the typical HVAC and appliance refrigerant gas (excluding ammonia) was non-toxic in the volumes used and non-flammable, the potential for gas leakage or explosion was not considered to be a safety concern, except under fire conditions… .*

> *Aside from locations where large quantities of refrigerant might be found (e.g., large commercial/industrial facilities), there has been limited concern for the safety of refrigerant-containing appliances in all manner of occupancies…*

The paper then contrasts traditional refrigerants with hydrocarbon refrigerants by warning of the fire and explosion hazards generated in the event of a flammable refrigerant leak. The hazard is significant given the likely proximity to ignition sources. The paper notes that [underlined emphasis added]:

> *Hot surfaces and electrical arcs, such as those present at the contacts of electrical switching contacts (switches, temperature and humidity controls, etc.), are the principle potential ignition sources in HVAC and appliances….*

> *Small quantities of flammable refrigerant discharged into an open area may disperse at a rate that ensures that the LFL is not achieved or is achieved for a very brief time period. However, for larger quantities of refrigerant, or in situations in which the leaked refrigerant is contained in a smaller volume space or in which the leaked refrigerant accumulates (e.g., heavier than air refrigerant), it is more likely that the LFL can be reached and sustained. [pp. 3-4]*

In the subject case, the leaked propane refrigerant discharged and accumulated into a small mechanical closet and then into the volume area directly around the occupant and the thermostat via the non-ducted return grille. The UL paper continues by discussing the challenges related to the transition of using more environmentally preferable refrigerants (including potentially flammable refrigerants) in appliances. Among the challenges are those involving installation and equipment standards. In that regard UL notes that:

> *…In the U.S., UL is the principal standards developer addressing electrical appliance and HVAC equipment safety. UL standards are part of an overall safety system of coordinated standards and codes to facilitate safe installation and use of equipment…*

> *ANSI/UL 1995, Standard for Safety for Heating and Cooling Equipment*

> *The standard is applicable to stationary equipment for use in nonhazardous locations… Cooling equipment examples include heat pumps, air conditioners,… condensing units, … and fan coil units. Currently, the standard does not address the subject of flammable refrigerants, which should be construed to mean that flammable refrigerants (aside from ammonia) are not permitted, an interpretation consistent with ASHRAE Standard 15.*

Conclusions

NFPA 921 defines the cause of a fire or an explosion as "*the circumstances, conditions, or agencies that brought about or resulted in the fire or explosion incident, damage to property resulting from the fire or explosion incident, or bodily injury or loss of life resulting from the fire or explosion incident*." The cause of the explosion was the arc ignition of accumulated fugitive propane vapors originating from the failed refrigerant line. Charging the split system residential heat pump of apartment unit P-3 with unapproved/unauthorized highly flammable/explosive propane refrigerant violated minimum adopted codes, standards, and safe industry practices. Had these codes and standards not been violated, the explosion would not have occurred.

Propane gas has a very low ignition energy requirement and subsequently can be ignited from most normally present ignition sources located within buildings. If there is an explosive concentration of fugitive propane gas in a building, it is very difficult to avoid contact with normally present ignition sources. Subsequently, the potential for a catastrophic explosion is substantial. The codes, standards, and industry literature note the foreseeability of refrigerant leakage in HVAC systems. Therefore, the use of highly flammable refrigerants is severely limited due to the high risk of a fire or explosion occurring.

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