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‡ Paper presented at the NAFE seminar held 1/14/17 in New Orleans, LA

* Paper presented at the NAFE seminar held 7/22/17 in Atlanta

Forensic Engineering Analysis of an Apartment Building Explosion Involving Flammable Refrigerant

By Jerry R. Tindal, PE (NAFE 642S)

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**.

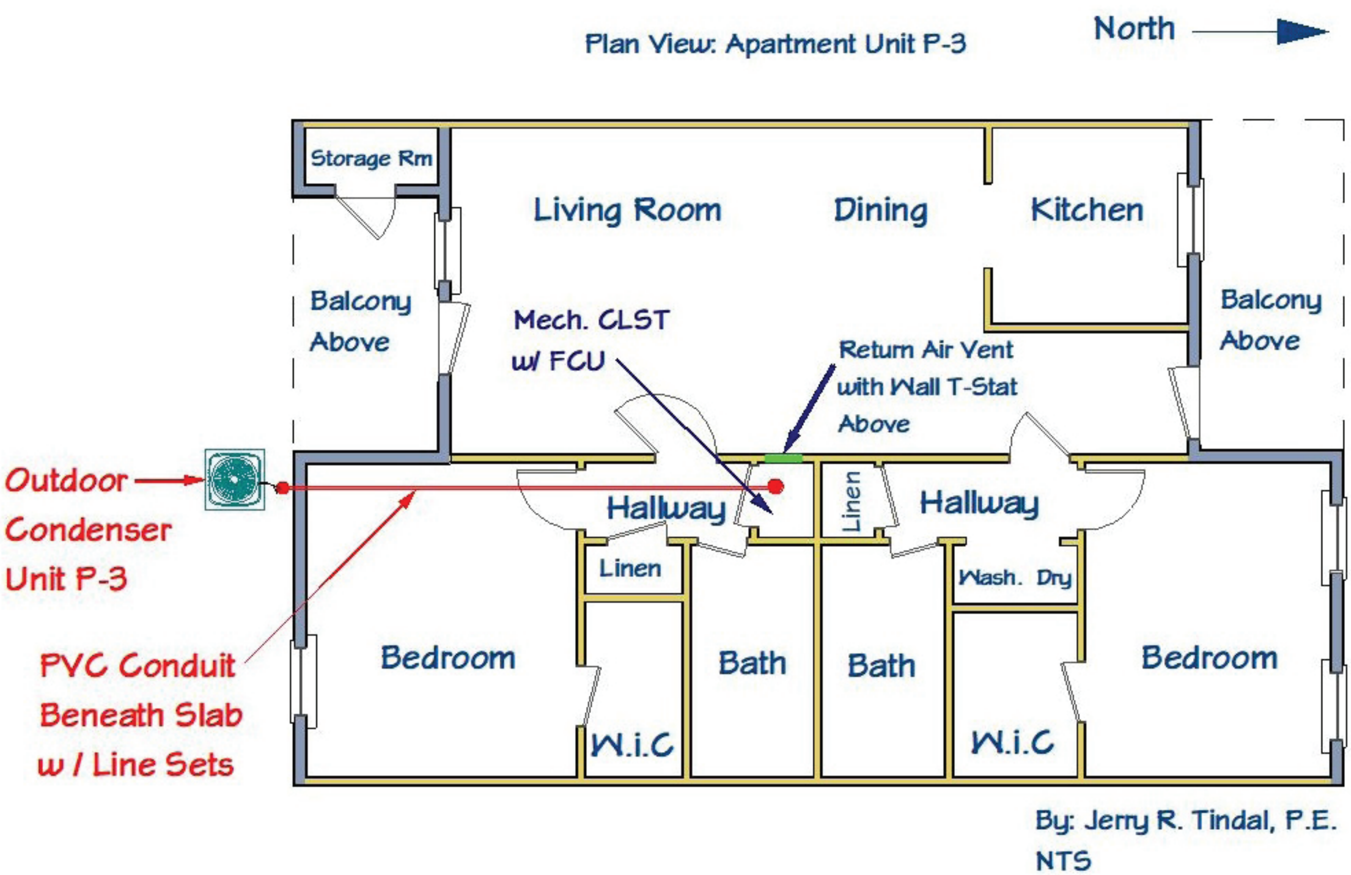

Figure 3
Floor plan of apartment unit P-3.

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.

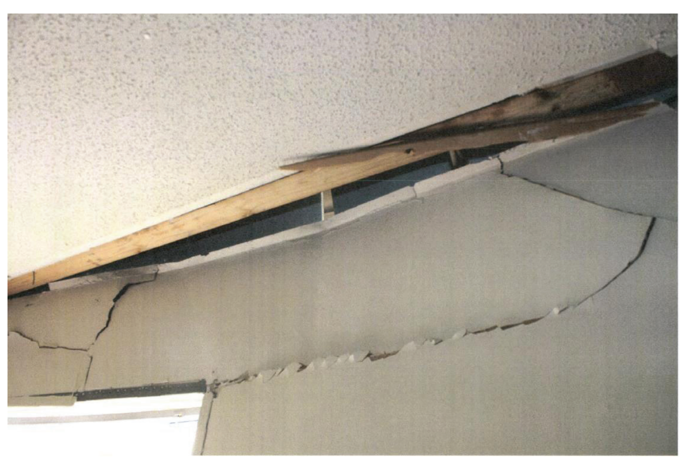

Figure 9
Wall / ceiling joint separation.

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 11
Exterior walls dislodged.

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

Figure 13
HVAC vent deformation and dislodgement.

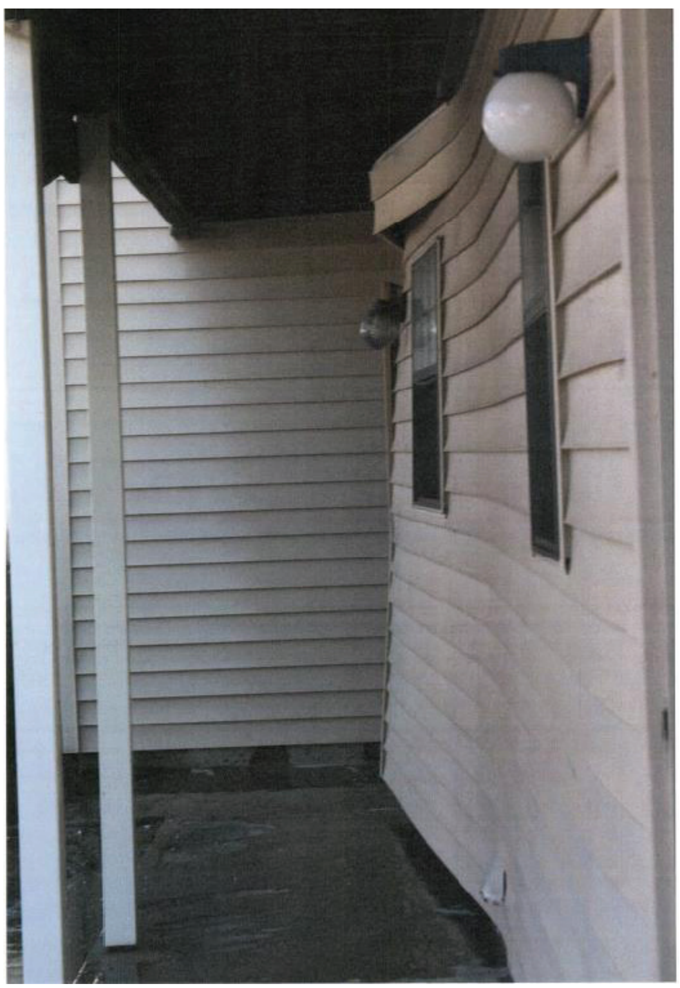

Figure 10
Exterior walls dislodged.

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

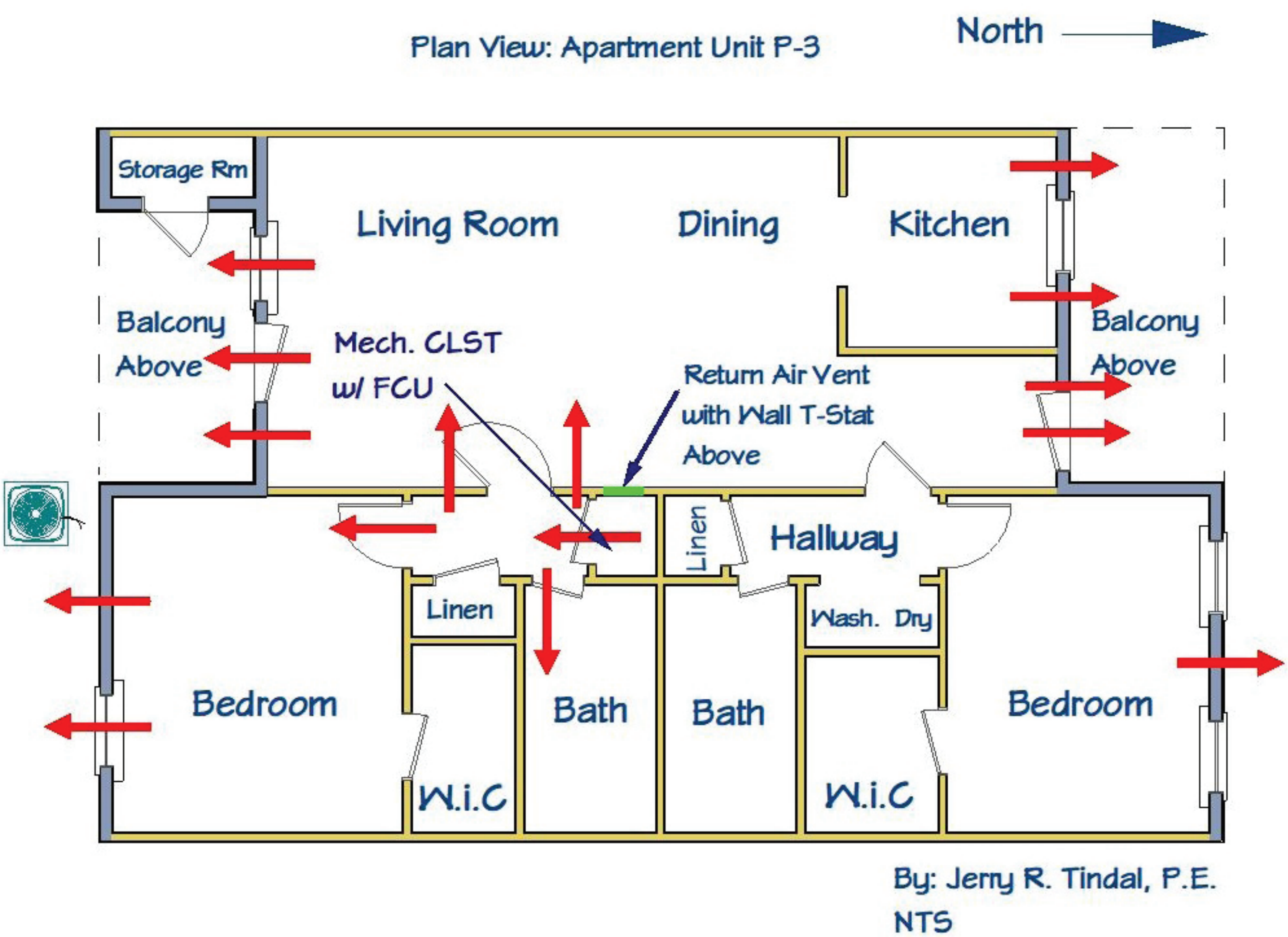

Figure 14
Explosion vector diagram.

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

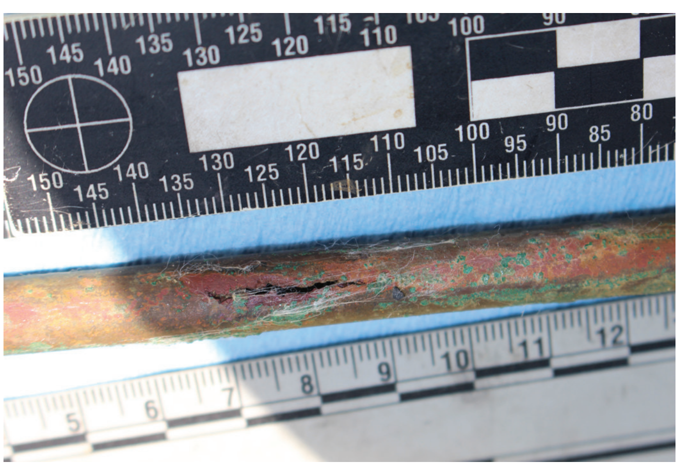

Figure 15
Failure point in liquid line.

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

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:

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

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

Therefore $P-P_o$ = (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.

References

1. NFPA 921-2014. Guide for fire and explosion investigations. Quincy, MA; National Fire Protection Association.

2. Pape R, Mniszewski K. Computational fluid dynamics methods of calculating gas dispersion in a building or outside as a result of gas leaks. Paper presented at: Natural Gas & LP Coordination Conference & Exhibition; 2005 Jul 25-27.

3. Filippo G, Davis S, Hansen O. A modern tool for the investigation of indoor flammable gas migration. Proceedings of the International Symposium on Fire Investigation Science and Technology. University of Maryland, University College. 2010; 243-254.

4. Society of Fire Protection Engineers. The SFPE Handbook of Fire Protection Engineering, 3rd Edition. Quincy, MA: The National Fire Protection Association; 2002.

5. White Paper: Revisiting Flammable Refrigerants. Underwriters Laboratories, Inc.; 2011, https://bit.ly/2DfPhN1.

6. Neal T, Lovasic S. Industrial flash fire and burn injury fundamentals with an instrumented manikin demonstration of protective clothing performance. Proceedings of the American Society of Safety Engineers Professional Development Conference and Exposition, 2002 June 9-12: Nashville, Tennessee.

7. EPA warns against use of refrigerant substitutes that pose fire and explosion risk. News Releases issued by the Office of Enforcement and Compliance Assurance. [accessed October 8, 2018] https://tinyurl.com/yc8mkc3e. Release Date: 07/01/2013.

8. Rules and Regulations for The State Minimum Fire Safety Standards effective 03-09-2010. Georgia Office of Insurance and Safety Fire Commissioner. [accessed October 9, 2018] https://bit.ly/2RHrtFO.

9. International Fire Code. Country Club Hills, IL: International Code Council; 2006.

10. International Mechanical Code. Country Club Hills, IL: International Code Council; 2006.

11. ASHRAE 15-2010. Safety Standard for Refrigeration Systems. Atlanta, GA; American Society of Heating Refrigeration and Air-Conditioning Engineers.

12. ASHRAE 34-2010. Designation and Safety Classification of Refrigerants. Atlanta, GA; American Society of Heating Refrigeration and Air-Conditioning Engineers.

Forensic Engineering Analysis of Test Equipment Manufacturing Capability in a Business Purchase Dispute

By Robert O. Peruzzi, PhD, PE (NAFE 954A)

Abstract

A privately owned semiconductor test equipment company was sold by its U.S. domestic owners (seller) to a purchaser having an overseas manufacturing location (buyer). The sale was to take place in several stages. The buyer asserted that when the agreement was made he was unaware that the seller's flagship product was being rejected by customers for not meeting specifications. When this came to light, the buyer refused to continue with the second and subsequent stages of purchase. The seller then sued the buyer for not complying with the agreement, and the buyer counter-sued for fraudulent deception. The author was retained by the buyer's attorney to review specification documents regarding the product, due diligence reports, and e-mail chains regarding product quality, field returns, and repairs.

Keywords

Forensic engineering, semiconductor, semiconductor wafer, integrated circuit, IC, IC test, automatic test equipment, ATE, wafer, chip, die, wafer test, wafer probe, probe-card, vertical probe

Introduction

This case relates to equipment used for testing an integrated circuit (IC) during its manufacture while it is still part of a semiconductor wafer. As background, an individual, bare, unconnected, integrated circuit is called a die (plural, dice). Each die is separately tested while still part of the wafer. A wafer-probe gets its name from the procedure of lowering needle-like metal probes onto the die where they pierce the surface of bump-like solder connection pads on the die to make electrical contact between the tester and circuitry on the die. The collection of probes and associated hardware is referred to as a " probe-card." A custom probe-card is designed for each IC product. Custom software controls general-purpose automated test equipment (ATE) for testing each IC product.

The very first wafer-probe test validates contact — electrical continuity between the tester and the die. Following the contact test, typically thousands of additional tests are performed on each die. When final testing is completed, the probes are lifted, and the wafer is shifted to bring the next die under the probes. The sequence of probe/test/shift is repeated until each die on the wafer has been tested.

After wafer-probe, the wafer is singulated (cut up) into individual dice. Those that failed wafer-probe are discarded; those that passed are mounted into packages. A finished IC package includes the die and connecting wires from the die to pins on the outside of the package.

The seller's company designed, manufactured, and sold probe-cards to semiconductor manufacturing companies. Early in its history, the seller's product was uniquely innovative and captured the lion's share of the probe-card market. After its leadership position was lost, financial difficulties ensued. As a result, the seller sold the company to the buyer. For multiple reasons, the buyer decided not to finish the purchase after the first stage of a multi-stage transfer. The two parties were not able to settle the dispute; therefore, the seller sued the buyer to force completion of the purchase.

Overview of Integrated Circuit Design, Fabrication, Testing, and Packaging

Integrated circuits contain highly concentrated

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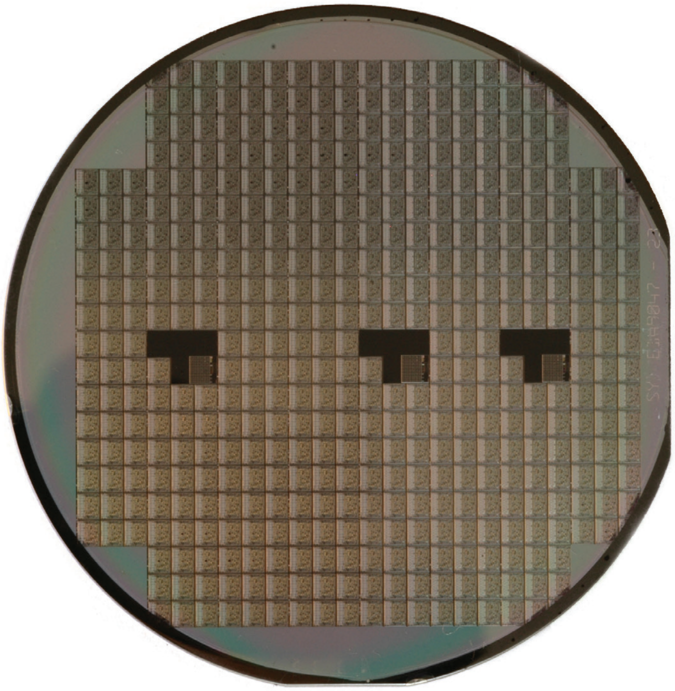

Figure 1
A semiconductor wafer with fabricated IC dice[4].

electronic equivalents of discrete components, such as resistors, transistors, capacitors, and inductors.

Figure 1 shows a finished semiconductor wafer with an array of IC dice visible on its surface. A diameter of 300mm is a typical wafer size[1]. Typical die sizes can range from about 2 by 2mm to 20 by 20mm^2. A typical package size for the types of ICs in this case[3] is about 40mm^2.

A critical part of the design process is to choose the physical location of IC input and output (I/O) pads on the surface of the die. Early integrated circuits placed I/O pads on the perimeter of each die. As more circuitry and I/O were added to ICs, the dimensions of the chip were governed by the perimeter length, which, in turn, was governed by the number of I/O. Valuable area on the inside of the die was wasted. By the early 1990s, the ball grid array packaging technique made it possible to design a two-dimensional array of hemispherical connecting pads distributed across the surface of the die. Ball grid array (BGA) I/O enabled the number of connecting pads to increase from hundreds to thousands. **Figure 2** illustrates BGA solder bumps. **Figure 3** shows BGA solder bump connectors[5]. In contrast, **Figure 4** shows an IC with all bond pads on its perimeter[6].

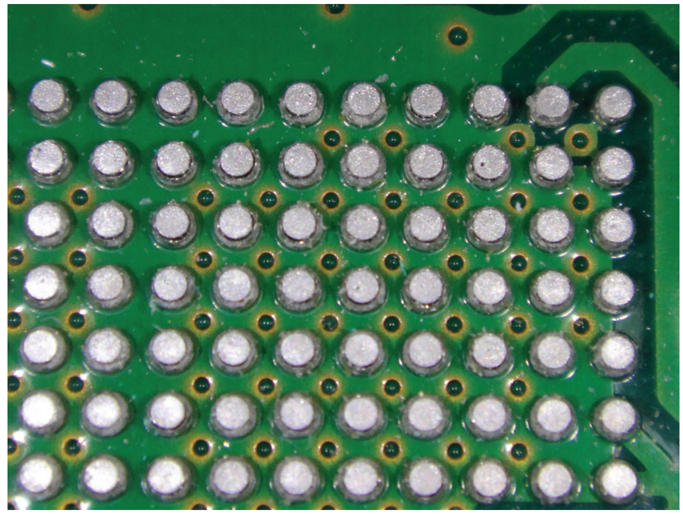

Figure 3
Close-up of solder bumps[8].

Figure 5 is an overhead photograph of a probe-card used for testing dice with peripheral bonding pads. This probe-card is typically about 6 inches in diameter. So-named cantilever probes extend from the perimeter of the empty square area in the center to a circular support ring where they attach to the copper-color wires connecting to printed circuit board traces. The PCB traces extend

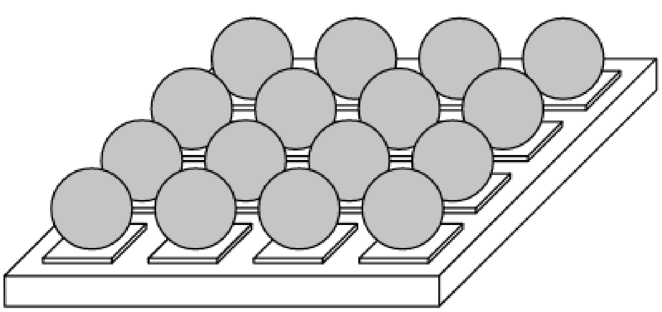

Figure 2
Illustration of a solder bump matrix[7].

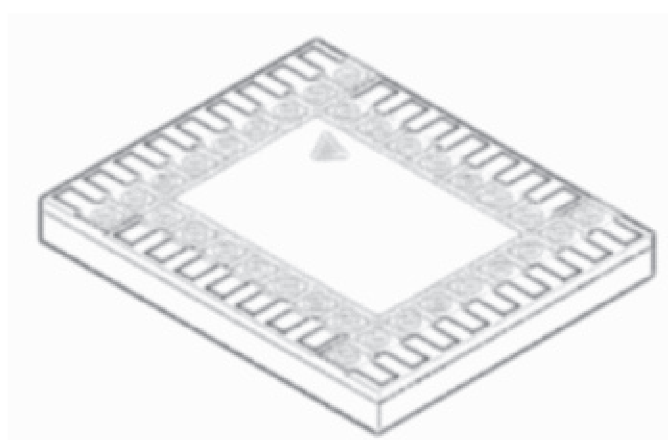

Figure 4
IC die with peripheral bonding pads[9].

Figure 5
Probe-card with cantilever probes for an IC with perimeter bond pads[10].

out to the circular ring of connecting pins that connect to the ATE drive/receive pins. The circular array of circular holes is for fasteners.

Figure 6 is a side-view diagram of a cantilever probe-card. It is the springy characteristic of bending the probes (one is encircled) that allows a controlled force and good electrical connectivity between the probe tip and the bond pad on the die.

In action, these probe elements “touch down” on the probe-pads of each die on the silicon wafer to test the die. The ATE applies voltage to the power supply pads to power up the chip. The ground pads on the chip are connected to a controlled zero-volt reference. The ATE sends test signals through the probe elements to the signal-input bond pads to stimulate the IC. The IC’s response signals are conducted back through the output bond pads, through the probes, and ultimately back to the tester. The output signal detected by the tester is compared to what is expected to determine if a given test passes or fails. If all tests pass, the IC is judged to be “good.” If any test fails, the IC is judged to be “bad.”

Specifics of the Business Dispute

According to discovery documents, during a business downturn (when the seller was in research and development mode), the decision was made to reduce the workforce. Internal memos and emails describe the resulting malaise that spread to core design team members. Certain key team members decided to retire or otherwise leave the company (or the industry as a whole). Despite the pressure on the engineers who stayed to complete the next-generation flagship product on time, the new product line ended up late to market.

Discovery documents showed that the new product received mixed reviews from initial customers. Customer feedback was that it proved satisfactory for testing the existing generation of customer ICs. But, as far as performance went, it did not make the desired leapfrog into the next technology. Large-volume IC manufacturers were demanding this performance.

Multiple discovery documents revealed that the seller’s latest generation probe-cards did not have adequate positional stability over time, temperature, and repeated usage. Not all the probes were reliably contacting all the solder bumps. After testing some number of dice on some number of wafers, contact tests would begin to fail

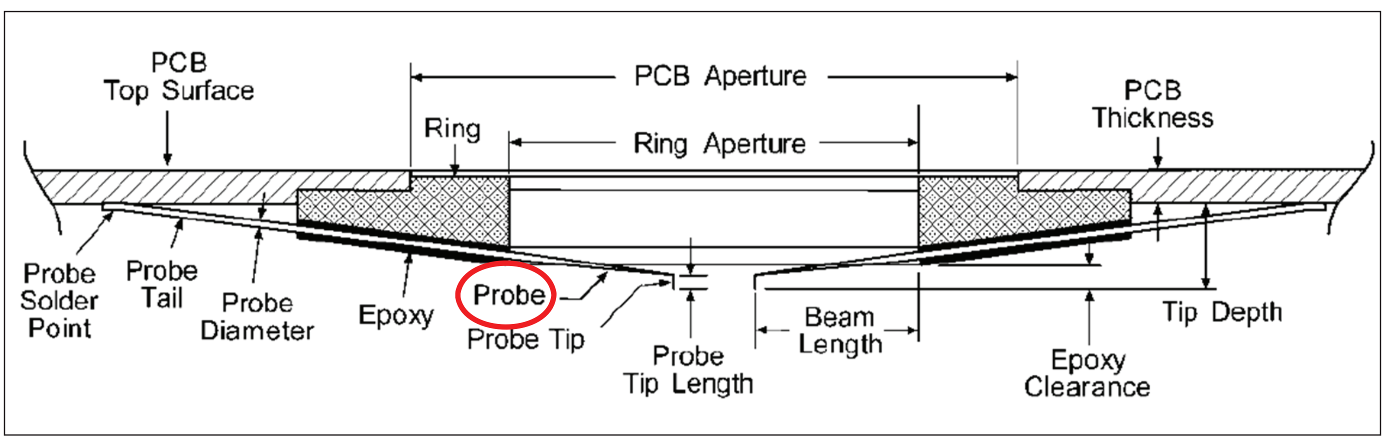

Figure 6
Cantilever probe-card, side view diagram[11]. *Diagram Copyright (C) Tektronix. Reprinted with permission. All Rights Reserved.*

more frequently. Testing ICs at 125°C was required by the seller's customers for certain military and consumer products. High-temperature testing resulted in contact failures occurring more frequently and after probing a smaller number of dice successfully.

A competing probe-card vendor's design team was able to solve the technology challenges for its new generation of probe-cards, and successfully shut the seller out of the market. The revenue increase expected from the new product line did not appear. Discovery documents included exchanges internal to the seller's executives leading up to the decision to sell the business.

A willing buyer was found overseas — a company that was experienced in IC testing products and wished to expand into a line of wafer probing equipment, including vertical probe-cards. The transaction was to occur in three stages.

The first stage began and ended with a down payment of $3 million. Upon this stage, the new company name was announced, and manufacturing continued in the seller's existing probe-card foundries with few personnel changes. Beyond the down payment, the buyer agreed to pay royalties to the seller for four years.

The second stage involved three milestones. A total of $2 million would be payable at their completion.

1. Seller's flagship probe-card product line had to be accepted by a certain well-known IC manufacturer (Customer A) for production-testing of its high-speed video processor IC. It had 8,000 solder-bump bond pads on its die. In addition, Customer A required that each die be tested at two temperatures – "ambient" and 125°C.

This first milestone was negotiated to include the words "or equivalent" for the Customer A IC — that is, if the seller could not convince Customer A to purchase its probe-cards to test its video processing chip, then the seller could alternately meet the milestone by selling the probe-card to some other IC manufacturer (Customer B) for testing an "equivalent" IC. However, the definition of "equivalent" was not stipulated in the sales agreement.

2. The second stage 2 milestone was for the seller to construct an assembly line at the buyer's overseas factory for fabricating older-generation probe-cards that were still being sold to IC manufacturers. Probe-card products manufactured on this new assembly line were required to pass all manufacturing tests and be accepted by customers for production testing of their IC products.

3. A final stage-2 milestone was for the seller to send its manufacturing technicians to the buyer's site to train them to take over the jobs they would eventually lose.

The third stage required the seller to construct an assembly line for the flagship probe-card product at the buyer's factory, and train the buyer's technicians in operating and maintaining that line. It required that the probe-cards pass all internal tests and be accepted by Customer A (or alternatively, Customer B) for IC production testing. A total of $1 million was to be paid at the completion of the third stage. Royalty payments from the buyer to the seller, based on total probe-card sales, were to continue until four years from the initial agreement date.

The Timeline, Dispute, and Ultimate Resolution

The buyer only had access to the day-to-day accounting and sales data for the seller after the agreement was signed, at which point the buyer realized that something was wrong. Communications between the seller and customers, including communications between the seller and Customer A that were unfavorable, had been withheld from the buyer during the pre-sale due-diligence period. The buyer now realized that customers were dissatisfied with the seller's latest product. Customers were returning latest generation probe-cards for repair or replacement in higher-than-expected numbers because the probes were not able to successfully test known good IC dice.

Considering each milestone of the second stage:

1. Customer A, the IC manufacturer of the high-speed video processors, did not accept the probe-card after many attempts to debug and redesign the units shipped to them.

At ambient temperature, Customer A was able to test all dice on one wafer. Too soon thereafter, spurious connectivity failures began to occur. A probe-cleaning procedure that normally was executed once per shift had to be executed after testing each wafer. Probe-cleaning (like knife sharpening) removes material from each probe tip, which are only 75 microns wide to begin with. Thus, each probe would have a shorter useful lifetime, adding to the cost of ownership. A second problem was that when testing at 125°C, the probes were not making reliably good contact with all the solder-bump bond pads. Customer A canceled all orders, and began purchasing its probe-cards from a competing vendor for testing its video processor IC.

Upon receiving this news, the seller proposed to the buyer that a different probe-card of its latest product line fulfilled the "or equivalent" wording of the milestone. This probe-card had been accepted by a different manufacturer (Customer B) for testing a different IC. The equivalence, or not, of these ICs became a matter of contention.

2. The seller had agreed to construct the prior-generation assembly line on the buyer's factory floor as a stage 2 milestone.

The seller's documentation was incomplete. E-mails turned over as part of the discovery process showed that the seller's employees searched through electronic documentation and hard-copy paper filing cabinets, but were not able to compile a complete fabrication document package. E-mail trails indicated that during the debug phase of development, ad-hoc changes to the fabrication procedure would be made by key technicians and were not recorded. The fabrication procedures were carried out by the designers and sometimes communicated verbally, if at all, to other technicians.

According to emails and return-documents from the buyer's customers, the probe-cards produced at the buyer's factory were of inconsistent quality and inferior to those produced at the seller's home factory. The conclusion was that the overseas assembly line was not producing probe-cards that could be sold to existing customers.

3. This same installation and production team was tasked with training the buyer's technicians to build, maintain, and operate similar production lines on their own. These trainers understood that they were training the people who would take over their jobs.

Language and cultural barriers impeded communication between the seller's trainers and buyer's employees (students). The incompleteness of fabrication documents added to the difficulty.

The buyer decided to call off the purchase, claiming that none of the three second-stage milestones had been met — that is:

- Customer A did not accept the probe-card. The buyer claimed that Customer B's product was not equivalent to that of Customer A's.
- Probe-cards produced at the buyer's site on the assembly line set up by the seller's installation team were rejected by existing customers.
- The seller's team was not able to train the buyer's technicians to operate (or duplicate) the assembly line at the buyer's factory.

The buyer intended to completely divest itself of any claim to ownership of the seller's company. The buyer did not ask for the return of the $3 million, but did refuse to make the remaining two payments and continue any royalty payments. The seller demanded that the transfer process continue to the third stage. The seller intended to continue to address the buyer's concerns with the second stage. The seller claimed:

- The IC for which the latest generation probe-card had been accepted for testing by Customer B was equivalent to the video processor IC of Customer A.
- The failure of the newly built assembly line was due to the incompetence of the buyer's workers.
- The training given by the team should have been sufficient for a reasonably competent technician.

Negotiations broke down. The seller brought suit against the buyer to pay for stage 2, to allow procedure to stage 3, and for the buyer to continue paying royalties. The buyer counter-sued for misrepresentation and fraud. The buyer's attorney retained the author through an expert witness agency. The author was asked to opine on:

1. The claimed equivalence of the two ICs.
2. The necessity for documentation.
3. The necessity for training.

Claimed Equivalence of the Two ICs

Since the agreement between buyer and seller did not define equivalence of ICs, the author proposed these three criteria:

- Number of pads: From the point of view of probing, the number of solder pads is a key differentiator between ICs.

- Clock rate: Clock rate is a differentiator between ICs. If the contact resistance between the probe and the pad is on the borderline of acceptable/not-acceptable at low clock rates, that same contact resistance may cause functional failures at significantly higher clock rates. In addition, capacitive or inductive cross-talk between probes increases with clock rate. The complexity of probe-card design decisions to minimize cross-talk increases with clock rate.

- Requirement for testing at multiple temperatures: Having multiple required testing temperatures is a differentiator between ICs. Destined to be part of products exposed to an uncontrolled temperature environment, ICs, such as mobile phones and laptops, may be required to be tested at multiple temperatures. Compensating for the change in physical dimensions of probes with temperature, as stated earlier, is one of the challenges of designing probe-cards.

Non-Equivalence of the Two ICs

The author's expert report opined that the two ICs were not equivalent from the standpoint of probing and testing via solder-bump bond pads because:

4. Number of pads: Company B's IC had only 600 bond pads as opposed to 8,000 bond pads in Company A's IC.

5. Clock rate: Company B's IC operates at less than half the clock rate of Company A's IC.

6. Requirement for Testing at Multiple Temperatures: Company B's IC permitted testing only at ambient temperature. Company A's IC specification required testing at both ambient and 125°C.

Necessity for documentation: A complete design document package was not provided by the seller. The author opined that for such a complex endeavor, such as constructing a probe-card assembly line, documentation should specify each construction step and specify incremental tests to validate that each step has been executed properly.

Necessity for training: Training by the seller ended early and was incomplete. Among other training problems, better language translation should have been provided by the seller. The author opined that for such a complex endeavor, such as constructing a probe-card assembly line, training of technicians requires excellent communication skills.

Ultimate Resolution

The expert report was submitted, and the author was deposed by the seller's attorneys. The owner of the seller's company and seller's expert was present at the deposition. The author was asked to be present when the seller's expert was deposed by the buyer's attorney. Within hours of the deposition of the seller's expert, the author was notified that the case had settled.

References

1. Facilities 450mm Consortium (F450C), "Evolution of the Silicon Wafer Infographic," 2018. [Online]. Available: https://bit.ly/2DeGkUn. [Accessed 31 January 2018].

2. C. Maxfield, "How many silicon chips are there on a 300 mm wafer?" EE Times, 28 June 2007. [Online]. Available: https://ubm.io/2Pqy8b6. [Accessed 31 January 2018].

3. U. Pirzada, "Hardware Report: Nvidia GP104 Pascal GPU Spotted on Zauba," 12 January 2016. [Online]. Available: https://bit.ly/2RHRrsS. [Accessed 31 January 2018].

4. B. Jackson, "Moore's Law," Cielotech Online, 10 June 2016. [Online]. Available: https://bit.ly/2AYJIkw. [Accessed 15 June 2017].

5. Integrated Circuit Engineering Corporation, "Chapter 10, GRID ARRAY PACKAGING: BGA AND CSP," National Museum of American History, 15 November 2002. [Online]. Available: https://s.si.edu/2DgvT2O. [Accessed 15 June 2017].

6. E. Bogatin, Roadmaps of packaging technology, Scottsdale, AZ: Integrated Circuit Engineering, 1997.

7. Twisp, "Flip Chip, bumps/solder dots, illustration made for w:Flip Chip," 1 March 2008. [Online]. Available: https://bit.ly/2AZXa85. [Accessed 1 February 2018].

8. Janke, "File:Solder ball grid.jpg," 27 March 2016. [Online]. Available: https://bit.ly/2qEhndq.

[Accessed 1 February 2018].

9. User:ZyMOS, “LAMINATED_UCSP_32L.gif,” 8 May 2006. [Online]. Available: https://bit.ly/2qAERQO. [Accessed 1 February 2018].

10. Rucker Kolls, Inc., “Cantilever,” 2012. [Online]. Available: https://bit.ly/2qEBUhW. [Accessed 19 June 2017].

11. O. Weeden, “Probe Card Tutorial,” Keithly Instruments, Inc., Cleveland, 2003.

Forensic Engineer Expert Communications: Lessons Learned from the March 2014 Oso Landslide Litigation

By Rune Storesund, DEng, PE (NAFE 474C)

Abstract

This paper presents lessons learned following an examination of expert discovery protocols related to the March 2014 Oso Landslide litigation in Washington State. An overview of the March 2014 landslide, its devastating effects, and the formulation of an expert team to evaluate allegations brought forth in the litigation are discussed. Challenges associated with developing the expert opinions in this case are reviewed, a chronology of expert disclosure protocols are discussed, and the court's interpretation/response is outlined. Finally, specific lessons are presented to inform future forensic evaluations requiring communication between expert team members. The controversy associated with disclosure protocols resulted, in part, with the State of Washington settling the case and not going to trial with the accumulated evidence addressing the plaintiff's allegations.

Keywords

Discovery, disclosure, expert teams, landslide, forensic engineering

March 2014 Landslide

In the morning of March 22, 2014, a deadly landslide emanated from the slopes above the north side of the North Fork of the Stillaguamish River, crossed the river, and ripped through the village of Steelhead Haven, Washington, which is located on the south side of the river. Tragically, this resulted in 43 fatalities. Steelhead Haven is located in Northern Washington State, approximately 60 miles north of Seattle in Snohomish County (**Figure 1**). This area has known landslide activity from the slopes above the river on both the north and south sides, which can be seen as physical expressions of the ground contours in aerial LiDAR-based digital elevation models available before the March 2014 landslide (**Figure 2**).

Based upon a review of available aerial photographs, previous landslides near Steelhead Haven occurred in 1951, 1967, 1988, 1996, and 2006. The 1967 and 2006 events were large enough to cross the North Fork of the Stillaguamish River and intrude into the Steelhead Haven neighborhood. Until the March 2014 landslide event, it was largely believed, based on available analyses and reports[1,2,3,4], that the most "probable worst-case" future event would be one equivalent in runout extent to the 1967 landslide event. In 1967, only a few uninhabited vacation cabins were destroyed, and these parcels were never redeveloped ("undeveloped" lots shown in **Figure 3**). The 2006 event was similar in magnitude to the 1967 event, which furthered the belief that the 1967 event was a "probable worst-case" future event.

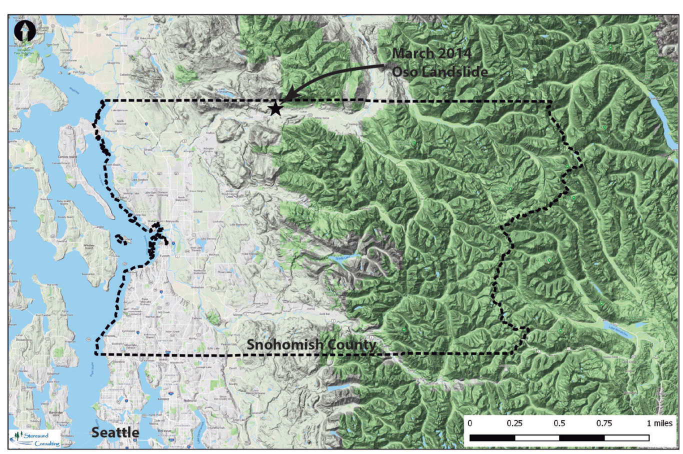

Figure 1
Oso landslide located approximately 60 miles northeast of Seattle.

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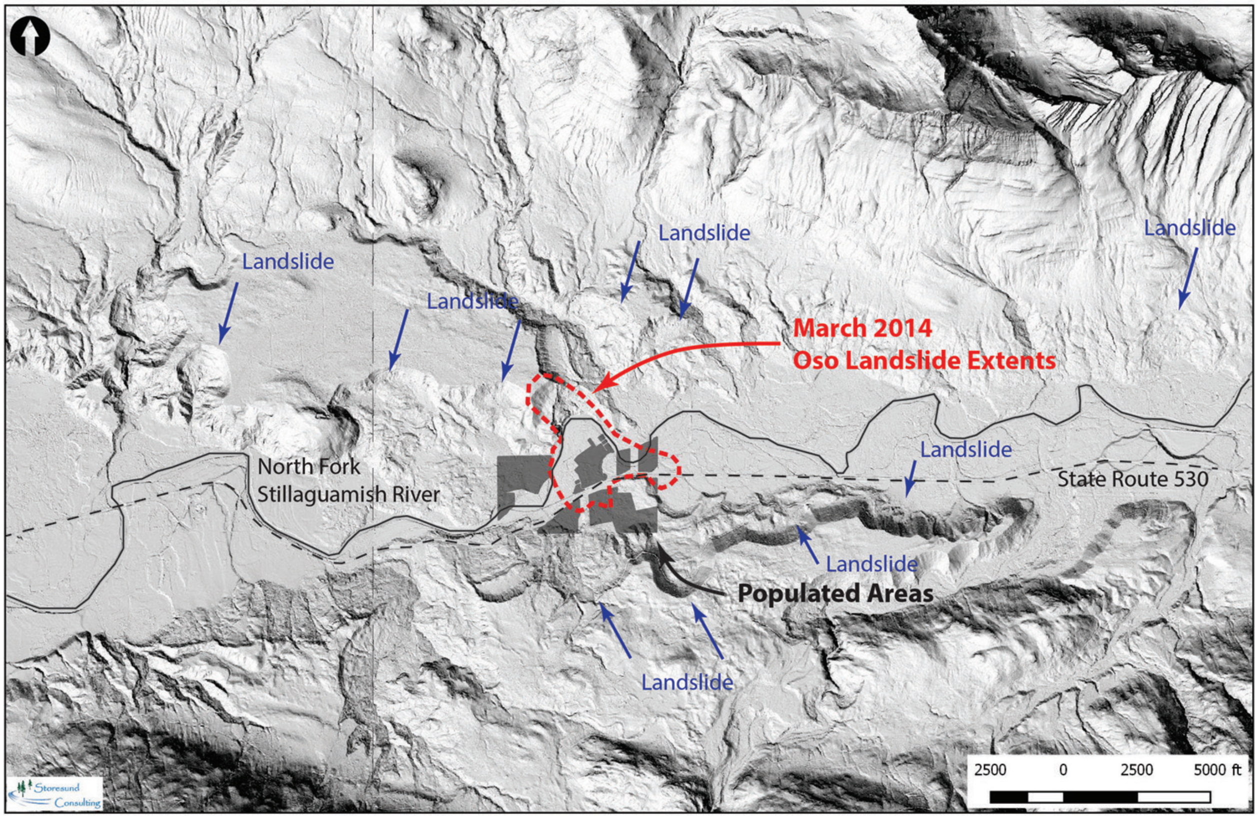

Figure 2
March 2014 Oso Landslide on aerial LiDAR DEM hillshade basemap.

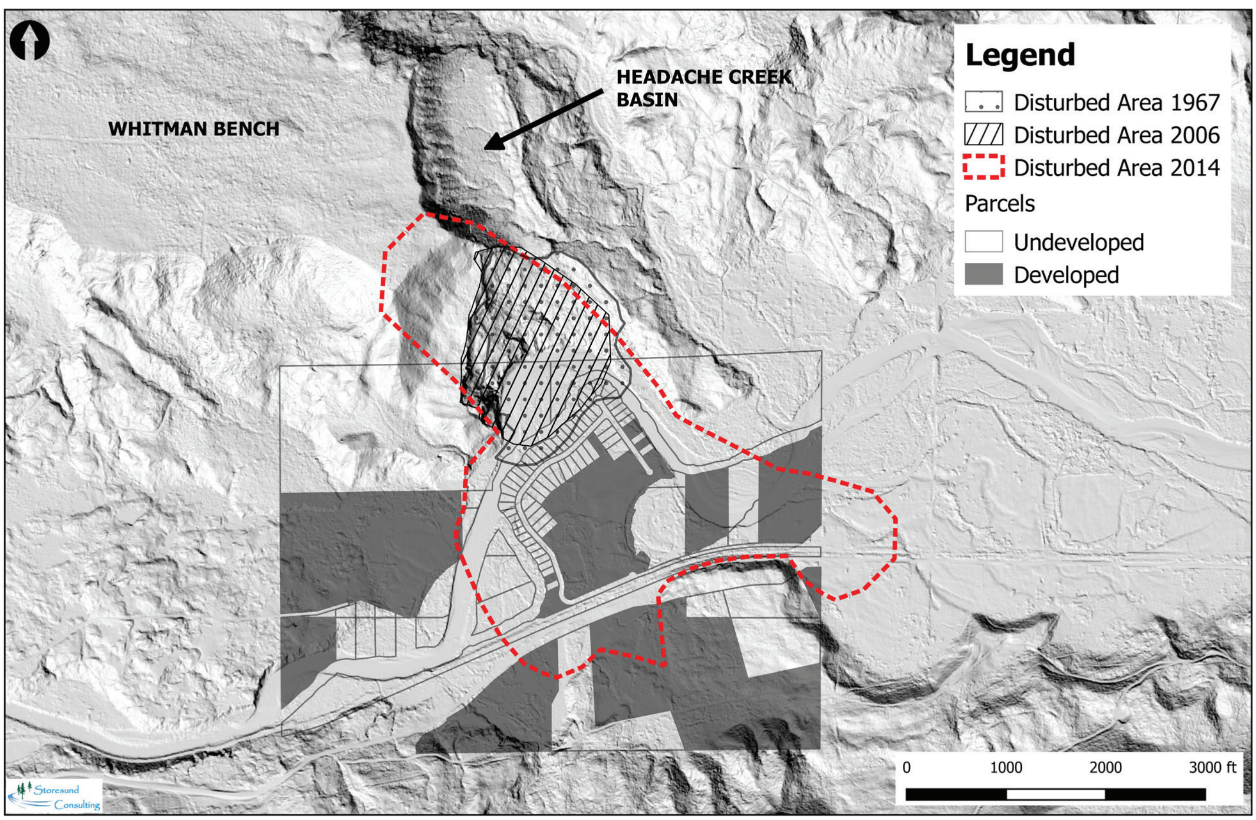

Figure 3
Overlay of runout extents from landslide events in 1967, 2006, and 2014.

The March 2014 Oso Landslide, however, was (regionally) unprecedented with respect to the volume of material displaced during the event, the speed at which the landslide debris traveled through the community of Steelhead Haven, and the distance traveled by the debris (runout). In a matter of 3 to 5 minutes, more than 10,000,000 cubic yards of material displaced, with landslide debris traveling up to a mile at the distal end. **Figure 3** shows a comparison between the 1967, 2006, and 2014 landslide extents. There was a sharp contrast in runout between an anticipated event (1967-type movement) and the largely unexpected event of 2014. A comparison of debris volume of known landslide events prior to the 2014 Oso Landslide, based on comparisons of aerial photos taken before/after each landslide occurrence, is shown in **Figure 4**. A view of the Oso Landslide body prior to the March 2014 event is shown in **Figure 5**, and a similar view following the March 2014 event is shown in **Figure 6**.

By all accounts, the perception that a landslide of this magnitude would affect residents within the Steelhead Haven community did not exist. This was an unusual event that would require a more thorough forensic investigation than recent past events (1951, 1967, 1988, 1996, and 2006).

The unexpected and severe nature of the March 2014 Oso Landslide raised a series of questions:

1. What was the underlying cause of such a severe failure?

2. What role did forest management practices have, coupled with precipitation events, on landslide triggering?

3. Was sufficient information available to characterize the hazard and enable the State of Washington/Snohomish County to provide actionable warnings?

State Expert Team

The State of Washington, along with Grandy Lakes Forestry and Snohomish County, were named as defendants by survivors of lost family members in the Oso Landslide in a consolidated litigation brought forth in July 2014. Then in the fall of 2014, a group of experts was retained by the State of Washington's Attorney General's Office (AGO) to evaluate the Oso Landslide and eventually offer expert opinions with respect to causation (state experts).

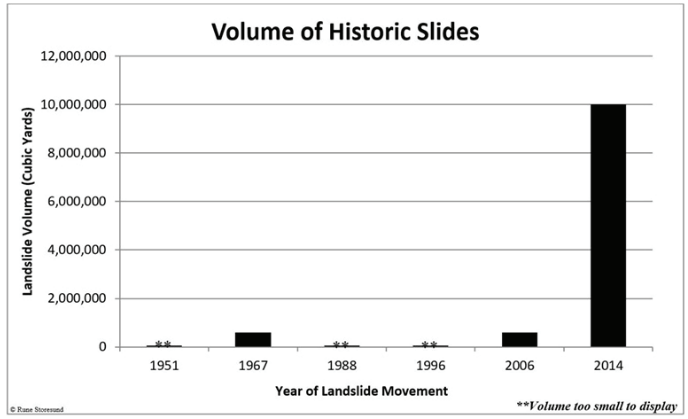

Figure 4
Comparison of landslide volumes and movements between 1951 and 2014.

Figure 5
View of the Oso Landslide area in August 2012, looking northeast (photo by R. Tart).

Figure 6
View of the March 2014 Oso Landslide in April 2014, looking northeast (photo by King County Sheriff's Department).

An overview meeting (for state experts) was organized by the AGO in March of 2015 to present initial understandings and data on topics in hydrology, forest management, natural resources, geology, and geotechnical engineering. The outcome of this initial meeting was a consensus that the body of knowledge relative to landslide triggering was deficient, and there was a dire need for site-specific data to responsibly evaluate landslide triggering and failure mechanism(s). What was recognized, based on the limited facts that were available (e.g., precipitation, previous forest management practices, previous slope movements, completed site reconnaissance, river discharge quantities), was an understanding by the meeting participants that there was no obvious trigger or trigger mechanism.

As early as the 1990s, it was understood that the landslide site was situated in an area with glacially deposited materials. Glacially deposited materials can be extremely heterogeneous and have even been described as "chaotic" with regard to depositional character. Glacial deposits warrant more investigation than traditional colluvial and alluvial depositional environments. However, minimal geotechnical evidence was available following the Oso Landslide other than surficial observations. Available information at the site included:

- A geotechnical assessment[1] after the 1951 landslide by an engineering consultant included some very limited subsurface information at four soil boring locations situated on the mid-portion of the slide.

- A geologic reconnaissance by a state geologist[2] after the 1967 event provided some additional insight as to the plausible/ location of the surface of rupture for the 1967 event.

- A surficial geotechnical reconnaissance[5] effort in May 2014.

- A set of geotechnical soil borings had been completed by the Washington Department of Transportation (WSDOT) in 2014[6], following the March 2014 landslide.

- Aerial LiDAR surveys from 2003, 2006 (following the landslide 2006 event), 2012, and 2014 (following the landslide 2014 event).

- A geologic map of the region prepared by Washington State Department of Natural Resources[7].

In aggregate, insufficient geotechnical site-specific evidence was available as of 2014 to complete forensic analyses without significant conjecture and speculation with regard to actual failure mechanism and triggering factors. Essential minimum data required for responsible forensic analyses (not available as part of the existing information in 2014) included:

- Surface of rupture location and geometry.

- Soil stratigraphy and material properties across the entire failure zone.

- Groundwater levels and hydrostatic pressures across the surface of rupture zone.

- Mapping of displaced soil units.

Compounding the challenge for the state expert team was a court schedule that envisioned trial proceedings would start in June 2016, only 16 months after the initial expert meeting in March 2015. In this time frame, the experts would need to outline, permit, mobilize a drilling contractor, drill, and collect geotechnical samples to unconventional depths of up to 300+ feet, install instrumentation (and collect data), perform geotechnical laboratory testing/forensic analyses, and complete expert reports detailing the analyses and resulting forensic opinions.

A general timeline of the state expert's activities is presented in **Figure 7**. State experts were initially retained in the fall of 2014. A general meeting occurred in March 2015. In May 2015, it was recognized that it would be necessary to collect minimum essential data (i.e., soil stratigraphy, soil engineering properties, location of the surface of rupture, pore pressure profiles) to perform meaningful analyses to address plaintiff's allegations and evaluate potential failure mechanisms. It is the author's contention that any forensic analyses performed without this minimum essential data would have been, at best, conjecture and speculation.

Planning of the field exploration program to collect this minimum essential data began immediately following the May 2015 geotechnical expert meeting. A preliminary report was issued by the state experts in May of 2015 that expressed the need for data collection before responsible expert opinions could be rendered. This report outlined the proposed field exploration and geotechnical laboratory testing. Before actual subsurface exploration could begin, site access agreements had to be obtained from private property owners, and permits for temporary roads, drilling, and environmental constraints had to be obtained from state agencies. In addition, extreme fire-hazard weather conditions limited work days. The plaintiffs were provided an opportunity to provide input on the field exploration program. Actual drilling began in July 2015 and lasted through December 2015. An interim report was released in January of 2016 that provided an update on data collection and reiterated the need for collection of this essential data prior to performing meaningful analyses representative of the actual failure mechanisms. Geotechnical laboratory testing to gain an understanding of engineering properties of the soil units occurred in early 2016. All collected data during the field exploration and laboratory testing was made available to all litigation parties (plaintiffs and defendants).

The state experts did not produce expert opinions until submission of the expert report on June 30, 2016 along with all reliance materials upon which the opinions were based. The lack of initial data, complexity of the site due to the glacial setting, and compressed timeline necessitated the experts working as an integrated group and rapidly exchanging logistical and coordination correspondence to respond to and give direction with regard to field data collection. This group had to frame the questions to be answered with respect to causation, assess the adequacy of available information to inform the questions being asked, and devise/implement a field exploration and laboratory testing program to develop the minimum data for analysis. It would not have been possible to collect the necessary site-specific data and perform the required forensic analyses without close coordination and continuous interaction between the state experts.

Expert Discovery & Communications

As the litigation progressed, there was a conflict over expert disclosure rules. In May 2015, no formal disclosure policy was presented by the AGO to the state experts. However, a review presented in "State of Washington's Response to Certain Plaintiffs' Motion for Sanctions Against Defendant State of Washington[8]," revealed:

- July 2014 - When the case was filed in July 2014, State of Washington Superior Court Rule (CR) 26 applied with respect to discovery protocols because the case was filed in state court[9]. CR 26 describes State of Washington general provisions governing discovery. It requires the identification of experts, discovery of facts, and opinions held by experts. The AGO had not identified its testifying and/or non-testifying experts. No AGO expert opinions existed.

- November 2014 – AGO served a request to plaintiffs' counsel requesting identifying information regarding any experts that plaintiffs' counsel intended to call as a witness and any documents provided to any expert. Plaintiffs noted their understanding that all expert-related discovery would be subject to a "yet-to-be-agreed-upon" expert disclosure protocol.

- March 2015 – Plaintiff and defense attorneys agreed to use of the federal disclosure rules (FRCP 26). FRCP 26[10] requires expert witnesses to produce a written report that presents a complete statement of all opinions to be expressed as well as the basis/reason for them, the facts

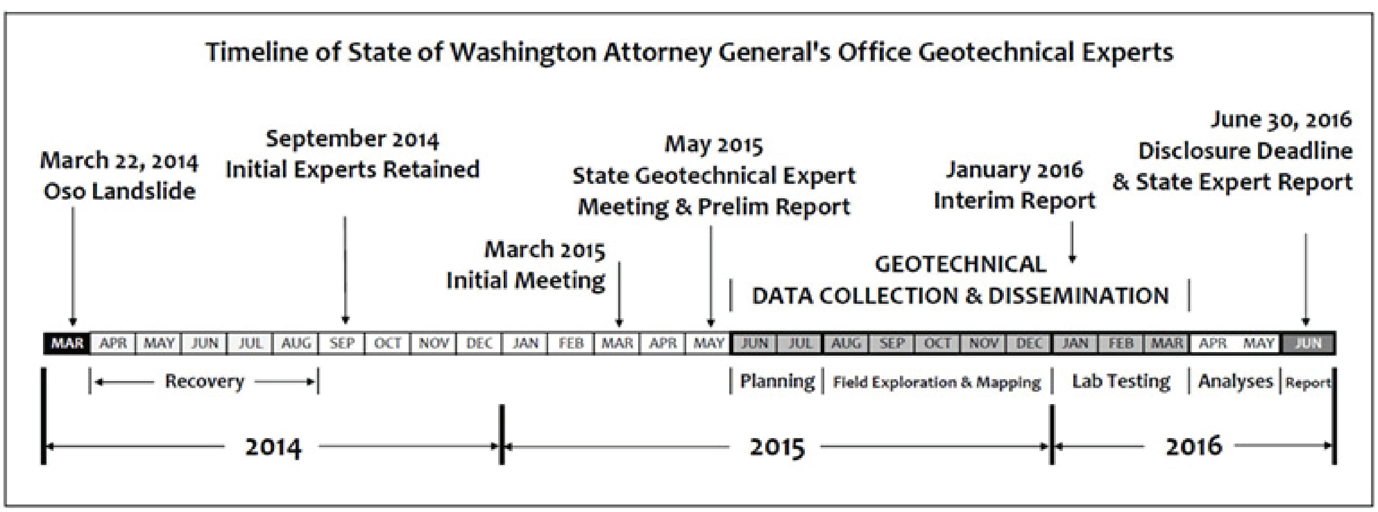

Figure 7
Timeline of geotechnical experts for the attorney general's office.

or data considered by the expert in forming opinions, any exhibits to be used, and qualifications and publications authored in the last 10 years.

• February 2016 – Plaintiff counsel proposed via email on February 2, 2016 that identified a list of expert materials to be provided to the other parties a minimum of 14 days before an expert's deposition. This list of materials would be "in lieu of individual document subpoenas." This list included:

- Materials relied upon by the expert in forming their opinions, including any papers or notes (Bates numbers for materials produced in the litigation also acceptable);

- Documents provided to, considered by, or created by the expert that contains facts or underlying assumptions that the expert considered in forming his/her opinion;

- Articles, paper, or reports authored or co-authored by the expert in the last 10 years relating to the area of expertise in their opinions;

- Communications between the expert and any other expert in the case;

- The expert's updated or most current CV; and

- The expert's invoices or time records for services provided relating to this case.

It was reported that all three defendant counsels agreed to this protocol proposed by the plaintiff counsel.

The terms of this February 2016 disclosure protocol were not shared with the state experts until June 2016. In the spring of 2016, state experts were encouraged by AGO attorneys to copy them on email communications with the understanding that (due to privilege rules) this would preclude the need to produce these email communications at a later date.

During depositions in August 2016, the plaintiff's counsel claimed they learned that email communications between state experts were not retained and produced as outlined in the February 2016 standard discovery protocols. A motion[11] for sanctions against the AGO was submitted by the plaintiffs on August 23, 2016. The motion alleged the following:

• Email communication among the state's expert team should have been preserved and produced.

• The state could not withhold discoverable expert emails by instructing its experts to "cc" the lawyers when the expert team communicated with each other to create a fake "privilege."

• The state conducted systematic deletion and withholding of expert email communication, which constituted systematic spoliation of important documents, and this was conducted in bad faith.

• The state's bad faith destruction of critical evidence had severely prejudiced plaintiffs and required the most severe judicial sanctions.

A rebuttal response was submitted to the court by the AGO on September 2, 2016. The AGO concurred that an error in discovery occurred, per the February 2016 standard protocol. However, the AGO argued that[8]:

• *The federal rules leave significant uncertainty as to aspects of required expert discovery.*

• *Any spoliation was minimal, not ill-intentioned, and will have no impact on plaintiffs' case.*

• *No sanction affecting the merits is appropriate; financial sanctions are sufficient.*

The judge appointed a Special Master to evaluate the merit of the plaintiff's allegations of discovery breach for the court. A Special Master is a designated agent of the court appointed by the judge to carry out some sort of action on its behalf[11]. The AGO was able to reconstitute the full email correspondence between the state experts in September 2016 for the period March 2015 to September 2016. Portions of the reconstituted email were made available to the court's Special Master. The full set of emails were not made available to the Special Master because the AGO was still in the process of reviewing and redacting email correspondence as the case settled just prior to the start of trial in early October 2016.

Court Interpretation

The allegations of evidence destruction were reviewed by the presiding judge and the Special Master. The court concluded[12]:

In summary, the State's discovery violations, as they occurred between March 2015 and September 2016, constitute more than an innocent, bumbling mistake. On the other hand, they constitute less than the conspiratorial cabal described by Plaintiffs. The Court finds that these violations occurred because: (1) the State's lawyers did not, apparently, understand their discovery obligations under the rules by which they agreed to abide; (2) the State displayed a degree of institutional arrogance; (3) the State made bad decisions not to immediately come clean when it became clear discovery violations were occurring; and (4) the State provided incomplete and inaccurate information to the Court about the timing and extent of their actions throughout the summer.

... Court finds the State destroyed potentially relevant evidence, thus requiring an analysis under the spoliation doctrine. The Court also finds the State violated discovery rules arising from its decision to delete emails, thus requiring a slightly different analysis under CR 26.

Lessons

This litigation was challenging from many aspects. First, a basic characterization of the geologic and geotechnical setting upon which to formulate responsible expert opinions did not exist. The lack of minimum required data necessitated rapid development and deployment of an exploration program to collect a basic suite of facts to evaluate purported causation allegations. Second, the multi-faceted nature of the slope failure necessitated a diverse team of geologists, engineers, forestry professionals, and hydrologists working in close coordination to rapidly formulate, execute, collect, and interpret fundamental data. Finally, this work needed to be accomplished within a highly compressed court-specified time frame.

Lesson #1: Strong consideration should be given by legal counsel to employ consulting experts in cases where significant coordination and logistics for data collection is needed. Unlike testifying expert witnesses, consulting experts are not necessarily subject to discovery. FRCP 26(b)(4)(D) states:

(D) Expert Employed Only for Trial Preparation. Ordinarily, a party may not, by interrogatories or deposition, discover facts known or opinions held by an expert who has been retained or specially employed by another party in anticipation of litigation or to prepare for trial and who is not expected to be called as a witness at trial. But a party may do so only…on showing exceptional circumstances under which it is impracticable for the party to obtain facts or opinions on the same subject by other means.

Communications and information exchange between consulting experts and expert witnesses, however, may be subject to discovery. Had a consulting expert been employed in this case with a separate and distinct task to orchestrate and implement the exploration and testing program, the expert witnesses would not have engaged in this work (unless solely through direction by counsel) and would not have been subject to disclosure rules. The developed field and laboratory data would need to be disclosed.

While the cost of experts is always a consideration factor, complicated and fast-paced litigation is certainly a setting where a fractional investment in a consulting expert can purchase significant "savings" by ensuring the sanctity of the expert witnesses and greatly minimizing the potential discovery vulnerability.

Lesson #2: The ambiguity of disclosure extents can be mitigated by establishing the standard disclosure protocols at the onset of the case and then clearly communicating agreed-upon disclosure protocols in writing to all retained experts. If undefined, all materials for an expert witness should be assumed to be potentially discoverable. Close coordination between attorneys is crucial to avoid mixed messages to opposing counsel.

There is no explicit requirement in CR 26 or FRCP 26 that requires preservation and disclosure of incidental email correspondence that do not contain facts, data, or basis for opinions. While reference is made to disclosure of communications where "facts or data that the party's attorney provided and that the expert considered in forming the opinions to be expressed" and "identify assumptions that the party's attorney provided and that the expert relied on in forming the opinions to be expressed," an expert witness should assume all materials are discoverable. Attorneys should ensure proper time and personnel have been allocated to review these materials within the court-appointed time frame.

Lesson #3: Protections are provided by federal rules for draft work products. FRCP 26(b)(4)(B) states:

Trial Preparation Protection for Draft Reports or Disclosures. Rules 26(b)(3)(A) and (B) protect drafts of *any report or disclosure required under Rule 26(a)(2), regardless of the form in which the draft is recorded.*

For a draft work product to qualify, it must bear substantial similarity to the final work product.

Conclusion

The March 2014 Oso landslide was catastrophic with respect to the volume of material displaced during the event, the speed at which the landslide debris traveled through the community of Steelhead Haven, and the distance traveled by the debris. The perception that a landslide of this magnitude would occur within the lifetimes of the residents within the Steelhead Haven community did not exist. This was an unusual event that required a more thorough forensic investigation than the previous landslide events of 1951, 1967, 1988, 1996, and 2006.

The lack of existing data, complexity of the site due to the glacial setting, and compressed timeline necessitated an integrated working group of experts to frame the questions to be answered with respect to causation; assess the adequacy of available information to inform the questions being asked; and devise/implement a field exploration and laboratory testing program to develop the minimum data for analysis. An additional challenge was the unconventional depth the soil borings were required to be drilled, necessitating real-time modifications to the drilling and sampling program to collect the required subsurface data.

Strong consideration should be given by legal counsel in future cases to employ consulting experts where significant coordination and logistics for data collection is needed. Consulting experts have more disclosure protection than expert witnesses. To be safe, an expert witness should assume all materials are discoverable. The ambiguity of disclosure extents can be mitigated by establishing the standard disclosure protocols at the onset of the case and then clearly communicating agreed-upon disclosure protocols in writing to all retained experts. Expert witness disclosures in this case resulted in significant conflict, sanctioning of the AGO's office, and the controversy associated with disclosure protocols resulted (in part) with the State of Washington settling the case.

The full forensic engineering analyses of the incident and robust determination of whether there were any pre-incident deficiencies (on the part of the authorities having jurisdiction) were never completed, due to the timing of the case settlement.

References

1. Shannon, William L. Report on Slide on North Fork Stillaguamish River, State of Washington Department of Game, Department of Fisheries. 1952.

2. Thorsen, Gerald W. Landslide of January 1967 which diverted the North Fork of the Stillaguamish River near Hazel. Department of Natural Resources, Geology & Earth Division, Olympia, WA, 1969.

3. U.S. Army Corps of Engineers. Stillaguamish River Ecosystem Restoration, Final Feasibility Report, Stillaguamish River, Snohomish County, Washington. November, 2000.

4. Miller, Dan and J. Sias. Environmental Factors Affecting the Hazel Landslide, Level 2 Watershed Analysis, Hazel, Washington. M2 Environmental Services. 1997.

5. Keaton et al. The 22 March 2014 Oso Landslide, Snohomish County, Washington. Geotechnical Extreme Events Reconnaissance (GEER), July 22, 2014 [accessed May 4, 2015]. https://bit.ly/2QuOGuR.

6. Badger, Thomas C. SR 530 MP 35 to 41 Geotechnical Study. Tumwater, WA. State of Washington Department of Transportation (WSDOT), 2015.

7. Dragovich, Joe D., et al. Geologic Map of the Mount Higgins 7.5-minute Quadrangle, Skagit and Snohomish Counties, Washington. Washington State Department of Natural Resources, 2003.

8. Tomisser, Rene. State of Washington's Response to Certain Plaintiffs' Motion for Sanctions Against Defendant State of Washington. 14-2-18401-8 SEA, Ryan M. Psonka, et al, Plaintiffs, v. Snohomish County, et al., Defendants; State of Washington King County Superior Court, September 2, 2016.

9. Courts, State of Washington. CR 26 GENERAL PROVISIONS GOVERNING DISCOVERY. Washington Courts. [accessed: December 10, 2016] https://bit.ly/2PnCfEs.

10. Rule 26 – Duty to Disclose; General Provisions Governing Discovery. Federal Rules of Civil Procedure 2017. [accessed: December 10, 2016.] https://www.law.cornell.edu/rules/frcp/rule_26.

11. Phillips, John W. Certain Plaintiffs' Motion for Sanctions Against Defendant State of Washington. 14-2-18401-8 SEA, Ryan M. Psonka, et al, Plaintiffs, v. Snohomish County, et al., Defendants; Superior Court of King County, August 23, 2016.

12. Legal Information Institute - WEX. Cornell Law School. [accessed 2018 Jul 5]. https://bit.ly/2qFGcpl

13. Rogoff, Judge Roger. Second Supplemental Order on Motion for Sanctions. 14-2-18401-8 SEA, Ryan M. Psonka, et al, Plaintiffs, v. Snohomish County, et al., Defendants; Superior Court of the State of Washington in and for King County, October 4, 2016.

Forensic Engineering Analysis of Unintended Movement of Powered Industrial Trucks

By Ben T. Railsback, PE (NAFE 713S), Richard M. Ziernicki, PhD, PE (NAFE 308F), Stephen Knapp, PE (NAFE 819S) and Ricky Nguyen, PE

Abstract

Unintended movement of powered industrial trucks after operators have left the operating position has led to serious — and sometimes fatal — accidents. Even though operators are trained to prevent unintended movement of powered industrial trucks, they can forget to shut off the power source or activate systems to prevent the unintended movement when leaving the truck. Operators are known to make mistakes, especially if they are working in a fast-paced environment and are required to frequently leave the trucks. Engineers have designed electrical interlocks and other systems (e.g., automatically applied parking brakes) to prevent unintended movement; however, not all powered industrial trucks are equipped with them. Furthermore, some of these systems only disconnect the power source from the truck's drivetrain. These trucks can continue traveling due to their initial momentum or by gravity if the truck was left on a slope. The purpose of this paper is to address the design of forklift operator presence detection systems and unintended movement of unoccupied forklifts through a safety and forensic engineering analysis, highlighting a brief case study to examine the concept of use and foreseeable misuse — and to review the legal concept of strict product liability.

Keywords

Forklift, powered industrial truck, parking brake, operator presence detection, interlock, forensic engineering

Introduction

Powered industrial trucks (also referred to as "PITs"), such as lift trucks (forklifts) and tow tractors, are material handling equipment used to move and/or store products and goods in various industries and workplaces, such as manufacturing plants, distribution centers, and airports. These PITs typically have drivetrains that are powered by internal combustion (IC) engines or electric motors — similar to those found in automotive vehicles. Just like automotive vehicles, these PITs can unintentionally move when operators forget to shut off the power source or to follow steps to prevent the unintended movement, such as putting the PIT's transmission in neutral and setting the parking brake. Forklifts are deceptively heavy, weighing three to four times the weight of a small car while having a smaller footprint than the car. For decades, the unintended movement of PITs has led to many serious or fatal injuries to operators and other personnel in the workplace when an unoccupied forklift crushes the operator or a pedestrian against a fixed object. Furthermore, these unintended movements may lead to significant and costly property damage.

Manufacturers provide instructions and procedures in the operator's manual that will prevent unintended movement if they are consistently followed by the operator. Employers also typically train these operators on such instructions and procedures to prevent the unintended movement. However, since these methods require operators to manually activate systems to prevent unintended movement, the methods are prone to operator error, and operators may forget to actuate the systems.

To prevent these deadly accidents, engineers have designed systems (or interlocks) that would automatically prevent unintended movement (i.e., an automatically applied parking brake). These systems have been available for more than a century. However, many manufacturers

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still do not equip PITs with these systems as a standard or even optional feature.

The Incident

At approximately 9 a.m. on a winter morning in 2007, a forklift operator was struck by an unoccupied powered industrial truck at a pallet re-manufacturing facility in St. Louis. The operator had reportedly dismounted the forklift inside a semi-trailer, without setting the parking brake, to hand stack some pallets that were located inside the trailer. The forklift had been driven into the rear of the trailer, and the front of the forklift was facing the front of the trailer. The forklift then rolled forward in the semi-trailer, pinning and crushing the operator between the forklift and the pallets. The operator normally used another model forklift, but was operating a new, rented forklift on the day of the accident. As a result of the incident, the operator sustained fatal injuries.

Photographs of the facility showed that the dock area sloped downward away from the building. The loading dock area also showed standing water out in front of the trailer, away from the building. Photographs of the trailer showed that the landing gear of the trailer did not level the floor of the trailer relative to the slope of the ground. Therefore, the ground and floor of the trailer sloped downward away from the building at the time of the accident, indicating that the floor of the semi-trailer sloped in the direction that the forklift rolled.

The performance of the subject truck was tested by a mechanic from a local service company. The mechanic concluded that there were no performance problems with the truck. Video of the mechanic's testing and photographs apparently taken at the forklift dealership/rental agency demonstrated that the parking brake held the subject truck against a 12.5% grade, and in a separate test, against the engine power at idle while in gear. Dissimilar to the forklifts that the decedent normally operated, the subject forklift was equipped with a presence detection system. One of the features of the presence detection system is a seat switch that is used to detect the presence of the operator in the seat. When the switch is open for more than 2 seconds, mast controls are disabled, the transmission controls are disabled, and the truck shifts into neutral (although the transmission stalk does not physically move). The parking brake does not automatically engage.

An eyewitness to the scene of the accident testified that the forklift was found with the transmission selector in the reverse position, and the parking brake was not set.

Strict Products Liability

The estate of the plaintiff filed a complaint against the manufacturer of the forklift, alleging that the forklift was defective under a strict products liability claim. *Black's Law Dictionary*[1] defines "strict products liability" as a "products liability arising when the buyer proves that the goods were unreasonably dangerous and that: (1) the seller was in the business of selling goods; (2) the goods were defective in the seller's hands; (3) the defect caused the plaintiff's injury; and (4) the product reached the consumer without substantial change in condition."

A strict products liability action is one of three legal theories that a products liability action can be based on. Products liability actions can also be based on negligence or breach of warranty. *Black's Law Dictionary* defines "negligence" as "the failure to exercise the standard of care that a reasonably prudent person would have exercised in a similar situation." A fundamental difference between a strict products liability action and a negligence action is the focus of the analysis that a forensic engineer performs. In a strict product liability analysis, the focus of the analysis is on the design of the product and whether the product was unreasonably dangerous. In contrast, in a negligence action, the focus will be on the conduct of the manufacturer in the design or production of the product and the conduct of the injured party.

Safety Engineering

The Codes of Ethics of ASME and the National Society of Professional Engineers state that "Engineers shall hold paramount the safety, health, and welfare of the public in the performance of their duties." Methodologies for proper product design and safety engineering principles have been published in many texts on safe product design[2,3,4,5] and have also been recognized in engineering standards[6,7]. In essence, when hazards are identified, a hierarchy of steps should be followed, including:

a. Eliminate hazards associated with products by design processes.

b. Guard against residual hazards. If the hazard cannot be eliminated by design, and effective guarding cannot be provided, then:

c. Warn about the hazards.

d. Instruct the operator.

Further, if it is technologically and economically feasible, designers should not use lower-tier hazard mitigation methods as a substitute for methods in a higher tier. For example, if the hazard could feasibly be designed out or guarded against, a designer cannot use warnings to forego the elimination or guarding of the hazard. Residual risks that cannot be addressed through design and guarding efforts should be mitigated with proper warnings and instructions. In performing the forensic engineering analysis of the case study, the authors of this paper first performed a safety engineering analysis of the forklift based on the engineering hierarchy.

The Hazard of Unintended Movement of PITs

PITs are used in the movement and/or storage of products and goods in various industries, such as manufacturing plants, distribution centers, and airports. Title 29 (29CFR1910.178) of the United States Code of Federal Regulations (OSHA General Industry Regulations) defines PITs as “fork trucks, tractors, platform trucks, motorized hand trucks, and other specialized industrial trucks powered by electric motors or internal combustion engines.”

PITs can weigh significantly more than automotive vehicles and are constructed with thicker steel panels and sometimes have solid metal counterweights that can weigh thousands of pounds. A lift truck operating in a warehouse typically weighs 9,000 pounds — more than two and a half times as much as a typical 3,500-pound sedan. Therefore, if traveling at the same speed, these trucks have more than two and half times as much kinetic energy and momentum as typical automotive sedans. The equations for kinetic energy and momentum are given in Eq. 1 and Eq. 2 below.

$$KE=\tfrac{1}{2}mV^2 \quad (1)$$

$$P=mV \quad (2)$$

PITs do not need to travel at a high speed to cause serious harm. A recent fatal accident investigation was conducted where a man’s chest was crushed in between a warehouse rack and a lift truck. Analysis of the accident indicated that 870 foot-pounds[8] of work energy was required to compress the man’s chest 6.7 inches. Based on Work-Energy Theorem (see Eq. 3 and Eq. 4), a 9,000-pound lift truck would only need to travel 1.7 mph to have enough energy to fatally crush the man’s chest.

$$W=\Delta E \quad (3)$$

$$W_{chest\ compression}=\tfrac{1}{2}mV^2 \quad (4)$$

Besides bodily injury, unintended movement of PITs can also lead to costly property damage, such as PITs running into and damaging structures like storage racks or building columns, and PITs driving off loading docks. Therefore, the authors of this paper have concluded that there is a significant hazard associated with the unintended movement of a powered industrial truck.

Foreseeable Use and Misuse

Even though PIT operators are trained on how to park these vehicles, operators are sometimes required to follow numerous steps to properly park the vehicle before leaving the operator position. For example, these are the following steps that operators follow to properly park a standard IC, hydrodynamic transmission lift truck:

1. Select a safe area to park. Do not block aisles or exits.
2. Apply the service brake and come to a stop.
3. Shift the transmission into neutral.
4. Set the parking brake.
5. Lower the forks.
6. Turn the ignition off.
7. If on an incline, block the wheels.

Further complicating the process is an exemption to the requirement for turning the ignition off if the operator intends to remain within 25 feet of the forklift (29CFR1910.178(m)(5)(iii)). Requiring operators to follow numerous steps to properly park a truck increases the chance for human error because operators tend to follow procedures that involve minimal physical and mental effort, discomfort, or time.

Foreseeability can be defined as the quality of being reasonably anticipatable[6]. The 1992 International Organization for Standardization (ISO 12100-1) standard entitled *Safety of Machinery – Basic Concepts, General Principles* states that “Intended Use” of the machine “also involves the compliance with the technical instructions laid down notably in the instruction handbook, taking into account reasonably foreseeable misuse[6].” The standard outlines that the following behavior should be taken into account for foreseeable misuse in the risk assessment:

- *the foreseeable incorrect behaviors resulting from normal carelessness, but not resulting from deliberate misuse of the machine,*

- *the reflex behavior of a person in case of malfunction, incident, failure, etc., during use of the machine,*

- *the behavior resulting from taking the "line of least resistance" in carrying out a task,*

- *for some machines (especially machines for non-professional use), the foreseeable behavior of certain persons, such as children or disabled.*

In the analysis of the subject incident , the question of foreseeability was not difficult to establish, given knowledge of similar incidents within the PIT industry. For example, an expert for the manufacturer was quoted in a forklift publication article regarding the mistakes operators make:[9]

"Before, lots of things were missed, such as how to go up and down a ramp, applying the parking brake, what to do when getting off the truck," [The Expert] told Modern. "Now we have a training program that helps them make better decisions."

The quote indicates awareness of the issue of not setting the parking brake and getting off of the truck — and a reliance on training rather than engineering design to solve the problem. Since the manufacturer's representative (and expert for the manufacturer) had already demonstrated awareness of the issue, foreseeability of the incident had been proven. Further, the forklift had been designed and equipped with an operator presence detection system. The system was designed to shift the forklift out of forward or reverse gear when the operator left the seat. The presence detection system prevents unintentional *powered* movement of the forklift, but does not prevent unintentional *unpowered* movement due to either the initial speed of the forklift, gravity or sloped surfaces, or other conditions. Therefore, the designer of the forklift was clearly aware of the hazard of unintended movement of the forklift.

Technical Feasibility of Preventing Unintended Movement of the PITs

The prevention of unintended movement of PITs is technically feasible. The manner in which the manufacturer chooses to prevent unintended movement depends on the power source of the truck and the control system of the truck.

Electric sit-down forklifts generally have electrically released brake systems that are applied by springs when power is removed from a solenoid. Operator presence or absence is generally detected by a seat switch. The accelerator pedal will return to neutral or zero when released. Electric stand-up forklifts have hydraulically released or electrically released brakes that are spring applied. Operator presence is detected using a "dead man pedal" that the operator must depress with a foot to release the brake. By lifting this foot, which the operator must do to exit the forklift, the brakes are applied. The accelerator, generally a joystick, returns to neutral after release. Therefore, electric PITs generally have designs that prevent unintended movement.

The largest group of PITs that do not prevent unintended movement are equipped with IC engines and hydrodynamic transmissions (torque converters). IC engine PITs, or IC forklifts, rely on the combustion of diesel, liquefied petroleum (LP), or gasoline. The IC engine power is transmitted to the wheels through a torque converter and transmission. When the operator leaves the forklift, if it is left in gear without a parking brake, the forklift will move under the engine power at idle. If the transmission is in neutral without the parking brake set, the forklift may move (or not), depending on the slope of the driving surface.

IC PITs that are equipped with hydrostatic transmissions prevent unintended movement of the forklift. Some manufacturers of lift trucks — Linde, for example — equips its truck with a hydrostatic drive system that uses a hydrostatic pump with a swashplate that controls the rate and direction of oil delivery to the hydraulic motors that power the wheels. When the swashplate is in the neutral position, there is no oil delivery to the wheel motors, and the wheels do not turn. When the forward direction is selected, the swashplate tilts, oil is delivered to the wheel motors, and the wheels drive forward. When the reverse direction is selected, the swashplate tilts in the opposite direction and delivers oil in the opposite direction to the wheels, and the wheels rotate in reverse.

During forward or reverse motion when the operator wants to decelerate, the operator releases the directional pedal. When the operator releases the pedal, the swashplate returns to neutral, oil delivery from the hydraulic pump is stopped. The hydraulic motors continue to rotate as the inertia of the lift truck is dissipated, converting kinetic energy to hydraulic pressure and heat. Since the swashplate on the hydraulic pump is in neutral, the hydraulic fluid cannot flow through the pump, and the truck automatically comes to a stop. After stopping, the neutral position of the swashplate balances pressure on the wheel motors, and prevents further motion. Unlike other lift trucks, an advantage of this system is that it does not require service brakes that will mechanically wear down[10,11].

With the hydrostatic transmission, the operator must select a direction of travel and acceleration input. When the operator releases the control, the control and the swashplate return to neutral, and the vehicle decelerates automatically. When the operator leaves a stopped forklift, the acceleration input will be zero, and the forklift will remain motionless. Therefore, unintended movement of the IC hydrostatic transmission forklift is well controlled.

The subject forklift was equipped with an IC engine, torque converter, and powershift transmission (an electronically controlled automatic transmission). The presence detection system on the forklift did detect when the operator left the forklift, detected that the forklift was left in reverse, and shifted the forklift into neutral. However, the forklift did not apply a parking brake or immobilize the forklift in any way. The subject manufacturer also offers an enhanced presence detection system for some forklifts in the European market. The enhanced presence detection system performs the same functions as the standard presence detection system, but also has the added feature of applying a parking brake when the operator leaves the seat[12].

A rough terrain forklift manufacturer has implemented a parking pawl design combined with an interlocked seatbelt. The parking feature on this lift truck uses a spring-loaded pawl that locks into a spline on the truck's axle. When the operator has the seatbelt latched, hydraulic pressure releases the spring-loaded pin and allows the axle to freely rotate. When the parking pawl is disengaged from the axle, powered travel is possible. However, when the operator unbuckles the seatbelt, the parking pawl in the transmission is applied, locking the axle and preventing motion of the truck from a stopped position. A limitation of the seatbelt interlock system is that the operator can latch the seatbelt and operate the forklift while unrestrained, defeating the interlock.

Since several manufacturers have developed and provide systems that prevent unintended movement of the forklift after the operator leaves the operating position, the authors concluded during analysis of the subject incident that at the time of the subject PIT's design, it was technically and economically feasible to manufacture a forklift that prevents unintended movement of the forklift after the operator leaves the operator compartment.

The subject case study incident occurred in 2007 with a new forklift. The legal case was litigated in 2010. The research and analysis of the incident was presented to the National Academy of Forensic Engineers in 2017. In 2018, Clark Material Handling introduced a new counterbalance lift truck with force-cooled, wet disc brakes. The new braking system features an automatically applied parking brake that would have also prevented the subject incident, on a truck equipped with a hydrodynamic transmission.

Design Standards and Regulations

Currently, federal regulation 29CFR1910.178 requires manufacturers to design and equip PITs to meet the 1969 revision of the American National Standards Institute ("ANSI") B56.1 *Safety Standard for Low Lift and High Lift Trucks*[13]. Although the B56.1 standard has been revised several times, federal regulations have not incorporated by reference more recent versions.

The B56.1 standard does require manufacturers to design and equip some electric lift trucks with systems that will only allow powered travel if the operator is in the normal operating position and to automatically apply the brakes when the operators leave the truck. Since the 1960s, the B56.1 standard has required electrically powered stand-up and sit-down trucks to be equipped with systems that would automatically disconnect the truck's drivetrain from the power source and automatically apply the brakes if the operator leaves the truck.

In the 2004 version of the B56.1 standard, changes were made to require IC trucks to be equipped with systems that would not allow powered travel until the operator is in the normal operating position. Manufacturers have responded to this change in the standard and equipped their trucks with presence detection systems, to prevent powered travel when operators are not in the operating position. However, there was no requirement for the automatic application of parking brakes for IC-powered sit-down and stand-up lift trucks. Since the standard does not require the lift truck's brakes to automatically apply when operators leave the operating position or require that motion due to gravity or initial speed be arrested, the truck can roll after the operator leaves the seat. Since there is no requirement to prevent motion due to gravity, or slope, the subject forklift was compliant with the B56.1 standard.

Although not required by the B56.1 standard, some manufacturers do equip their PITs with deadman switches/controls that would automatically apply the brake, like the enhanced presence detection system offered by the subject manufacturer. Further, since IC PITs with a hydrostatic transmission will prevent movement on slopes (by balancing hydraulic pressure across the wheel motors with a neutral swashplate) when the operator is out of the operating position, there are safer designs that are technically and economically feasible. Therefore, the subject forklift was not compliant with standards of good machine design that require hazards to be designed out or guarded against when feasible.

Conclusion

Accidents caused by the hazard of unintended PIT movement have been known for decades. The unintended movement of the PITs could be guarded (or interlocked) against with deadman switches/controls that would automatically prevent the hazard of the PITs unintended movement from occurring when operators leave the operating position.

Even though deadman switches/controls have been available for more than a century, there are manufacturers that still rely on operators following warnings on the PITs and instructions or procedures in the operator manuals to prevent the unintended movement of the vehicle. Had these manufacturers followed recognized and effective design methodologies to produce safe products, these PITs would have been equipped with deadman/controls switches that would automatically prevent the PIT from unintentional movement. Instead, these manufacturers did not follow methods to design out or guard against the hazard of the PITs unintended movement and relied on warnings and/or instructions to prevent accidents caused by the hazard.

A criticism of deadman switches/controls has been that they can be an inconvenience to operators — and that operators will attempt to remove them or make them inoperative. However, for the design of safety systems/designs to be effective, the manufacturers must design the deadman switches/controls in such a way that they are durable and not easily defeated. Furthermore, federal regulations do not allow user modification that affects the safe operation of the PITs without manufacturer approval, and users can be cited for removing or defeating manufacturer installed deadman switches/controls.

Based on recognized and effective safety methodologies for proper product design and safety engineering principles, manufacturers should not rely on operators following warnings and instructions or procedures to prevent unintended movement. Warnings and instructions are only intended to address residual risks and are not intended to address design defects. Instead, manufacturers should design out the hazard by equipping these PITs with systems (or interlocks) that would automatically prevent movement when the operator is not in the truck. These systems would not only prevent powered travel, but they would also slow down and stop moving PITs or prevent them from traveling down a slope when the operators leave the operating position. Therefore, equipping PITs with systems that would prevent unintentional movement would increase the safety of the PITs, and would bring the designs up to the engineering design standard of care for safety.

Appendix Notation

KE = kinetic energy
m = mass
V = velocity
P = momentum
W = work
ΔE = change in energy

References

1. Black's law dictionary. St. Paul (MN): West Group; 2000.

2. Hammer W. Handbook of system and product safety. Englewood Cliffs (NJ): Prentice Hall; 1972.

3. Hammer W. Occupational safety management and engineering. Englewood Cliffs (NJ): Prentice Hall; 1981.

4. Roland H, Moriarty B. System safety engineering management. Hoboken (NJ): John Wiley & Sons, Inc.; 1990.

5. Brauer R. Safety and health for engineers. Hoboken (NJ): John Wiley & Sons, Inc.; 1994.

6. ISO/TR 12100-1:1992. Safety of machinery – basic concepts, general principles for design. Geneva, Switzerland; International Organization for Standardization.

7. ANSI Z244.1-2003. Control of hazardous energy, lockout/tagout and alternative methods. Washington, DC; American National Standards Institute.

8. Kent R, Sherwood C, Lessley D, Overby B. Age-related changes in the effective stiffness of the human thorax using four loading conditions. Paper presented at IRCOBI 2003. Proceedings of the International Research Council on Biomechanics of Injury Conference; 2003 Sep 11-13; Gothenburg, Sweden: pp 249-263.

9. Forkliftnet.com: lift truck OEMs and OSHA: allies in industrial safety. Guangzhou (China): Forkliftnet.com; 2007 [accessed 2011 Oct 24]. https://bit.ly/2Bruxj4.

10. Spotlight on Linde Hydrostatic Drive. Linde Material Handling GmbH; 2016 [accessed 2018 Nov 5]. https://bit.ly/2QIgP5J.

11. "PMT Linde Hydrostatic Drive Forklift No Brakes Transmission low cost of fuel." PMT Forklift Corp. 2014. [accessed 2018 Nov 5]. https://bit.ly/2S7JQ7G

12. Escutia M. Productivity taken to a maximum with our new DP/GP40-55N range. Guangzhou (China): Forkliftaction.com; 2010 [accessed 2017 Aug 21]. https://bit.ly/2rHUp5A.

13. ANSI/ASME B56.1-1969. Safety standard for powered industrial trucks. New York (NY); American Society of Mechanical Engineers.

Forensic Engineering Analysis of an Electrical Substation Fire in a Manufacturing Plant in Brazil

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Abstract

A cable splice failure in one of the cables associated with one of the 6 MVAR capacitor banks in an electrical substation at a manufacturing plant in South America caused a fire in the 88/4.16kV electrical substation. The fire caused the plant to stop production for approximately 29 days while temporary repairs were made. Operating two shifts per day/seven days a week, and stopping for maintenance once a year, the manufacturing production generates approximately $750,000 in revenue per day. The cable splice failure caused an electrical short circuit in the substation 4.16kV distribution system for approximately 120 seconds. The cable splice failure ignited the adjacent cables in the cable tray, causing damage to various sections of the 4.16kV cables, three 88kV disconnect switches, and four 88kV – 4.16kV transformers. The cable fire in the electrical substation resulted in property damages and business interruption losses with an estimated value of $20 million. The four 88kV – 4.16kV transformers that were in service at the time of the substation fire were exposed to voltage transients and electromagnetic forces produced by the short-circuit currents for approximately 120 seconds.

Keywords

Forensic engineering, transformer, generator, harmonics, controls, distribution

Definitions

Ferroresonance or nonlinear resonance is a type of resonance in electric circuits that occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance, and the circuit is subjected to a disturbance such as opening of a switch. Ferroresonance can cause overvoltage and overcurrent conditions in an electrical power system, and can pose a risk to transmission and distribution equipment as well as operational personnel.

Introduction

A manufacturing plant in South America that began operations in the mid-20th century went through several expansion cycles to meet increased product demands. The plant expansions required increases in the supply of electrical power from the local utility and its own 88kV to 4.16kV electrical substation located within the plant.

The electrical power for the plant is provided by the local utility via two 88kV overhead transmission lines. Only one of the 88kV lines is required to meet the power demand from the plant, and the second is used as a secondary power source in case of an outage (**Figure 1**).

The electrical substation is located on the southeast corner of the property. Initially, the substation consisted of two 88kV – 4.16kV, 7,500kVA stepdown transformers labeled Transformer Nos. 1 and 2. As the plant expanded in subsequent decades, two additional 88kV – 4.16kV, 15,000kVA step-down transformers were added (Transformer Nos. 3 and 4). These transformers were located adjacent to the existing Transformer Nos. 1 and 2 (see **Figure 2** and **3**).

To improve the power quality of the electrical system in the plant, two 6.0 MVAR, 4.16kV capacitor banks with filters were installed in the 1990s. The 6.0 MVAR, 4.16kV capacitor banks are connected to two 4.16kV switchgear — one connected to Transformer No. 3 and the other to

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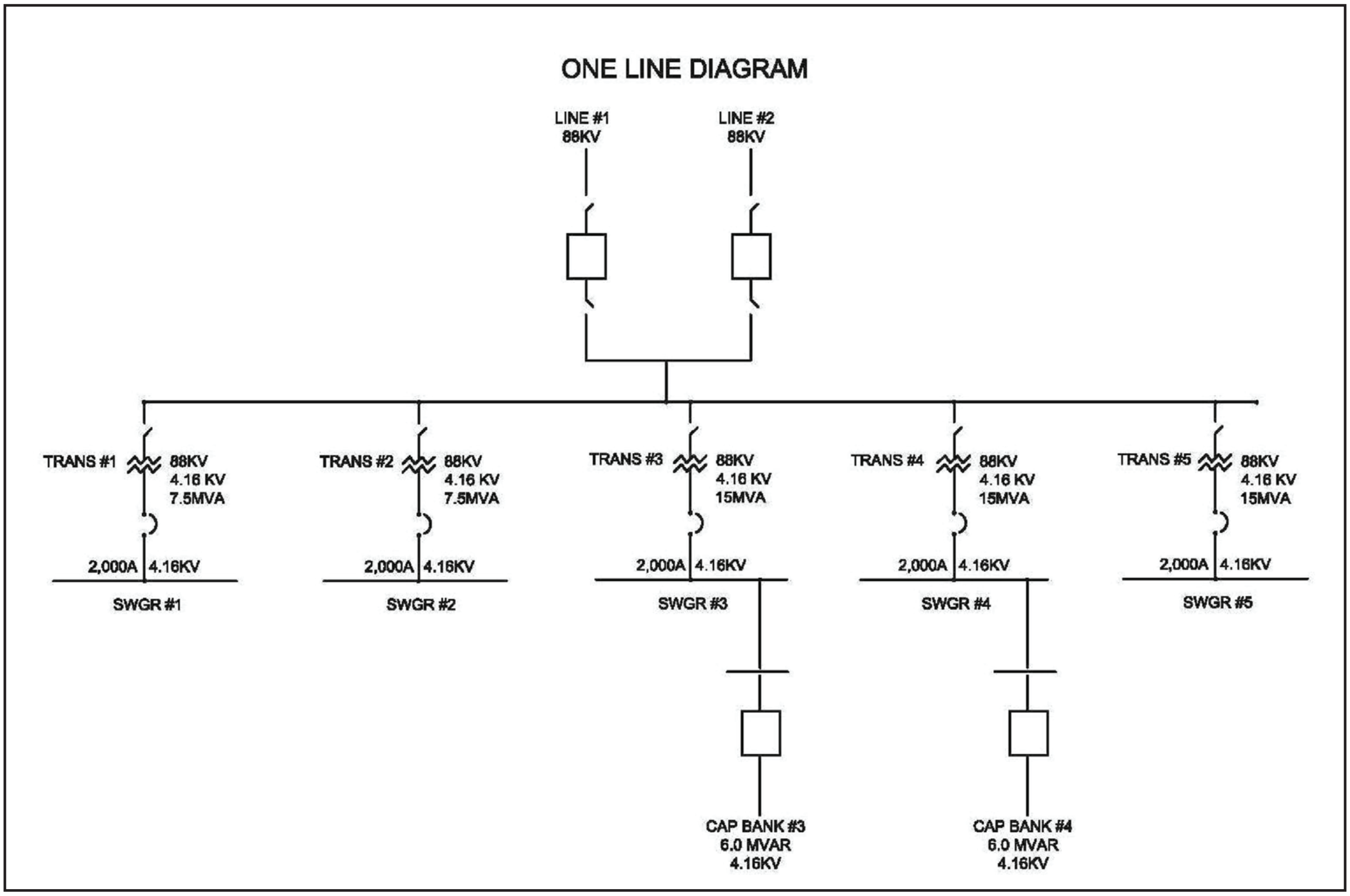

Figure 1
One-line diagram of substation.

Transformer No. 4.

As the plant continued to grow, a new 88kV – 4.16kV, 15,000kVA step-down transformer was installed in the early 2000s (Transformer No. 5). The installation of this transformer required both 4.16kV, 6 MVAR capacitor banks to be relocated to make room for this new

Figure 2
Partial view of substation (north view).

Figure 3
Partial view of substation (south view).

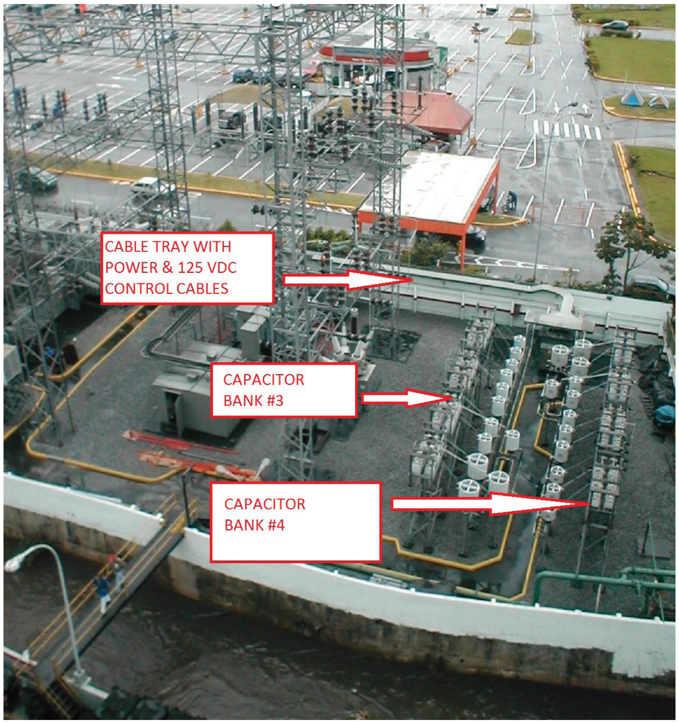

Figure 4
Relocated capacitor Bank #3 and #4.

Transformer No. 5 (**Figure 4**). The power cables in the trays were spliced with additional cables to reach the relocated capacitor banks (**Figure 5**).

When the 4.16kV, 6 MVAR capacitor banks were relocated to make room for the new Transformer No. 5, the circuit breakers associated with the capacitor banks were also relocated close to the capacitor banks, approximately 100 meters away from their original location.

The power cables for the capacitor banks were spliced in the cable tray, which was located on the outside wall along the property line. This cable tray also contained 125 VDC control cables used for the protection and control of the 6.0 MVAR, 4.16kV capacitor banks.

The electrical power for the 4.16kV, 6 MVAR capacitor banks was derived directly from the 4.16kV busbars in the substation. In light of this, the spliced power cables (from the 4.16kV substation busbars to the relocated circuit breakers and capacitor banks) were not protected by the 4.16kV distribution system in the substation, since the spliced power cables became an extension of the substation 4.16kV busbars.

In 2014, a cable splice failure occurred in one of the power cables associated with the capacitor bank connected

Figure 5
Cable tray for capacitor bank cables.

to Switchgear No. 4. The cable splice failure was detected by the protection system of the circuit breaker in Switchgear No. 4, which tripped the capacitor bank and prevented damages to other equipment in the substation. When the failed cable splice was repaired, the capacitor bank was restored to service.

In the spring of 2015, a second cable splice failure occurred in one of the power cables associated with one of the capacitor banks. The cable splice failure caused a short circuit and a fire in the cable tray where the power and 125 VDC cables for the capacitor banks were located (**Figure 6** through **9**).

The fire in the cable tray caused the catastrophic failure of the entire 125 VDC control system in the substation. This prevented the 88kV and 4.16kV circuit breakers in the substation from providing the protection and control for all the equipment in the substation. The only

Figure 6
Capacitor bank cable splices.

protection left for the substation was provided by the local utility company on the 88kV overhead transmission lines.

As a result of the short circuit in the power cables associated with both capacitor banks and the failure of the protection system cables, the 88kV incoming power from the utility continued to provide electrical power to the substation and sustained the short circuit in the cables associated with the capacitor banks. The short circuit in the cables for both capacitor banks remained for approximately 120 seconds, as depicted on the voltage graph recorded by the voltage recorder (**Figure 10**). In addition, the voltage graph in the voltage recorder shows that while the short circuit was occurring, the voltage in the incoming 88kV system went into overvoltages as much as 11kV (27%). In addition, the voltage in the secondary side of the 88 - 4.16kV transformers went into oscillations ranging in voltage from 0.5kV to 4.16kV.

Figure 7
Cable tray with cable splice failure.

Figure 8
Cable splice failure.

Since the voltage recorder in the substation does not have the resolution to detect the amplitudes and frequencies of the voltage oscillations in the 88kV incoming power from the utility, the author was not able to

Figure 9
Cable tray with cable splice failure.

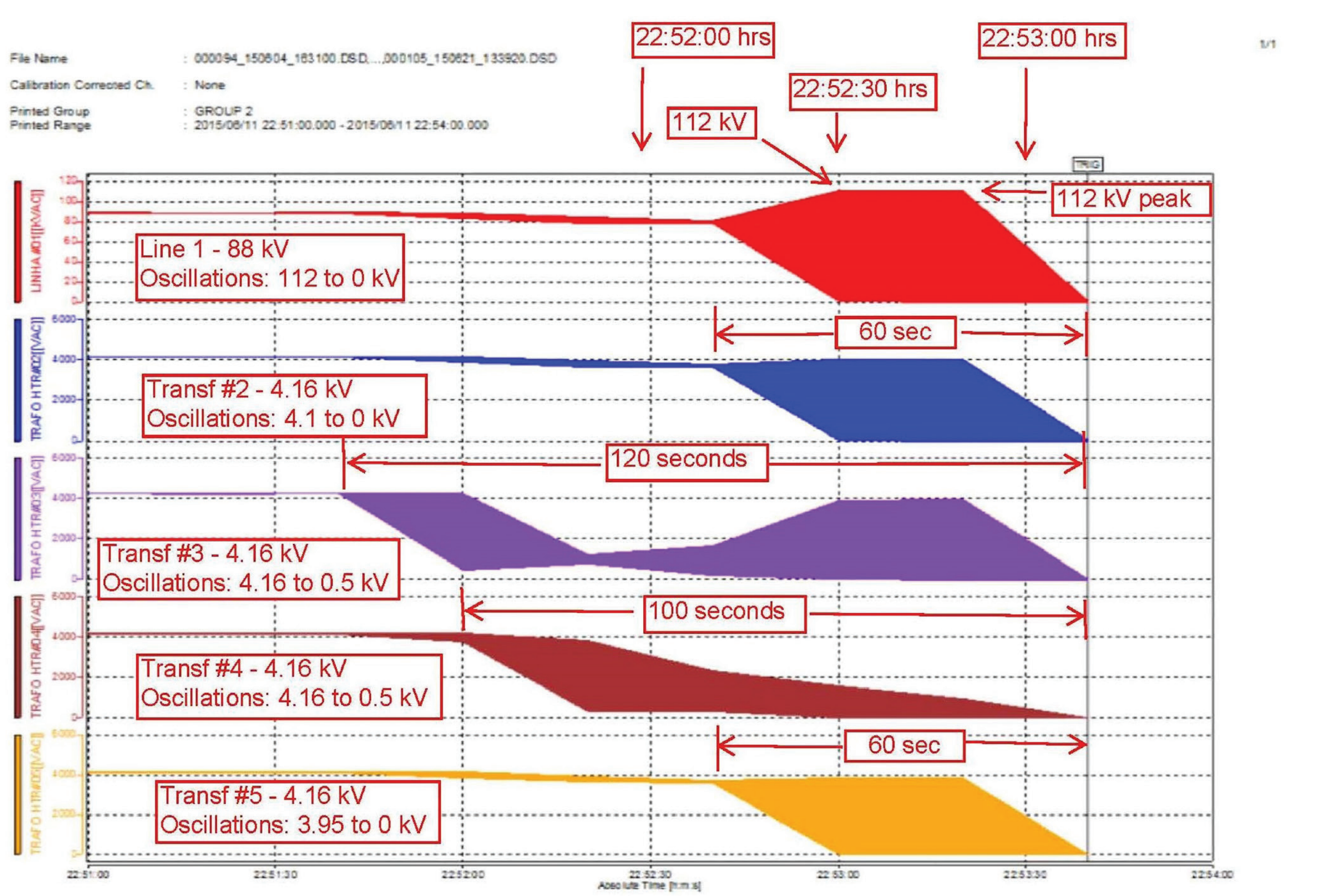

Figure 10
Recorder graphs — 88kV utility overhead line and customer Transformers 2 through 5.

determine if ferroresonance occurred during the 120 seconds of sustained short circuits in the substations. This substation did not have a sequence-of-event recorder that would have captured the electrical transient events and provided detailed information of the voltage amplitudes and frequencies of the electrical transient.

Given the fact that overvoltages of as much as 27% occurred in the 88kV incoming power from the utility, it is very likely that the cause of these overvoltages was the result of a ferroresonance[1,2,3,4] condition produced by the electrical transients in the substation after the splice failure.

Ferroresonance is a type of resonance in electric circuits that occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance, and the circuit is subjected to a transient such as opening of a switch, short circuit, etc. Ferroresonance can cause overvoltage and overcurrent conditions in an electrical power system, and can pose a risk to transmission and distribution equipment as well as to operational personnel.

The 88kV – 4.16kV substation configuration at the time of the fire had four 88kV – 4.16 kV stepdown transformers, two 4.16kV filters, and the transmission lines that provided the inductance required for ferroresonance to occur. In addition, the two 4.16kV, 6 MVAR capacitor banks and the transmission lines provided the capacitance required for ferroresonance to occur. Therefore, it is very likely that the oscillations and overvoltages in the 88kV incoming line were the result of a ferroresonance condition in the substation that occurred when the short circuit and fire occurred in the substation.

Since four of the 88kV – 4.16kV transformers and their associated switchgear were energized during the fire, they were exposed to high short-circuit currents and electrical voltage transients. In addition to the short circuits that occurred in the cable tray where the power and control cables for the 4.16kV capacitor banks are located, other short circuits occurred in the 4.16kV switchgear Nos. 3 and 4, resulting in fires around them and damaging these 4.16kV switchgear and cables around them (**Figure 11** through **16**).

Methodology

Due to the need to restore the electrical power for the plant to continue operating, temporary repairs were performed to the 88kV and 4.16kV substations in order for the plant to return to service within approximately 29 days. The temporary repairs included installing new cables, cable trays, replacing one of the 4.16kV switchgear, and repairing the other damaged 4.16kV switchgear.

Prior to returning the five 88kV – 4.16kV transformers to service after the fire, oil samples were taken from the transformers to analyze the effect that the short circuits and fire had on them. The oil samples showed elevated levels of carbon dioxide to carbon monoxide ratios. These values were compared to industry-recognized levels for similar transformer size and ratios. The levels of carbon dioxide to carbon monoxide levels are used to determine the health of the insulation in the transformer windings. Ratios that are higher than the industry-recognized levels reveal weakening of the insulation in the transformer windings, as was the case with Transformers 2, 3, 4, and 5. Transformer 1 at the time of the fire was not

Figure 12
4.16kV switchgear fire damage.

Figure 11
Cable tray fire damage.

Figure 13
4.16kV switchgear damage.

Figure 14
4.16kV switchgear fire damage.

Figure 15
4.16kV circuit breaker damage.

Figure 16
88kV - 4.16kV transformer damage.

in service. See **Figure 2** for the transformer oil sample results. The oil in Transformers 2, 3, 4, and 5 tanks was replaced prior to returning these transformers to service.

The forensic investigation of the damages in the electrical substation was performed after the temporary repairs were completed. Several site visits were conducted by the author starting in February 2016 in order to review the technical documents related to the substation and to investigate the damage to the various pieces of equipment. The results of these investigations are now detailed.

Cable Splice Failure

The cable splice failure and fire occurred at night when daytime weather featured scattered clouds with temperatures reaching 90°F. The temperature at that time was reported as approximately 72°F with a relative humidity of 89% and a barometric pressure of 29.93 inches. Since the cable splice was consumed by the fire, a detailed failure analysis of the components could not be performed.

OIL ANALYSIS OF TRANSFORMERS AFTER FIRE

Date		Hydrogen (H)	Oxygen (O)	Nitrogen (N)	Methane (CH2)	:arbon Mor (CO)	Carbon Dio (CO2)	Ethelyne (C2H4)	Ethane (C2H6)	Acetylene (C2H2)	Interface Dielectric	Water Content	CO2/CO Ratio
6/15/15	Transf. 1	12	23160	43838	1.5	16	398	1.7	0	0			24.9
6/15/15	Transf. 2	11	1588	63665	238	79	4226	53	485	0	63	10	53.5
6/15/15	Transf. 3	7	1602	79834	78	223	2865	9.5	63	0.3	60	12	12.8
6/15/15	Transf. 4	20	1764	46308	53.6	97	2149	16.2	85.8	0	59	21	22.2
6/15/15	Transf. 5	13	9547	48177	5.6	790	1291	0	0.2	0	95	5	1.6

Figure 17
Transformers 1, 2, 3, 4, and 5 oil analysis after fire.

Transformer No. 2

The voltage graph of the secondary winding of Transformer No. 2 recorded by the voltage recorder during the fire shows that Transformer No. 2 went into oscillations for approximately 60 seconds. The voltage oscillations ranged between 0kV and 4.16kV (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 2 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations for approximately 60 seconds, ranging from 0kV to 112kV for approximately 60 seconds or as much of as 27% of its rating (**Figure 10**).

The oil analysis performed by a laboratory on oil samples taken from Transformer No. 2 the day after the accident shows a ratio of CO_2/CO of 53.495 (4226/79). IEEE Standard C57.106-2006[5] indicates that a CO_2/CO ratio greater than 15 is an indication of insulation degradation in a transformer winding (**Figure 17**).

Transformer No. 3

The voltage graph of the secondary winding of Transformer No. 3 recorded by the recorder during the fire shows that Transformer No. 3 went into oscillations for approximately 120 seconds. The voltage oscillations ranged between 0.5kV to 4.16kV (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 3 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations ranging from 0kV to 112kV for approximately 60 seconds or as much of as 27% of its rating (**Figure 10**).

In addition, the oil analysis performed on oil samples from Transformer No. 3 the day after the accident show an acetylene[6] content of 0.3 ppm. The results of the oil analysis performed on this Transformer No. 3 six months prior to the fire revealed that the acetylene level was 0.0 ppm. Acetylene content in large concentrations greater than 0.5 ppm is the result of a thermal process such as local overheating, and in small concentrations due to partial discharge, which decomposes the mineral oil. Although the acetylene level obtained after the cable splice failure did not exceed 0.5 ppm, the fact that it increased from 0.0 ppm to 0.3 ppm after the cable splice failure is an indication that this Transformer No. 3 experienced localized overheating and partial electrical discharges in its windings caused by the short circuits in the cables associated with Capacitor Bank #3 (**Figure 17**).

Transformer No. 3 also experienced short circuit currents of as much as 31,600A for as long as 120 seconds. These high short circuit currents caused high electromagnetic forces in the primary and secondary windings overstressing the mechanical supports of the transformer windings and core.

Transformer No. 4

The voltage graph of the secondary winding of Transformer No. 4 recorded by the voltage recorder during the fire shows that Transformer No. 4 went into oscillations for approximately 100 seconds. The voltage oscillations ranged between 0.5kV to 4.16kV (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 4 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations ranging from 0V to 112kV for approximately 60 seconds, with overvoltages of as much of as 27% of its rating (**Figure 10**).

The oil analysis performed by a laboratory on oil samples taken from Transformer No. 4 after the incident shows a ratio of CO_2/CO of 22.15 (2149/97). Again, industry standards indicate that a ratio greater than 15 is an indication of the transformer winding insulation degradation (**Figure 17**).

Transformer No. 4 also experienced short circuit currents of as much as 28,500A for as long as 120 seconds. These high short circuit currents caused high electromagnetic forces in the primary and secondary windings, overstressing the mechanical supports of the transformer windings and core.

Transformer No. 5

The voltage graph of the voltage recorder shows that while the short circuit was occurring in the cables of Capacitor Banks #3 and #4, the voltage in the secondary winding of Transformer No. 5 went into oscillations ranging from 3.95kV to about 0kV for approximately 60 seconds (**Figure 10**).

In addition, the voltage graph of the primary winding of Transformer No. 5 (88kV) recorded by the voltage recorder during the fire shows that the primary winding voltage went into oscillations ranging from 0kV to 112kV for approximately 60 seconds with overvoltages of as much of as 27% of its rating (**Figure 10**).

88 kV Utility Overhead Line #1

The voltage graph of the 88kV line 1 recorded by the voltage recorder during the fire shows that the 88kV line 1 went into oscillations 60 seconds after the short circuit occurred in the cable splices, and such oscillations remained for approximately 60 seconds. The voltage oscillations first went up from 88kV to approximately 112kV, then leveled off at 112kV for about 20 seconds, and then went down to 0kV in the next 20 seconds. The voltage oscillations coincided with the start of voltage oscillations in Transformer Nos. 2 and 5, which is an indication that the voltage disturbances in the utility 88kV system directly affected Transformer Nos. 2 and 5 (**Figure 10**).

The voltage signal for the voltage recorder is connected to the 88kV potential transformers in an open “Delta” configuration as shown on the one-line diagram (**Figure 1**). The voltage signal for the secondary windings of Transformer Nos. 2, 3, 4 and 5 is connected to the 4.16 kV potential transformers in an open “Delta” configuration.

The waveforms recorded by the voltage recorder show the voltages for the 88kV and 4.16kV transformer windings in Transformer Nos. 2, 3, 4, and 5 before, during, and after the short circuit occurred. The waveforms are depicted in **Figure 10**, and show a sampling rate of 20 seconds with a scan interval of 1 second (default setting). The voltage recorder records the maximum and minimum voltage values for every scan interval. That is, the voltage oscillations shown on the graphs for the 88kV and the secondary windings of Transformer Nos. 2, 3, 4, and 5 clearly show that oscillations took place following the short circuit in the cable splice. Prior to the short circuit in the cable splices for Capacitor Banks #3 and #4, the waveforms show straight lines, which is representative of the maximum and minimum voltages for the 88kV and 4.16kV systems. Since this recorder does not record the information that an oscillograph would, the author cannot determine the frequency of the oscillations.

Conclusion

The forensic engineering analyses concluded that the cable splice failure associated with the power cables for the capacitor bank caused a short circuit and fire in the 4.16kV distribution system in the 88kV – 4.16kV electrical substation of the plant. Since the substation’s 125VDC control system was damaged due to the fact that the 125 VDC control cables for the capacitor banks were routed in the same cable tray as the power cables, the substation’s protection system did not operate, thus allowing the short circuit to remain for approximately 120 seconds while the fire in the substation was raging.

The state-of-the-art cable installation practices for 4.16kV power and 125 VDC control cables require that these cables be installed in separate cable trays or with metal barriers separating the power and control systems in order to prevent failures such as those described above.

The 88kV circuit breakers in the utility 88kV overhead transmission system were extremely slow to sense the short circuit in the customer’s 88kV – 4.16kV substation and did not trip the 88kV overhead transmission line when the cable splice failure occurred. This allowed the electrical power to continue to flow to the substation for approximately 120 seconds while the short circuit was occurring in the substation and the fire was raging.

Since the 88kV circuit breakers in the utility 88kV overhead transmission system did not trip for the first 120 seconds after the cable splice failure, the four 88kV – 4.16kV stepdown transformers were exposed to very high short circuit currents and electromagnetic forces damaging these transformers.

The overvoltage and frequency oscillations in the incoming utility 88kV transmission line appear to be the result of a ferroresonance condition in the substation that occurred when the short circuit occurred in the substation. The ferroresonance condition occurred due to the inductance and capacitance in the 88kV – 4.16kV substation provided by the transformers, filters and capacitors that were energized during the duration of the short circuit (120 seconds).

References

1. Price E. Voltage transformer ferroresonance in transmission substations. 25th Annual Conference for Protective Relay Engineers. Texas A &M University, March 1977.

2. Rudenberg R. Transient Performance of Electric Power Systems. New York (NY): McGraw Hill Company; 1950.

3. Martinez E, Antonova G, Olguin M. Ferroresonance phenomenon in CFE, its origin and effects. 39th Annual Western Protective Relay Conference. Spokane, Washington. October 16-18, 2012.

4. Jacobson D, Menzies R. Investigation of station service transformer ferroresonance in Manitoba Hydro's 230kV Dorsey Converter Station. International Conference on Power System Transients. Rio de Janeiro. June 24-28, 2001.

5. IEEE C57.106-2002. Guide for acceptance and maintenance of insulating oil in equipment. Piscataway (NJ); Institute of Electrical and Electronics Engineers.

6. ABNT NBR 7070 - 2006. Sampling of gases and mineral insulating oil of electrical equipment and free and solved gases analysis. Rio de Janeiro; Associacao Brasileira de Normas Tecnicas.

Bibliography

ASTM D1816 – 2012. Standard test method for dielectric breakdown boltage of insulating liquids using VDE electrodes. West Conshohocken, PA; ASTM International.

ASTM D3612 – 2002r2009. Standard test method for analysis of gases dissolved in electrical insulating oil by gas chromatography. West Conshohocken, PA; ASTM International.

IEC 60156 Ed. 2.0-1995. Insulating liquids - determination of the breakdown voltage at power frequency. Geneva, Switzerland; International Electrotechnical Commission.

Forensic Engineering Metallurgical Analysis of PTO Air Compressor Rupture and Fire

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Abstract

The coalescer of an air compressor mounted on a utility truck ruptured, resulting in the expulsion of burning oil onto a nearby employee. An investigation ensued to determine the root cause of the injuries. Many potential contributing factors were examined, including system and component manufacture, design, installation, maintenance, and use. Metallurgical and failure analysis procedures were used to determine root cause of the system failure and related injuries. A power take-off (PTO)-driven compressor operates at high temperature (200°F) and pressure (110 psig), creating opportunities for dangerous conditions. The system has a safety shutdown control to prevent the system from going over temperature and pressure limits. The exploded coalescer and fire in this case indicated the temperature and/or pressure systems were compromised as well as the control system. Compressor failures are not uncommon; however, violent failures that cause fire and injury are much less common. PTO compressors are relatively simple machines with only about 25 components. However, the proper function of most components is essential to the safe operation of the unit. In this investigation, it was necessary to look at each component relative to its fitness for service and potential contribution to the system failure.

Keywords

Compressor, fire, coalescer, fatigue failure, rupture strength, metallurgical investigation, forensic engineering

Introduction

In May 2008, a utility truck operator in Georgia was burned while restarting an air compressor system after it shut down due to high temperature oil, high pressure air, or a combination of both. The incident occurred on an 80°F afternoon near the end of the day shift. The operator was attempting to restart the compressor to allow the utility workers to complete their task for that day. After multiple attempts to restart the compressor, the pressurized coalescer ruptured, allowing burning hydraulic oil to be expelled onto the operator who was standing at the gauge panel located near the air compressor system. Statements from the injured worker and his coworkers confirmed that the injured operator manually held the reset button at the "in" position, allowing the override of the automatic high temperature shutdown prior to the incident. It was this action that precipitated the accident.

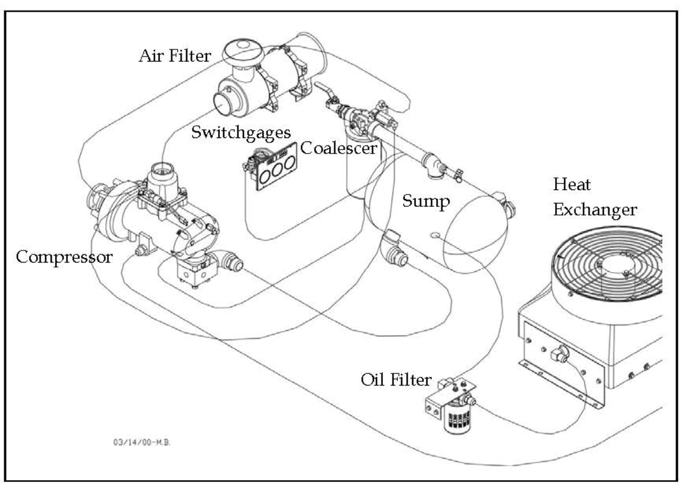

Figure 1
Diagram of air compressor system showing the major components.

Background

The subject truck's air compressor system was used by utility crews to operate heavy pneumatic equipment. A schematic diagram of the subject system is shown in **Figure 1**. The air compressor system was mounted to the truck's chassis behind the passenger side step except for the heat exchanger that was mounted at the rear of the

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Figure 2
Pictures showing relationships between truck, step, reset button, gauges, and coalescer.
Coalescer perspective is what the operator would see when in position to restart the air compressor system.

truck between the frame rails.

The compressor was rated to operate at 110 psig with delivery flow ranging from 80 to 185 CFM, depending on the PTO angular velocity. The pressure and temperature were monitored by analog pressure and temperature switch gauges designed to switch the system on/off at approximately 175 psig sump pressure or 250°F oil temperature.

The compressor required lubrication to protect the compressor's mechanical components and assist in the movement of air through the compressor's pumping section. The manufacturer recommended that the lubricant have specifications comparable to Dexron III automatic transmission oil[1, 2]. The oil is injected into the compressor where it is mixed with air and flows with the air into the sump.

The oil/air mixture enters the sump tank, which acts as both a pressure tank and an oil sump. The oil collected in the sump is circulated through a filter that removes particulate prior to entering the heat exchanger where the oil is cooled and returned to the compressor. The pressurized air leaves the sump and is circulated through a coalescer to reclaim atomized oil before exiting the system and going to the work tool. The coalescer was ruptured, as shown in **Figure 2**, allowing the release of burning oil in the direction of the operator.

The compressor system included features such as an automatic blowdown device to vent the system upon planned or unexpected system shutdown, as well as automatic regulation of the air supply based on the real-time system load. Additionally, a thermal switch controlled the heat exchanger fan to regulate the oil temperature between 160°F and 200°F. The compressor system included pressure and temperature monitoring switch gauges adjusted to turn the compressor off at 150 psig or 240°F. In addition, a pressure relief valve designed to discharge at 175 psig was installed in the system.

The safety system shutdown was controlled by a latching reset switch that, upon switching of either the pressure or temperature switch gauge, would energize an electromagnet located internally within the reset switch and halt the compressor system. The reset switch could then be used to reset the system once the system was no longer in an alarm state. However, during the investigation, it was discovered that the safety condition could be manually overridden by simply pressing and holding the reset button at the fully inward position.

Testing and analysis were performed on a near-exact exemplar of the subject compressor system. The exemplar system make, year, model, and location of components within the truck matched the subject truck with the exceptions that the operator controls were located within an enclosed storage compartment at the rear of the truck, and the heat exchanger was mounted vertically.

Forensic Investigation of the Subject Truck and Compressor System

The ruptured compressor coalescer was the obvious source of the burning oil that caused the injuries to the operator. The air compressor system is integrated with operation of one component dependent on the operation of other components and subsystems.

A strategy was developed to test each component and subsystem of the air compressor. By doing so, two objectives were pursued:

1. The root cause might eventually be determined, if for no other reason than by the process of elimination.
2. Ensure credibility of objective data by the participation of all parties in proof testing.

As mentioned, an exemplar vehicle with essentially the identical year and model air compressor system was found and procured for the investigation. This unit became a test bed for testing of components and theories. Situations and remedies could be demonstrated on the exemplar, thus reinforcing objectives 1 and 2.

The inspection of the subject truck and compressor consisted of multiple inspections over multiple years. The initial inspection included basic photography of the subject truck in the post-incident condition. An image of the subject truck at the accident site is shown in **Figure 2**. The sump was located behind the rear-most section of the step with the sight glass visible to the operator. The pressure and temperature switch gauges were mounted in a cluster attached to the step as seen in **Figures 2** and **3**. An additional rectangular cutout was located approximately 12 inches toward the rear from the gauge cluster. The cutout did not appear to serve any purpose.

Sequential inspections included the disassembly of the major compressor components. As the investigation progressed, forensic examinations became more focused on the design and operation of individual system components.

Evaluation of the subject truck and compressor system led to the conclusion that the forensic analysis must proceed along five separate but related lines of investigation. These were:

1. System and component function and fitness
2. System and component design
3. Installation design and fitness
4. Maintenance
5. Training

These are discussed in the following sections.

System and Component Function and Fitness

The PTO compressor system is relatively simple with about 25 interrelated component parts that have active functions in the compressor's operation. Components are also grouped together to perform a subsystem or system functions. It was expedient to test each component regardless of its potential to actively contribute to an explosion and fire centered at the coalescer.

Inspection and Testing

The individual components of the subject vehicle and air compressor were removed during a joint inspection with all interested parties present. The components were examined and tested during several scheduled inspections. The component testing required the fabrication of multiple test systems to accurately reproduce a component's intended use and determine if the component functioned in the way it was intended.

Figure 3

Damaged temperature and pressure switch gauges. The reset button switch is shown to the right mounted 2½ inches from the switch gauge cluster. Note instructions. Manufacturer names are hidden.

Components Found Fit for Service

Based on function, examination, and testing, the following were determined to have no relevance to the explosion, nor did they impact the injuries suffered by the operator.

- Air filter

The air filter and canister appeared to be clean.

- System circuit breaker.

The air compressor system was protected from over current conditions using a circuit breaker. The circuit breaker was damaged from internal corrosion that was attributed to post-accident exposure.

- PTO drive

The PTO was visually inspected, photographed, and the solenoid operation was tested. All operations were as intended.

- Sump

The relationship of the sump to the incident was the potential of a flash fire developing inside it. The sump was clean except for soot residue that was observed near the connection to the coalescer manifold.

- Automatic blowdown valve

The purpose of the automatic blowdown valve was to relieve pressure from the system when it was shut down. **Figure 4** shows the testing apparatus used for testing pressure-related components such as the automatic blowdown valve. It proved to be operating as designed.

- Oil filter assembly

The oil filter assembly consisted of the oil filter and filter head. Inspection and testing of the assembly showed that the filter was not clogged, and the bypass valve was open in the filter head. Thus, oil filtration was compromised but oil flow was not impeded.

- Heat exchanger cooling coils

The cooling coils were examined by x-ray, borescope, and water flushing to prove that the path was unobstructed.

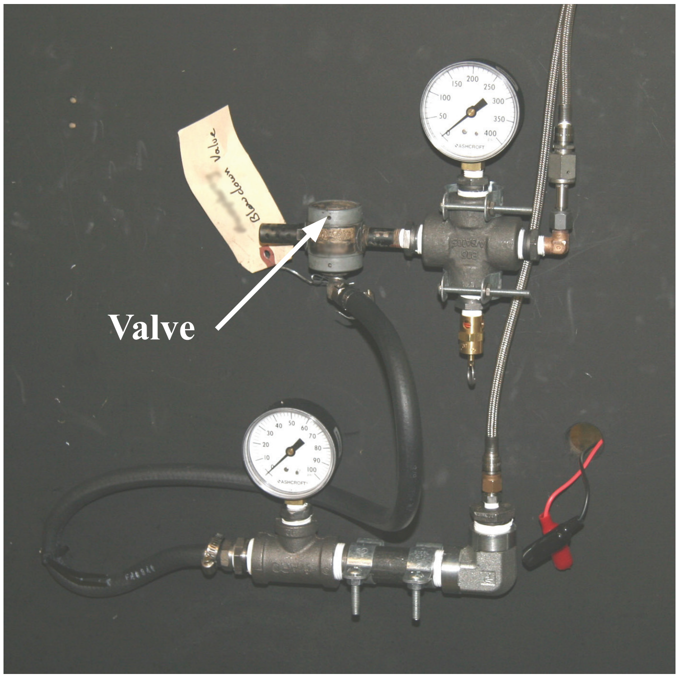


Figure 4
Test apparatus used to test the automatic blowdown valve and the pressure switches. The system is shown with the automatic blowdown valve installed.

The coils were found to function as intended.

- Pressure switches

The air compressor system used two pressure switches that were responsible for performing certain control operations by converting mechanical pressure into an electrical response. The pressure switches were tested by pneumatically actuating the devices (**Figure 4** typical) and monitoring the pressure at which the contact state changed. The testing showed that both pressure switches operated as intended.

- Pressure relief valve

The air compressor system was designed with a pressure relief valve (PRV) to release the system pressure when the system exceeded the set point of 175 psig. The PRV was visually examined and tested to determine its operation by incrementally applying pressure and monitoring the pressure that resulted in PRV venting. Testing of the PRV showed that the device functioned as intended.

- Modulation control valve and air inlet valve

A series of valves operated together to control the air flow and pressure during compressor operation. The purpose of the intake valve is to control compressor capacity by opening when air demand is high and closing when it is low. The signal to open or close is supplied by the modulation control valve installed downstream of the air inlet valve. A pressure drop at the modulation control valve results in opening of the air inlet valve and vice versa. The modulation control valve and air inlet valve were tested and determined to operate as intended.

- Thermal switch

The air compressor system was designed to operate within a specific range of oil temperature, which was critical to its successful and safe operation. The thermal switch was designed to close and energize the heat exchanger fan when the temperature exceeded the high temperature threshold and remained closed until the oil temperature decreased below the low temperature threshold, resulting in approximately a 20°F temperature differential.

The thermal switch was tested by immersing in silicone oil and progressively heating until the contact closed. **Figure 5** shows the test setup. The temperature was monitored using a K-type thermocouple connected to an Omega Model 120 thermocouple display. The closing temperature was recorded by monitoring the continuity through the switch. The heat was removed from the system, the oil was allowed to cool until the switch opened, and the opening temperature was recorded. The testing

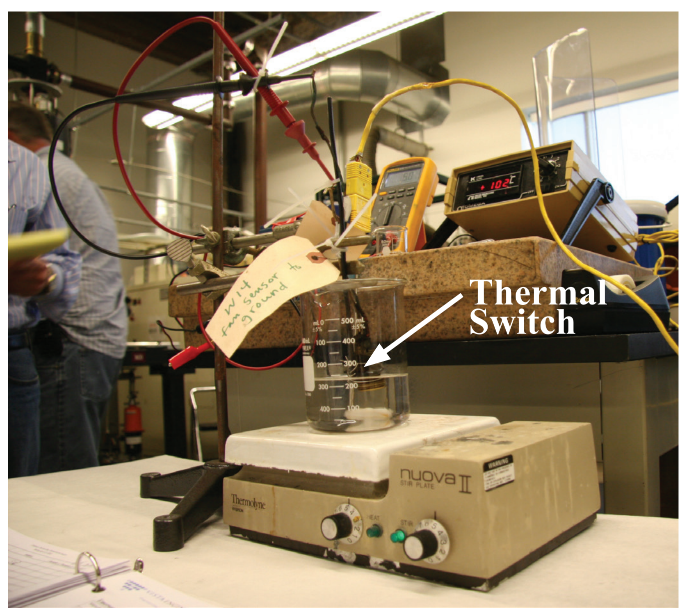


Figure 5
Test apparatus to measure the high and low temperature threshold of the thermal switch used to energize the relay controlling the heat exchanger fan motor.

showed that the thermal switch operated as intended.

A second series of tests was performed on the thermal switch to test its long-term cyclic performance. **Figure 6** shows the thermal switch mounted in a heat sink connected to a 350W Omega resistive heating element. Heat was applied to the thermal switch until the contacts changed state, simultaneously energizing a 12V relay to turn off the heating element, turn on the 12V fans for cooling, and increment a step counter. The step counter would not increment until the next high temperature cycle. The test was a fully automated process and was not halted until the consensus of the experts agreed to conclude. The testing showed that the thermal switch operated as intended.

- Various relays and relay timer

The air compressor system contained various relays that performed duties such as heat exchanger fan control and controlling engine speed based on air demand requirements. The relays and relay timer were visually examined, and their operation was tested based on their manufacturers' recommendations. The testing of the relays and relay timer showed that the devices all functioned as intended.

- Compressor oil

a. The compressor oil was tested and found to be acceptable from the point of not likely to be the source for a compressor malfunction or combustion. The oil was tested using the following standard methods:

i. ASTM D93-1999c, "Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester"

ii. Wear metals analysis by energy dispersive spectroscopy in a scanning electron microscope

iii. ASTM D6080-2010, "Standard Practice for Defining the Viscosity Characteristics of Hydraulic Fluids"

iv. ASTM D5853-2011, "Standard Test Methods for Pour Point of Crude Oils"

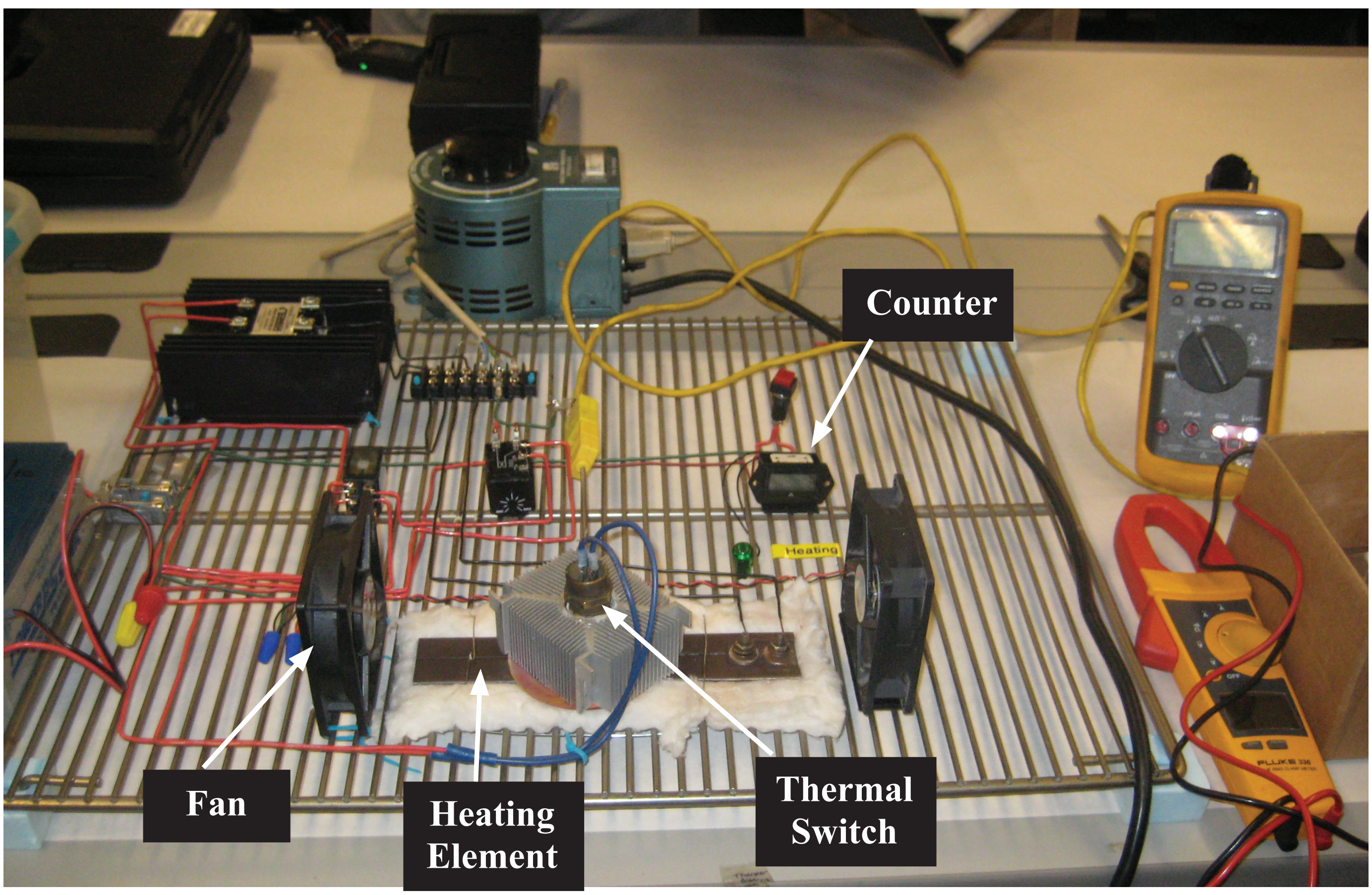


Figure 6
Test apparatus to measure cyclic temperature performance of thermal switch.

v. SAE ARP5088A 2006, "Test Method for the Determination of Total Acidity in Polyol Ester and Diester Gas Turbine Lubricants by Automatic Potentiometric Titration"

Components Found Unfit for Service (Whether Defective or Not)

- Heat exchanger fan

The oil temperature of the air compressor system was controlled by a fan-operated heat exchanger. The fan was controlled by the combination of the thermal switch and a 12V relay; both were shown to be functional. Inspection of the fan and fan grill showed that the fan grill had suffered damage by an outside source, such as road debris. The fan blades and motor are attached to, and supported by, the grill, which is attached to the heat exchanger shroud by four grill wires. Three of the four grill support wires had suffered fatigue failure. The broken support wires allowed the fan to fall downward, pinning the fan blades against the shroud. The fan, in the final resting position, is shown in **Figure 7**.

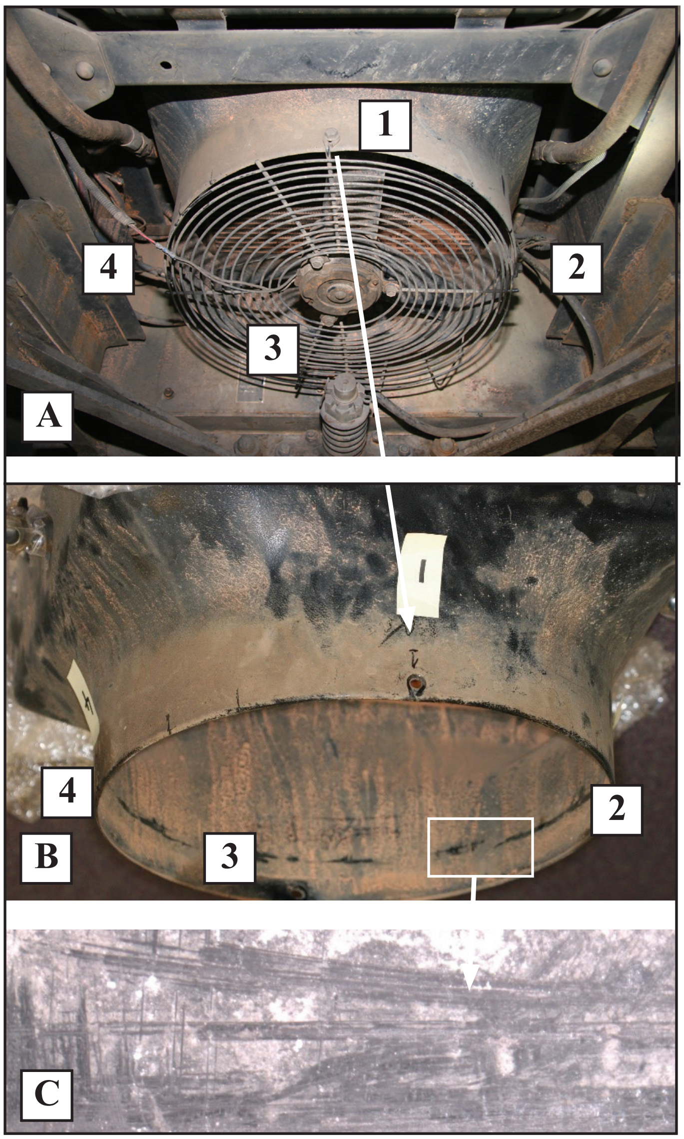


Figure 7
Subject fan shown at top (A) with its four grill support wires identified as shown (1 – 4). Witness marks on the inside surface seen in B and C of the heat exchanger shroud showing that the fan ran against the shroud for short time before binding. The grill was held in place at wire [1] which was not broken.

Notice the witness marks on the inside surface of the shroud, indicating contact between the fan blades and the shroud. The fan grill fell when wire #3 broke, causing the fan to bind. The fan motor could only generate approximately one pound of force at the tip of the fan blade to move the blades at startup. This would have made it improbable for the fan blades to dislodge themselves from the shroud. Without fan cooling, the air compressor oil would overheat. Testing on the truck with exemplar air compressor proved this to be true.

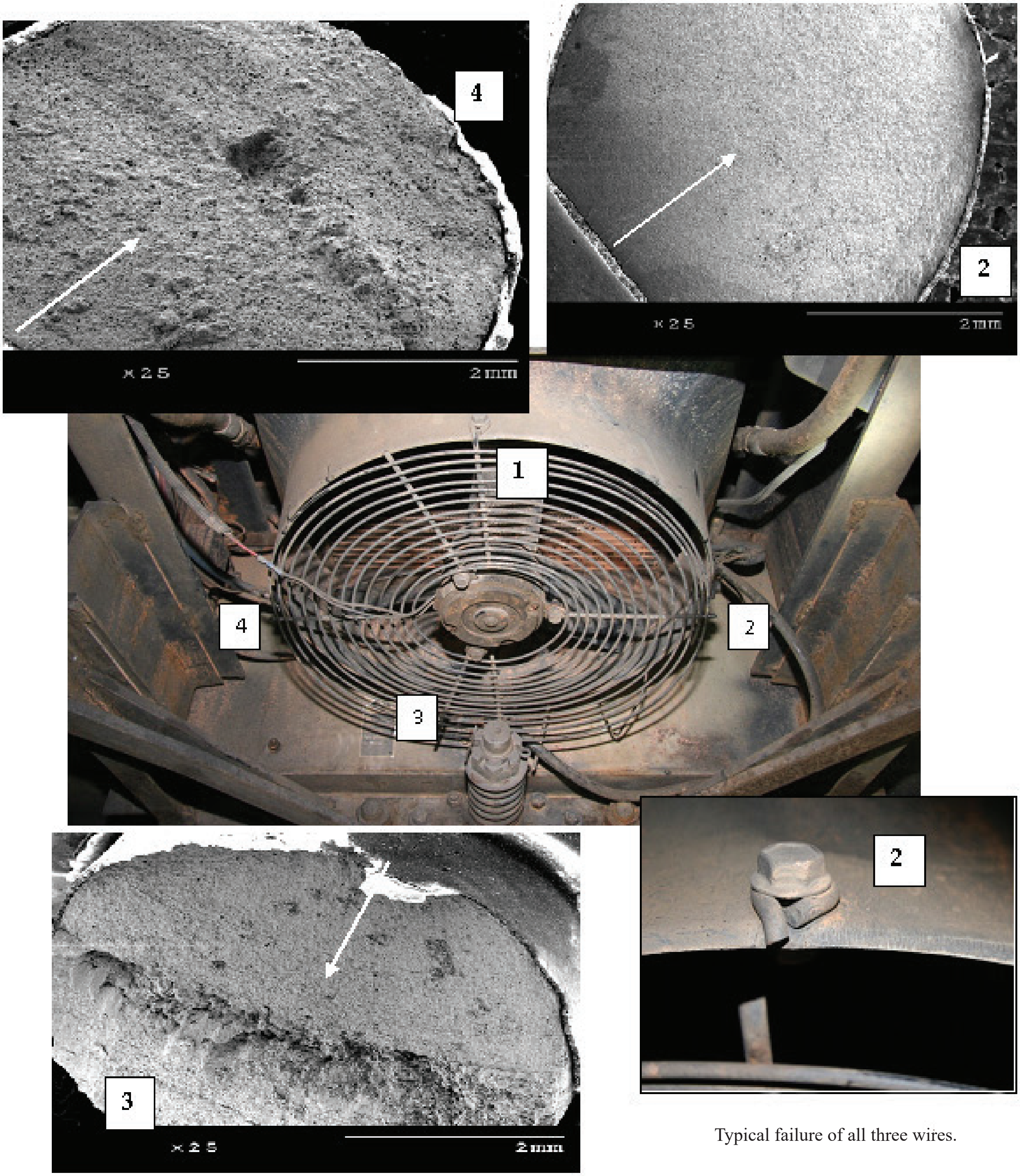
Scanning electron microscope (SEM) examination of the broken wires showed they had failed in fatigue — and failed progressively in order 2 – 4 – 3 (**Figure 8**). The root cause of the fan failure was fatigue of the grill support wires. The wires were overloaded by the weight of the fan motor and blades when they were subjected to vibrational loading from the vehicle while installed in its horizontal orientation. A single impact from roadway debris did not cause failure of the grill.

The fact the wires failed in fatigue[3,4] (and failed sequentially) suggests that there was a time when the fan grill could have been identified by inspection as "going bad" before it fell down, causing the fan to bind.

It was also discovered that the fan was wired so that the fan blades rotated in the opposite direction from their design, thus reducing the air flow. The air flow difference was tested and confirmed. This defect in installation would reduce the cooling efficiency of the heat exchanger and potentially lead to overheating. However, when the reversed leads were tested in the exemplar compressor, the temperature never reached the over temperature limit.

- Coalescer (no defect found in the coalescer, but included here because it was the source of the rupture)

As mentioned, the air compressor system contained



Typical failure of all three wires.

Figure 8

Subject fan shown in center with its four grill support wires identified as shown (1 – 4). SEM pictures of the fractured wires show their progression of failure by fatigue. Wire 1 is unbroken. Wire 2 broke with a flat fracture surface, indicating it broke first under the lowest load. Wire 4 exhibited the next most uniform fracture, indicating it failed second and wire 3 showed a fracture with higher loading and less uniformity, indicating it failed last after 2 and 4 were broken. The progression of failures suggests that maintenance had an opportunity to find the problem grill before it suffered its final failure.

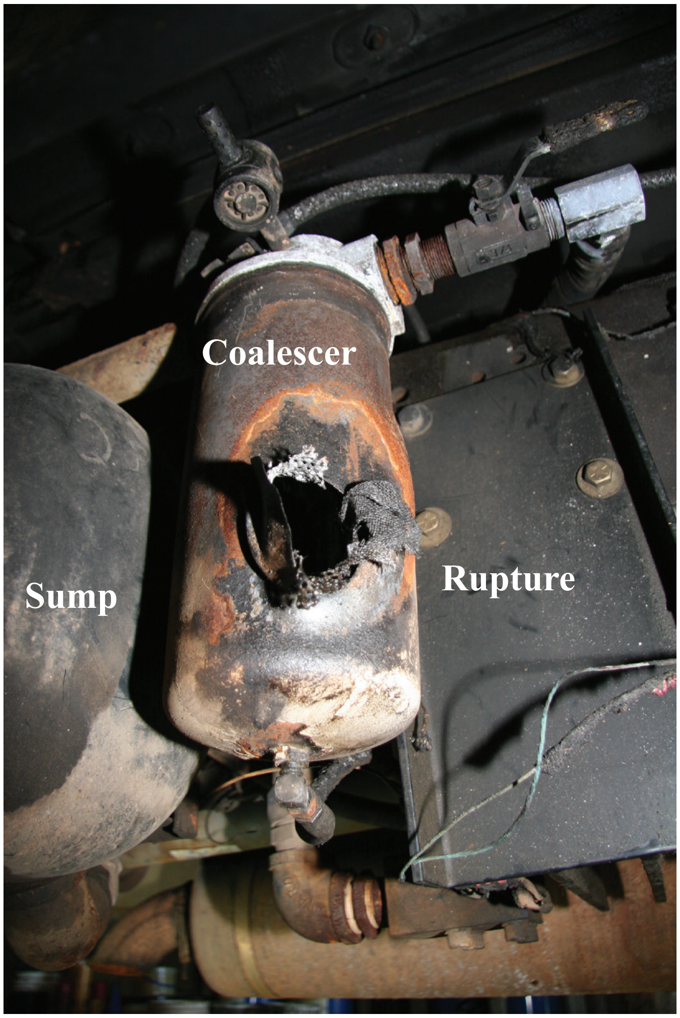


Figure 9
Image of the coalescer rupture after the step was removed. The coalescer is located forward of the sump directly behind the rear hole in the passenger side step.

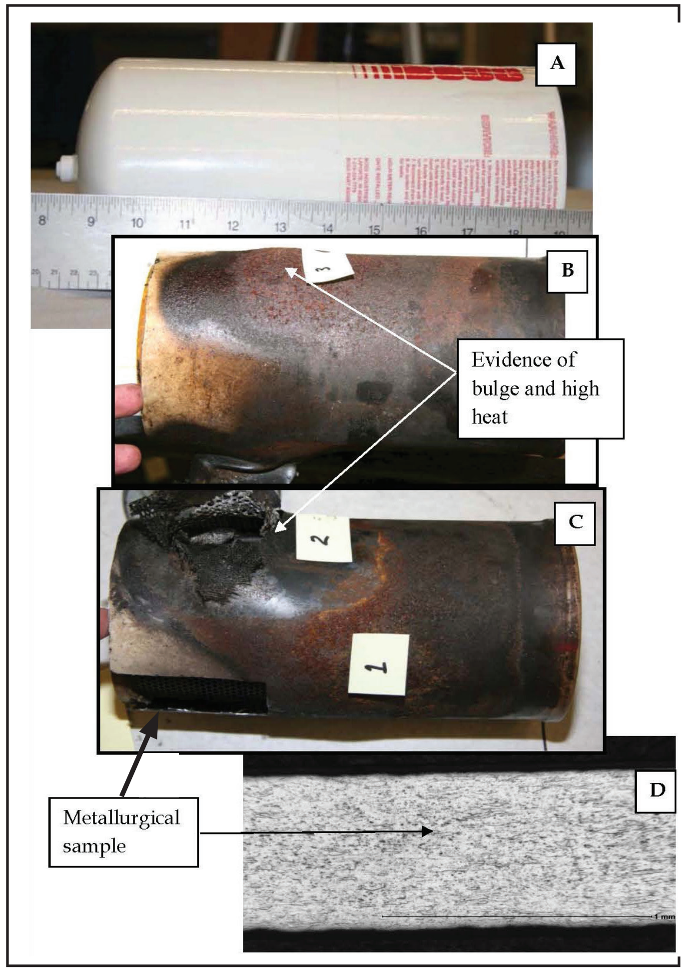


Figure 10
Subject coalescer seen in B and C exhibits bulging at the location of highest heat. The rupture occurred in the bulged area. The metallurgical structure of the thin-walled coalescer is cold-worked low carbon steel. Exemplar A shown for pre-cut comparison.

a coalescer to remove oil vapor from the air supply upon exit and return the reclaimed oil to the compressor. The coalescer contained a large rupture, as shown in **Figure 9**, which allowed rapid depressurization and the instantaneous release of burning oil at high pressure. The location of the rupture aligned with the release of burning oil in the direction of the operator. The coalescer was examined by visual inspection, X-ray inspection, and CT inspection. The properties of the metal were examined metallurgically and by microhardness testing.

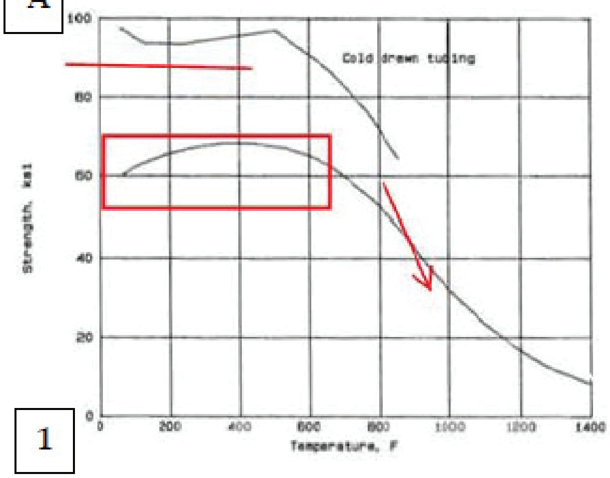
The coalescer showed heat damage and plastically deformed bulging at the location of the rupture as seen in **Figure 10**. The rupture was consistent with a localized hot spot failure. An analysis of the hoop stress on the coalescer is seen in **Figure 11**. The subject coalescer was capable of withstanding two to four times the maximum air compressor pressure up to about 400°F (**Figure 11**). However, at temperatures in the range of 1,000 to 1,400°F, the subject coalescer would exceed its yield strength, allowing the coalescer to bulge[5]. The next step would then be rupture as the temperature increased still further and damage accumulated from yielding of the metal.

The bulged coalescer was evidence that the internal heat occurred while the coalescer was pressurized, thus the fire started in the coalescer prior to rupture. The source of the ignition is unknown. The heat produced was enough to soften and weaken the metal as shown in **Figure 10**. This would have allowed the rupture to occur at normal operating pressure of the system. Thus, the root cause of the coalescer rupture was heat from its internal fire.

- Reset button (and safety shutoff), temperature

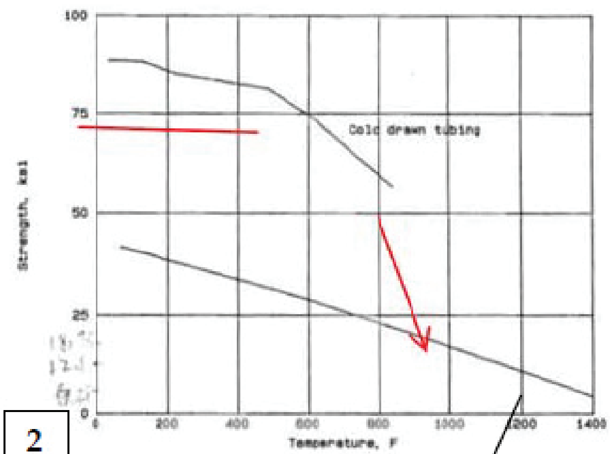
Mechanical Properties

A



1

AISI 1015: Tensile strength. Data from several test programs on specimens in the annealed, normalized, hot rolled, stress relieved, oil quenched and tempered, and cold worked conditions. Cold drawn tubing data shown separately. Source: Ref 21, p 12



2

AISI 1015: Yield strength. Data from several test programs on specimens in the annealed, normalized, hot rolled, stress relieved, oil quenched and tempered, and cold worked conditions. Cold drawn tubing data shown separately. Source: Ref 21, p 12

B

Coalescer Calculations
Thin-walled vessel
Hoop stress P(hoop) = p(D)/2t

Internal p psi pressure	D In. diameter	t in. wall thickness	P(hoop) psi hoop stress
20	5.0	0.019	2,632
40	5.0	0.019	5,263
60	5.0	0.019	7,895
80	5.0	0.019	10,526
100	5.0	0.019	13,158
120	5.0	0.019	15,789
140	5.0	0.019	18,421
160	5.0	0.019	21,053

E

540	5.0	0.019	71,053
560	5.0	0.019	73,684
580	5.0	0.019	76,316
600	5.0	0.019	78,947

C

1015 steel strength

F Temperature	psi Yield str
75	43,750
200	39,000
400	35,000
600	28,000
800	23,000
1000	18,000
1200	11,000
1400	6,000

D

Hardness measure of coalescer
HV 100gram
180
Tensile strength conv.
88,000 psi
Typical Yield str approx
75,000 psi

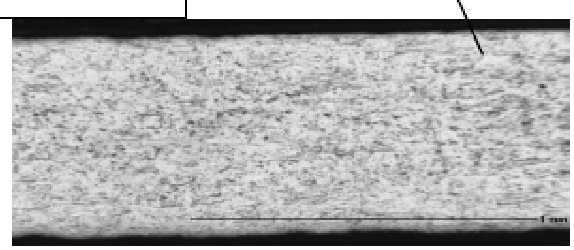


Figure 11

Subject coalescer had an as-manufactured hardness of 180 HV corresponding to a tensile strength of over 80,000 psi (D). The hoop stress on the coalescer (B, E) as a function of the compressor pressure shows a safety factor of 2-4 at temperatures up to 400°F. At temperatures of 1000 - 1400°F (A, C, B) the coalescer will plastically yield (bulge) and rupture within the normal operating range of the compressor (B).

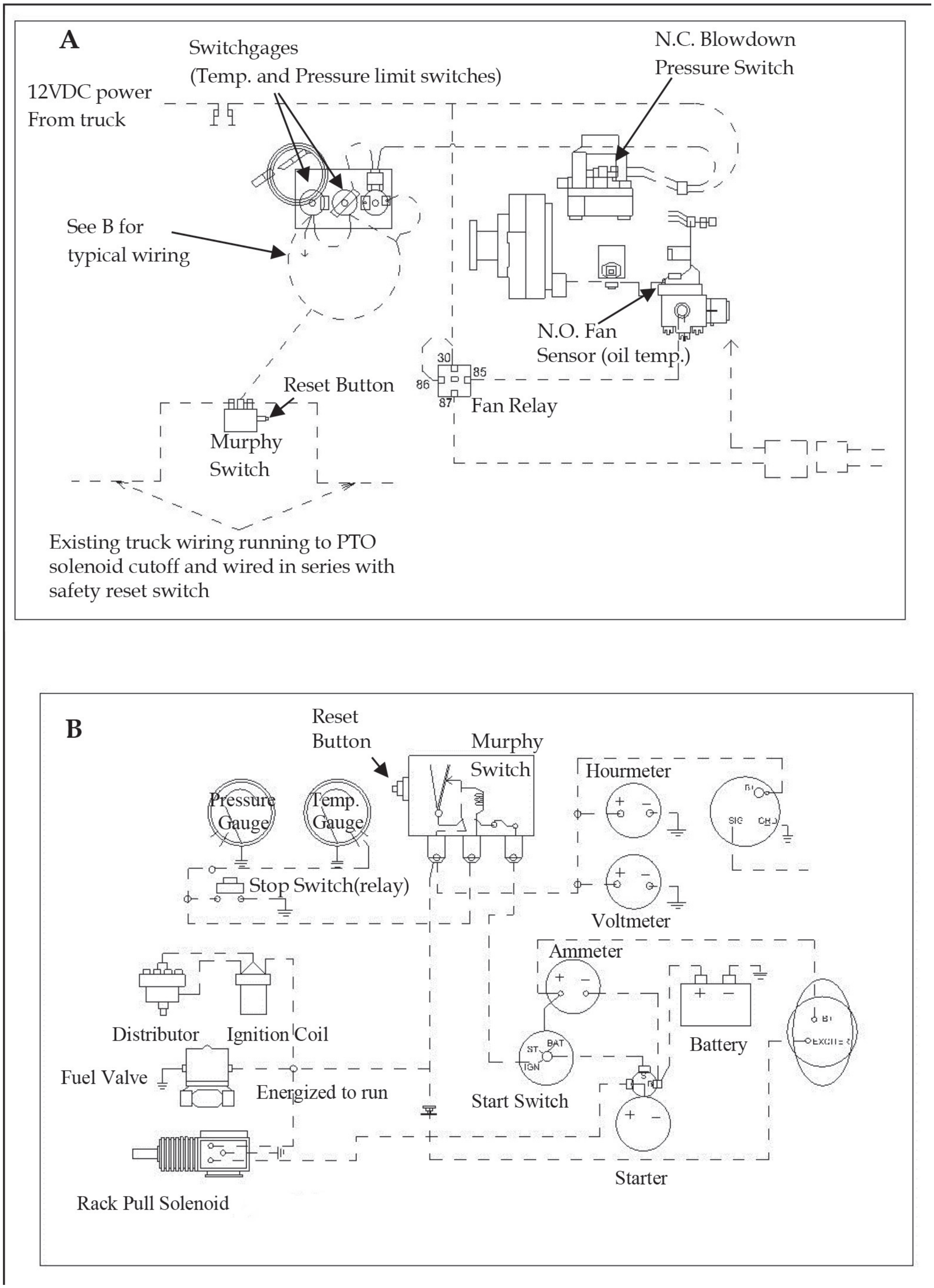


Figure 12
A. Diagram showing the air compressor manufacturer's subject safety shutoff circuit that allows the operator to manually override the out-of-limit condition and continue operating the air compressor system. B. Component manufacturer's design of a typical circuit (stop switch [relay] and reset button) resulting in same override outcome.

gauge, and pressure gauge

The reset button (and safety shutoff), temperature gauge and pressure gauge are individual components that are designed and produced by the same company to perform as a control system that monitors the air compressor temperature, and pressure — and that shuts the system down if one or both exceed its operating limit. Although these components are sold separately, the company provides design drawings on how to connect them together as a control system. **Figure 12** shows the control circuit of the subject air compressor with the component manufacturer's circuit design for comparison.

The subject air compressor system was monitored with the temperature and pressure gauges that were electrically connected to the reset button (and safety shutoff). The evidence of a faulty oil cooling system suggested that the gauge setpoints for the temperature and pressure thresholds were operating properly to shut the system down due to overheating. The switches within the gauges remain open during typical operation and close when the condition exceeds its threshold. The gauges were damaged during the incident, rendering them unsuitable for testing.

The reset button (and safety shutoff) was used to halt the system when the operating limits were exceeded. The device was a mechanical latching switch with an externally accessible reset button to initialize the switch to the closed (latched) position, as seen in **Figure 13**. The latched position allowed the compressor to run while the unlatched position shut the system down. The device contained an internal electromagnet that was electrically connected to the vehicle battery at one pole and to ground

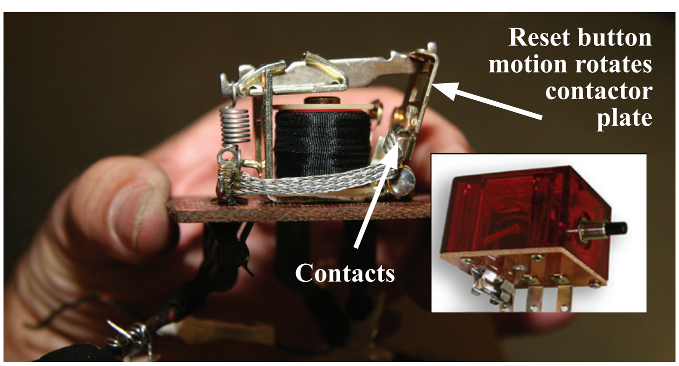


Figure 13
The subject safety shutoff switch in the unlatched position. To reset, push the spring-loaded contactor to the left and lock it in place on the hook. When the electromagnet is energized, the hook is pulled down, causing the contact linkage to unhook and rotate to the unlatched position (system out of limit condition).

through the temperature and pressure gauges at the second pole. **Figure 13** shows the device with the outer housing removed to show the internal electromagnet and latching device. Upon actuation of the electromagnet by a gauge over-limit condition, the electromagnet mechanically unlocks the latching mechanism by pulling the hook arm down and releasing the contacts to open and the system to shut down. Pressing the reset button forces the contacts closed, which engages the air compressor whether or not the electromagnet is active.

The subject reset button (and safety shutoff) switch was tested by connecting it to exemplar temperature and pressure gauges matching the manufacturer and model of those involved in the incident. Continuity through the contacts was measured. The testing showed that the reset button (and safety shutoff) switch operated as designed; therefore, the functionality of the component was not defective or faulty. However, depressing and holding the reset button closes the contacts and restarts the system regardless of the temperature and/or pressure condition of the system. Thus, it was possible to hold the reset button to engage the contacts and operate the system in either or both of over pressure/over temperature condition(s). Testimony agreed that the operator was using the reset button to override the system at the time of the coalescer rupture.

System and Component Design

The system/component design was evaluated relative to the accident events. The installation's influence on the accident events is treated separately in another section. Generally speaking, system design should be holistic in approach[6]: vehicle, air compressor system, installation, maintenance, and training. This system had technical interaction at each of these levels. However, interaction alone does not ensure that shortcomings will be prevented. Such was also the case as evidence showed failures between the manufacturer and safety control component supplier as well as the manufacturer and system installer.

Through the testing and evaluation process, it was determined that all individual components operated as intended by their manufacturer except for the heat exchanger fan grill. However, the air compressor (coalescer rupture) was found to fail unexpectedly due to the design of the reset button (and safety shutoff) in the safety shutoff circuit of the air compressor. The design of this component/system is discussed below.

<u>Design of reset button (and safety shutoff) including safety shutoff circuit</u>

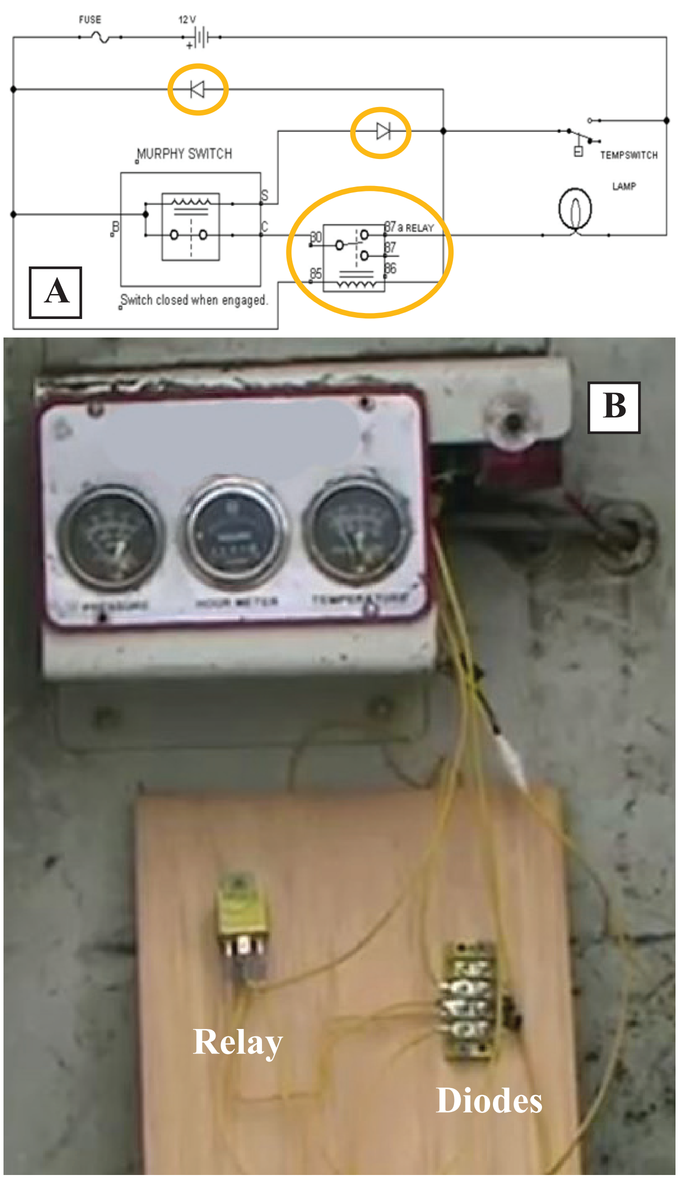


Figure 14
A) The authors' safety shutoff circuit that deactivates the system and prevents the operator from energizing the air compressor while an out-of-limit condition exists.
B) The revised safety shutoff circuit installed and tested on the exemplar truck and air compressor. The out-of-limit condition cleared before the operator could restart the system.

For a circuit to be an acceptable safety shutoff circuit, it must at least accomplish the following criteria.

1. The circuit must monitor a state of the system in a timely manner and provide needed feedback to the control circuit.

2. The control circuit must receive the needed feedback from the monitoring devices and react in a manner that allows the system to regain control of conditions through an orderly shutoff before bad things happen.

The device in question could perform the above functions. More to the point, the device in question did this function during the events of the subject accident. However, due to the device's function as a reset button, the device had a flaw in its functional behavior. The reset button provided a method to activate the system while the present state of the system was outside of its critical operating parameters. Thus, the reset button acted as an override of the intended safety device.

The inherent danger in this flaw is that while the air compressor is operating in an already dangerous condition, the condition can get worse[2, 7-9]. In this case, it was found that the broken fan on the heat exchanger allowed the oil temperature to continue to increase when the compressor was actuated with the reset button. The high oil temperature led to the flash fire in the coalescer, causing it to rupture.

This finding led to a redesign of the subject control circuit that would prevent the restart of the air compressor while it is out of its intended operating parameters. Again, a schematic of the subject electrical circuit is shown in **Figure 12**. The control circuit was redesigned using a 12-volt relay and two suppression diodes. The revised design allows the system to shutdown at an over-limit condition and prevents the operator from restarting the system until the over-limit condition has reversed (i.e., temperature and/or pressure is back in operating range).

A schematic of the revised design is shown in **Figure 14**. The revised design was fitted onto the exemplar truck, and testing showed that the design prevented manual override of the air compressor by the operator. The engineering desire to eliminate hazard conditions through the design process has been well discussed[10, 11].

The redesign used a relay identical to those already being used in the system. The cost of the redesign was less than $10 per unit.

Installation Design and Fitness

The air compressor system was installed on the truck by a third-party company that supplied the finished unit to the utility company. The installation created at least four situations that were critical to the eventual injuries in this case. The installation was questioned on the following points:

- Location and orientation of the heat exchanger
- Location of the coalescer
- Location of the temperature gauge, pressure gauge, and reset button cluster
- The open hole cut in the step at the location of the coalescer

Problems with the failure of the fan grill support wires and fires/rupture of the coalescer were reported by the manufacturer during depositions in the case. The installer also had knowledge of the coalescer fire/ruptures.

Never was a method of reporting and evaluating these incidents acknowledged by either the manufacturer or installer. A methodology[12] to evaluate the prior failures and consider changes to design could have led to improved designs for the heat exchanger fan grill, its placement, and the coalescer protection and placement.

Location of heat exchanger

The location of the heat exchanger was questioned due to the exposure of the fan grill to road debris and the fact that the fan supports failed in fatigue. As was found in this investigation, the fan grill supports the fan, which is critical to the cooling of the compressor oil. The compressor manufacturer offered an alternative heat exchanger that installs vertically, forward of the engine in the location of the vehicle radiator (shown as the typical installation in product manual, **Figure 15**). The weakness in the grill design for horizontal installation was known to the manufacturer and testified to by their expert.

Location of the coalescer

The coalescer was known to both the system manufacturer and the installer to be susceptible to failure by rupture and fire. Its location should be a point of interest based on this history and the potential for harm if it failed. Locating the coalescer behind the heavy metal steel step provided significant protection. However, as shown in an analysis of the oil path at rupture in this case, the oil can blow under the step to exposed locations along the ground. Given the subject events and other cases, an argument can be made for an oil deflection skirt to be added to the coalescer installation.

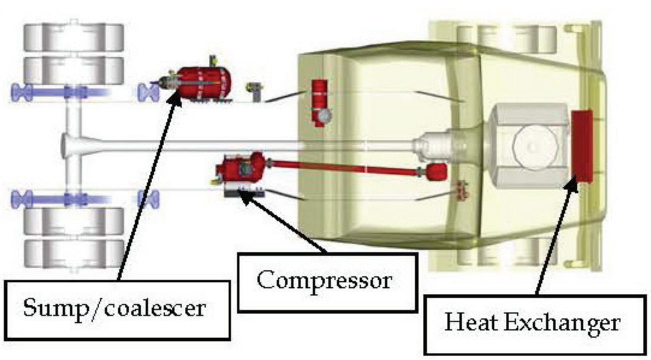


Figure 15
Typical system installation presented by system manufacturer. Heat exchanger vertically mounted.

Open hole cut in the step at the location of the coalescer

The passenger-side step had two holes cut; one for the gauge cluster and another for unspecified reasons (**Figure 2**). The open cutout happened to be located at such an angle to the coalescer that the rupture direction aligned with it.

The oil spray pattern analysis is shown in **Figure 16**. A significant question arose as to who cut the open hole. That question was addressed by a metallurgical examination of the cutting method. The edge of the cut (both in the open cutout and the cutout containing the gauge cluster) was most likely produced by a plasma arc process. **Figure 17** shows an examination of the cut edge that proved the commonality of the two cuts. Since both cutouts were made using the same method and the gauge cluster hole was cut by the system installer, it is likely that the open hole was also cut by the system installer. Neither the utility company nor the maintenance company had plasma cutters.

Although no one ever admitted to cutting the open hole, it is possible that the hole was cut to accept the oil level gauge on the sump. Such an arrangement was seen on the exemplar truck (**Figure 18**). However, the subject oil level gauge fell to the left of the step in the subject installation, and thus a hole prepared for it would not have been needed.

The open hole proved to be the opening that the burning oil needed to exit the truck and strike the operator over a large part of his body (**Figure 16**). The path of the oil, from the rupture through the open hole, was analyzed and shown to be consistent with the injuries in the case. A root cause of the injuries suffered was the open cutout in the step.

Location of the temperature gauge, pressure gauge and reset button cluster

Figure 16
Operator at location required to operate reset button. B-D. Perspectives of fluid spray from coalescer.

The subject gauge cluster was located only inches away from the coalescer (**Figures 2, 3,** and **16)**. Its location draws the operator to the coalescer at times of highest risk, that is, when the air compressor has been shutoff due to extreme temperature and/or pressure. In this case, the gauge cluster drew the operator to the coalescer to reset and override the safety switch (**Figure 16**).

The leads to the gauges and reset button are such that they can be run long distances; hence, the gauge cluster can be located anywhere on the vehicle. The location on the exemplar vehicle is on the back of the utility compartment. This is also the location that the utility company moved the gauge clusters to on its other trucks outfitted by the third-party installer.

Maintenance

There were serious failures in the maintenance of the air compressor system. The company contracted for maintenance of the truck did not perform maintenance on the compressor system per its records. The air compressor system did not receive oil or filter changes for five years prior to the accident. Testing of the filters and oil showed that they were not actively involved in the events of the accident. However, failure to find and repair the broken fan grill on the heat exchanger was a significant contributing factor in the events of the accident. The utility company and their maintenance company were at odds on who had responsibility for maintenance of the air compressor system.

Training and Warning

The issue of personnel training was not investigated. The organization and responsibilities of the work crew were likewise not investigated. The failure of the operator to understand the potential consequences of his actions is not in question. However, the failure of the manufacturer to understand the potential consequences of the operator's actions is likewise not in question.

The manufacturer never evaluated or considered the consequence of the reset button energizing the air compressor. The language on the reset button shown in **Figure 3** even invites the operator to attempt to restart the air compressor regardless of the present state of the system's temperature and pressure. The subject reset button instructions are different from the component manufacturer's instructions (**Figure 3**). However, the component manufacturer's instructions are even more inviting to hold the reset button. It is not operator error to perform a

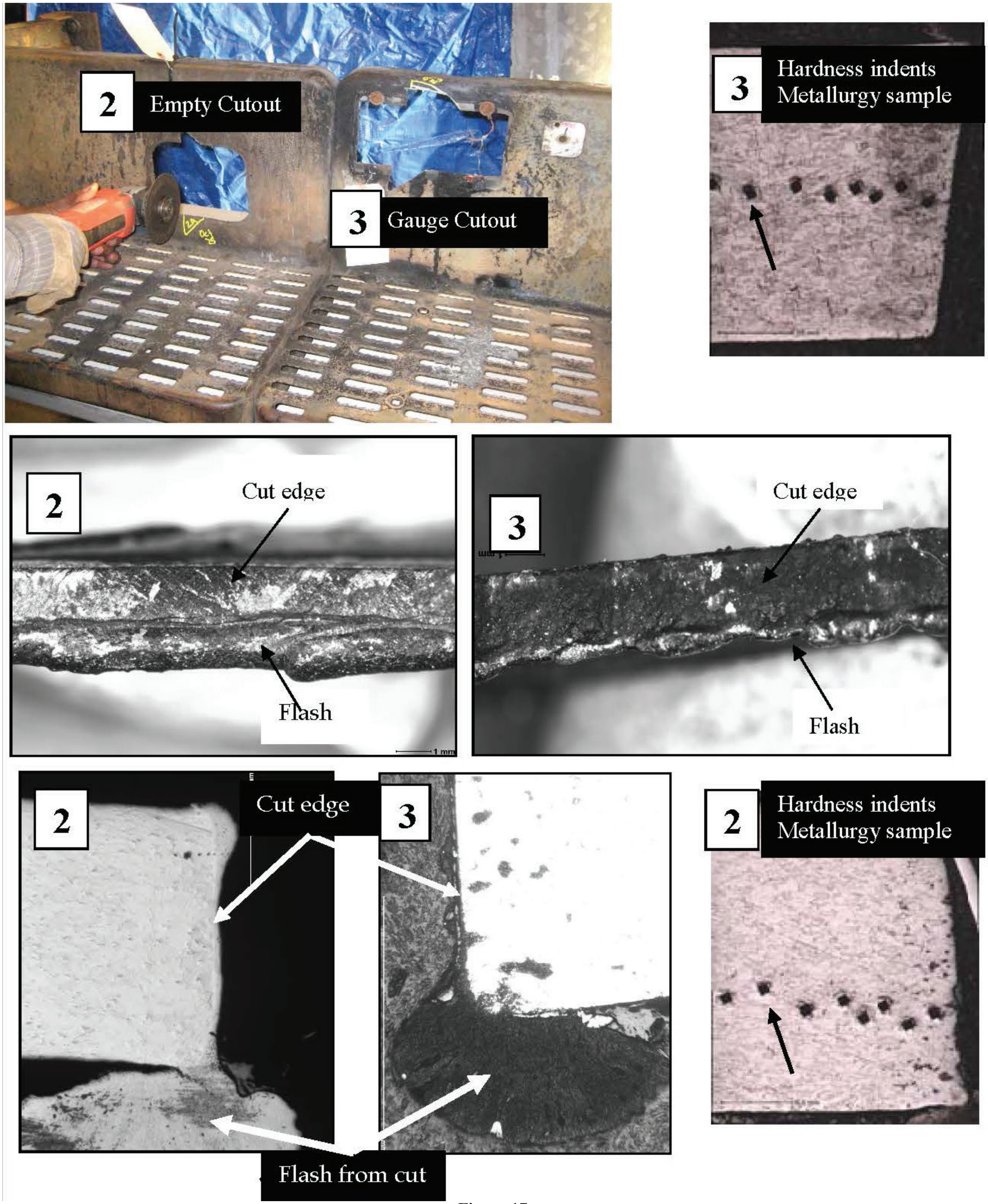


Figure 17

Samples taken from cutouts in step. 2. Cutout #2 is the empty cutout. 3. Cutout #3 is the gauge cluster cutout. The cut edge with metal and oxide flash was found to be the same in each cut. The hardness and metallurgical heat zone were found to be the same in both cuts.

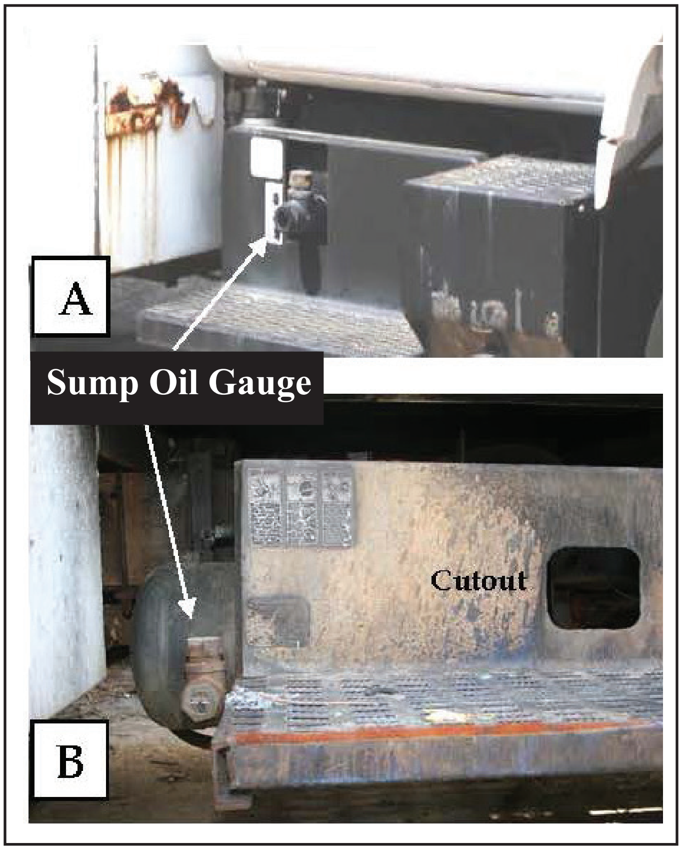


Figure 18
Exemplar truck oil gauge location. B.
Subject truck oil gauge location and open cutout.

function that is instructed on the component.

Conclusions

The rupture of the coalescer in an air compressor system caused its operator to be severely burned by flaming oil that was expelled under high pressure. The lengthy investigation that followed successfully demonstrated that most of the components of the system operated as they were intended. The causes of the accident were eventually narrowed down to error(s) in product installation, product maintenance, product use, and product design.

The events that occurred in this accident that directly led to causation of injuries — and thus could be referred to as root cause[13] — were, in sequence:

1. The cooling fan failed due to fatigue failure of its support wires causing the system to initially overheat,

2. The reset button on the safety shutdown was actuated by the operator, restarting the air compressor and causing a flash fire in the coalescer,

3. An open cutout in the step, in front of the coalescer, allowed burning oil at high pressure to pass through the step and caused severe injury to the operator.

Each of the above is factual, and mitigation of each would have separately prevented (or greatly reduced) the injuries suffered in this case. However, at the failure of the cooling fan, the initial overheating was properly handled by the system and shut off the air compressor. The manufacturer states: "SHUTDOWN SWITCH - Works in conjunction with temperature and pressure switch gauges, sending a signal to stop the compressor power source in cases of high temperature or pressure." The findings of this case showed that pressing the reset button overrides the safety shutdown and restarts the air compressor.

The reset button and safety shutdown should have been designed so that the air compressor would not energize until all out-of-limit conditions were cleared. As was demonstrated, this could have been done for less than $10 using components that the manufacturer was already using.

References

1. "Chevron Automatic Transmission Fluid MD-3", TTF-20, Chevron, September 24, 2014, [Online]. Available: https://bit.ly/2GHOEiF. [Accessed Nov. 29, 2018].

2. W. Perry, "Basics of Rotary Screw Compressor Lubricants", Kaeser Compressors, [Online]. Available: https://bit.ly/2LL9T1W. [Accessed Aug. 15, 2014].

3. H. E. Boyer, Ed., "Fractography and Atlas of Fractographs", Metals Handbook, vol. 9, 8th ed., Materials Park, OH: ASM International, pp. 324-330, 1974.

4. "Fracture Surface Analysis", Advanced Materials & Processes, vol. 165, no. 12, Dec., pp. 21 – 23, 2007.

5. M.F. Rothman, High Temperature Property Data: Ferrous Alloys, Materials Park, OH: ASM International, pp. 2.8 - 2.17, 1988.

6. Air Force System Safety Handbook, Air Force Safety Agency, Kirtland AFB, NM, pp. 27-28, July 2000.

7. S. J. Luzik, "How to Limit Fire and Explosion Hazards with Oil-Flooded Rotary Screw Compressors", Mining Engineering, pp. 881-884, September 1988.

8. T. Laughlin, “Combustion of Number 2 Fuel Oil, Domestic Pressure Atomizing Oil Burners, Pumps & Piping”, Controls, North Carolina Petroleum and Convenience Marketers, March 2009.

9. Liquid-Liquid Coalescer Design Manual, ACS Industries, LP, Houston, TX. [Online]. Available: https://bit.ly/2SjVn3P. [Accessed Nov. 29, 2018].

10. G. E. Dieter, Engineering Design, A Materials and Processing Approach, New York, NY: McGraw-Hill, 2000.

11. B.S. Dhillon, Engineering Design: A Modern Approach, Chicago, IL: Irwin, 1996.

12. M. Villacourt and P. Govil, “Failure Reporting, Analysis and Corrective Action System”, Sematech, Austin, TX., #94042332A-GEN, 1993.

13. R. K. Mobley, Root Cause Failure Analysis, Oxford, UK: Butterworth-Heinemann, 1999.

Bibliography

“Standard Practice for Defining the Viscosity Characteristics of Hydraulic Fluids”, West Conshohocken, PA: ASTM International, 2010.

“Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester”, West Conshohocken, PA: ASTM International, 1999.

“Standard Test Methods for Pour Point of Crude Oils”, West Conshohocken, PA: ASTM International, 1999.

“Test Method for the Determination of Total Acidity in Polyol Ester and Diester Gas Turbine Lubricants by Automatic Potentiometric Titration”, Warrendale PA: SAE International, 2006.

Forensic Engineering Investigations of Residential Clothes Dryer Fires

By William R. Keefe, PE (NAFE 481M)

Abstract

Residential clothes dryers are common in the United States, and thousands of residential fires involving clothes dryers occur each year. Forensic engineers are called upon to conduct scientific analyses of the causative factors in these fires. Forensic engineering investigations of clothes dryer fires consider design, installation, use, and maintenance of clothes dryers as well as evaluate ignition sources, first fuel ignited, fire containment and fire spread. A forensic engineering methodology for investigation of clothes dryers will be presented in this paper, drawing on experience from hundreds of residential clothes dryer fire investigations.

Keywords

Clothes dryer, lint, self-heating, dryer exhaust duct, transition duct, combustible plastic, forensic engineering

Introduction

The purpose of this paper is to provide information and general guidelines to the forensic engineer for investigating fires involving residential clothes dryers.

After a fire has occurred — and an origin and cause (fire) investigator suspects the area of origin to be at or within a clothes dryer — a forensic engineer is often called upon to investigate whether the appliance caused the fire. In some instances, the forensic engineer is engaged early in the investigation and has the opportunity to participate in the fire scene examination. In other instances, the fire scene examination is performed by other investigators, and the forensic engineer is called upon to evaluate the evidence and participate in laboratory examination of the artifacts. NFPA 921, *Guide for Fire and Explosion Investigations*, provides a reliable and recognized methodology for conducting the investigation[1].

Thousands of fires attributed to clothes dryers occur annually[2]. The proportion of fires involving electric dryers versus gas dryers is roughly proportional to the population of electric dryers in use versus gas dryers in use[3]. This paper addresses conventional vented residential clothes dryers. Condensing clothes dryers and heat pump clothes dryers, which have been recently available in the United States, are not explicitly addressed.

Residential Clothes Dryer Configurations

Typical vented clothes dryers in the United States dry laundry items by pulling a stream of heated air through the laundry load as it is tumbled in a drum rotating on a horizontal axis. The moisture-laden exhaust is discharged to the outdoors through an exhaust duct system. The source of heat can be one or more electric heating elements or a gas-fueled burner. Air is moved through the dryer by an electric motor driven blower located in the base of the dryer cabinet. The blower drive motor also powers drum rotation through a drive belt. The blower is positioned to pull the air through the dryer during operation so that most of the dryer is at a negative pressure during operation. Laundry is loaded into and removed from the drum through a door on the front of the dryer.

The intended normal flow path of air (and combustion products in a gas-heated dryer), through an operating dryer, is generally as follows (**Figure 1**):

- Ambient air (room air) enters the dryer cabinet

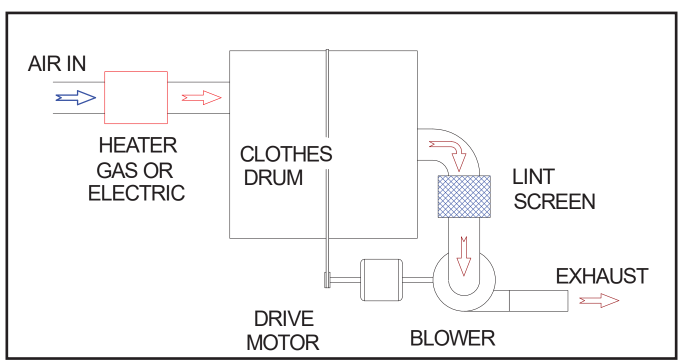


Figure 1
Clothes dryer air flow.

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through small louvered cabinet openings, cabinet seams, and other cabinet openings.

- Air passes through the interior of the dryer cabinet to the inlet of the burner or the electric heater assembly.

- The air is heated as it is pulled through the heater assembly. The heated air (and combustion products in a gas dryer) enters the rear of the dryer drum.

- The heated air is pulled through the drum where it picks up moisture and lint fibers from the laundry load.

- The air/moisture/lint mixture is then pulled through the lint screen trap where the screen collects some of the lint.

- The air with some lint is pulled from the lint trap into the blower.

- The blower pushes the air through the dryer exhaust tube at a positive pressure and into the external exhaust duct.

- The exhaust is discharged to the outdoors through the exhaust duct system.

There are several configurations of dryer design commonly found in use. One type, known as a bulkhead or open-back drum design, uses a drum that is open at its front and rear ends. Each end is supported by a bulkhead. The rear bulkhead forms the rear wall of the drum. There are two common variations of this open-back drum design.

In the first version of the bulkhead/open-drum design,

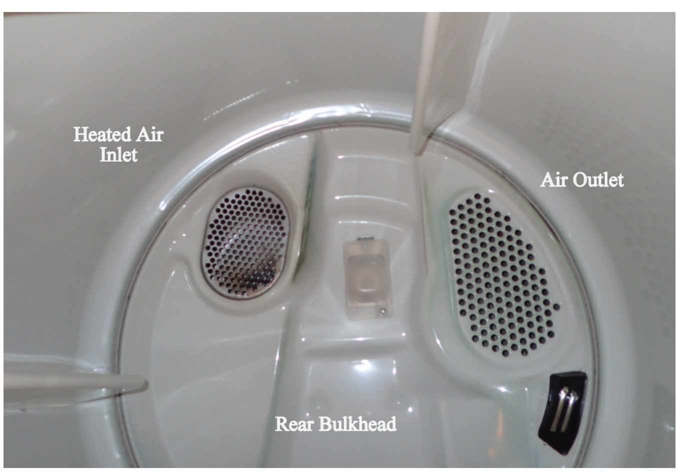

Figure 2
Bulkhead dryer.

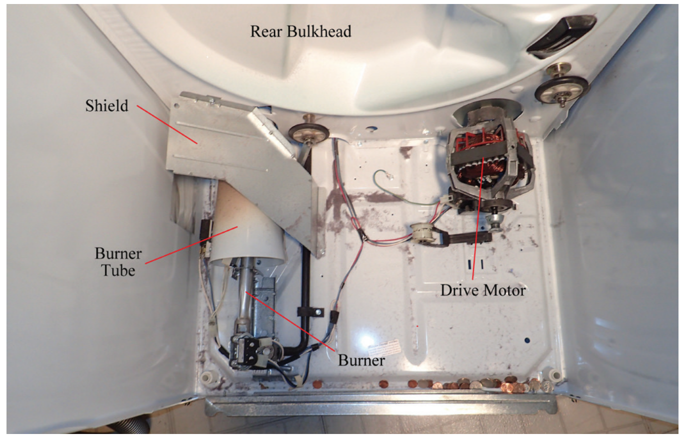

Figure 3
Base of gas-heated bulkhead dryer.

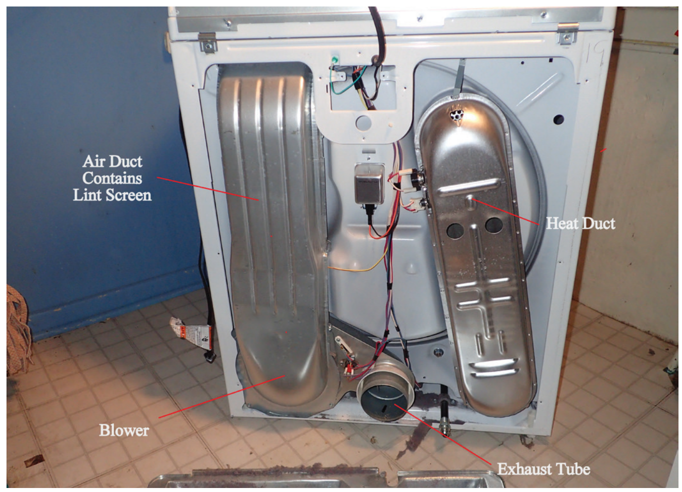

Figure 4
Rear side of bulkhead dryer.

heated air enters the drum through an opening at the upper left portion of the bulkhead and exits the drum through an opening at the upper right portion bulkhead (**Figure 2**):

In gas-heated versions of this design, the gas burner is located in the base of the dryer cabinet. The heated air is directed into the drum through a heat duct, which extends up the rear side of the bulkhead from the burner to the inlet opening. In electrically heated versions of this design, the heating elements are contained within a heater box or canister, located in the base of the cabinet or in the vertical heat duct. The discharge opening from the drum to the lint trap is located at the upper right portion of the rear bulkhead. A vertical air duct extends from that opening down to a blower at the lower, right rear corner of the dryer. The lint trap is positioned within that air duct. The blower discharges the exhaust through a horizontal, 4-inch-diameter duct on the rear side of the dryer (**Figures 3** and **4**).

Another variation of bulkhead/open-back dryer differs from the above described bulkhead dryer in that the location of the air discharge and lint trap is at the lower front edge of the drum. An air duct extends from that opening to a blower in the base of the cabinet. The lint trap is positioned within that air duct. The blower discharges the exhaust through a horizontal 4-inch-diameter duct on the rear side of the dryer (**Figures 5** and **6**).

In gas-heated dryers of this type, the gas burner is located in the base of the dryer cabinet. In electrically heated versions of this design, the heating elements are contained within a heater box or canister, also located in the base of the dryer. The heated air is directed into the drum through an opening in the upper right portion of the bulkhead. A heat duct extends up the rear side of the bulkhead from the burner to the opening (**Figure 7**).

Another dryer configuration is commonly known as a ball hitch or closed-back drum dryer. In a ball hitch dryer, the rear end of the drum is enclosed by a perforated metal sheet, which rotates with the drum. The front end of the drum is supported by the front cabinet panel. The rear end is supported by a rear drum support shaft and ball hitch, which extends from the center of the rear side of the drum (**Figures 8** and **9**) to a support bearing (**Figure 10**) on the rear wall of the cabinet. In one gas-heated ball hitch design, a burner tube is located at the lower left portion of the cabinet base. A heat duct extends upward from the burner discharge to a heater pan, located on the rear side of the drum. The heater pan is a vertically oriented shallow cylinder located on the rear side of the drum (**Figure 11**). Heated air and combustion products flow from the burner into the heater pan and then through the perforations in the rear side of the drum. The discharge opening and lint trap are located at the lower front edge of the drum (**Figure 12**). Exhaust air is directed from the drum to the blower through an air duct (**Figure 13**). In electrically heated ball hitch dryers, the electric heating element is arranged in a circular pattern in the heater pan directly behind the drum.

In all of the dryer configurations described above, the dryer operating cycle is controlled by electro-mechanical cycle timer controls or electronic control systems. The normal regulation of the dryer temperature and cycling of the heat source is controlled by an operating thermostat, positioned to measure the temperature of the air exiting the dryer drum. A typical thermostat control is set to open at 155°F and close at 135°F. Newer electronically controlled dryers use a thermistor in place of a mechanically actuated switch.

All of the described dryer configurations are also equipped with a high temperature limiting device that functions independently of the primary temperature control device. In all of these configurations the high temperature limiting device is located between the gas or electric heater and the inlet of the drum.

In many clothes dryer models, one or more additional temperature-limiting devices are included. These additional temperature-limiting devices are of the manual-reset or non-resettable (single use) type, are not accessible to the user without disassembling the dryer, and require manual reset or replacement before continued use of the dryer.

There are many variations of control arrangements in

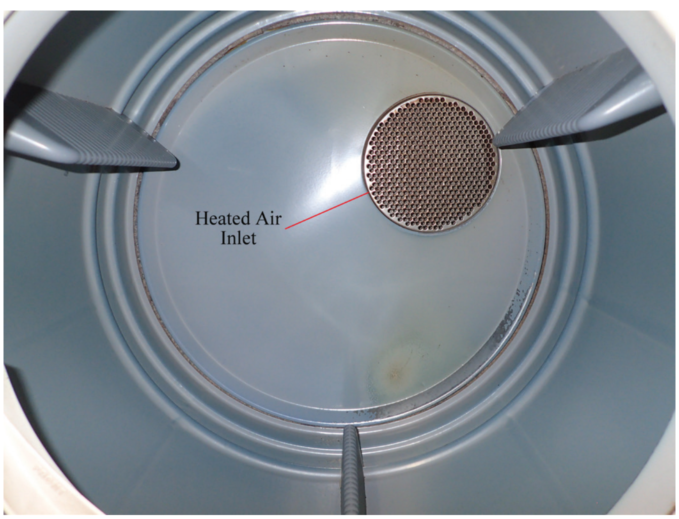

Figure 5
Variation of bulkhead dryer.

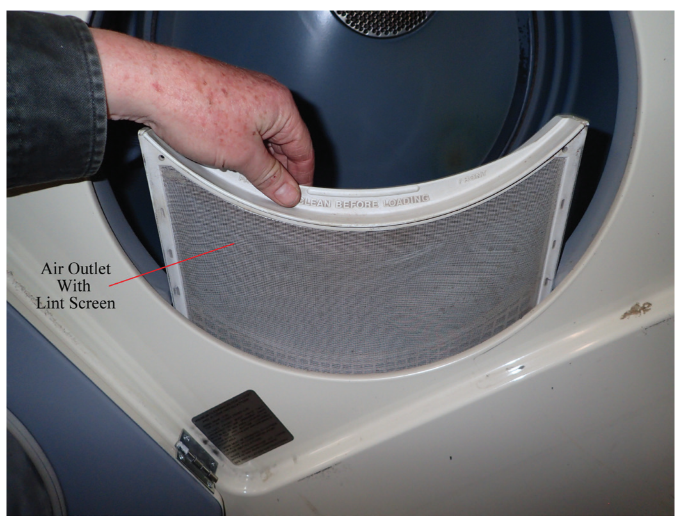

Figure 6
Variation of bulkhead dryer.

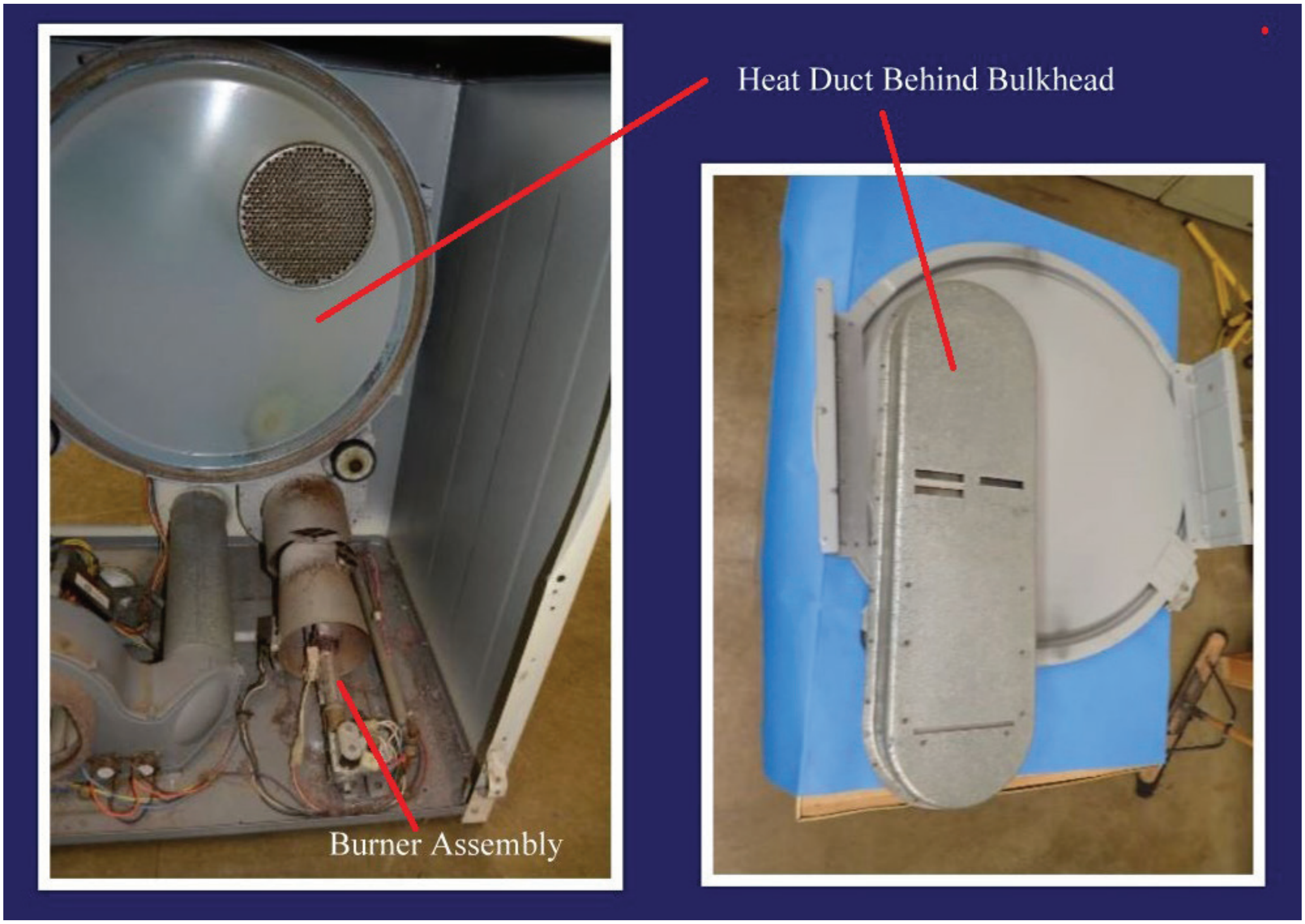

Figure 7
Variation of bulkhead dryer.

Figure 8
Rear side of ball hitch dryer drum.

Figure 9
Ball hitch.

Figure 10
Rear bearing assembly.

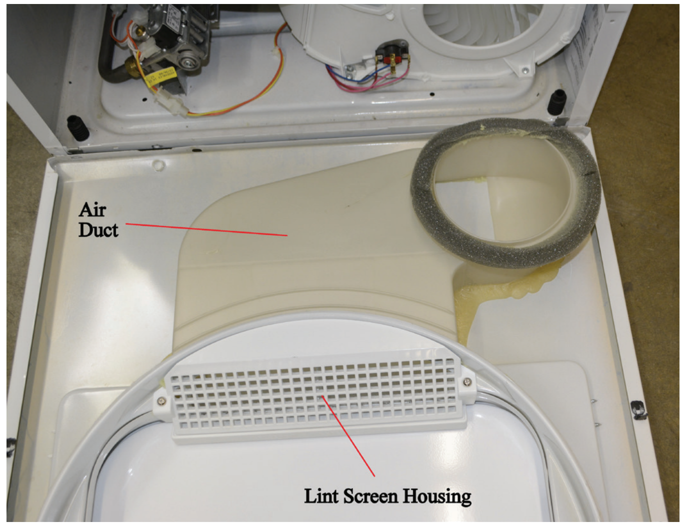

Figure 13
Ball hitch dryer.

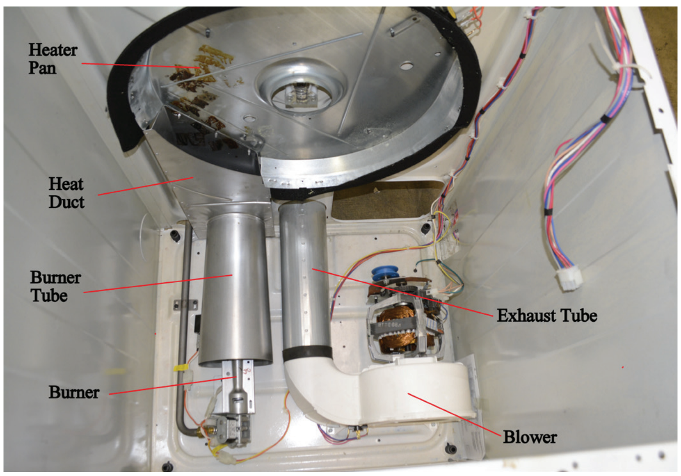

Figure 11
Base of gas ball hitch dryer.

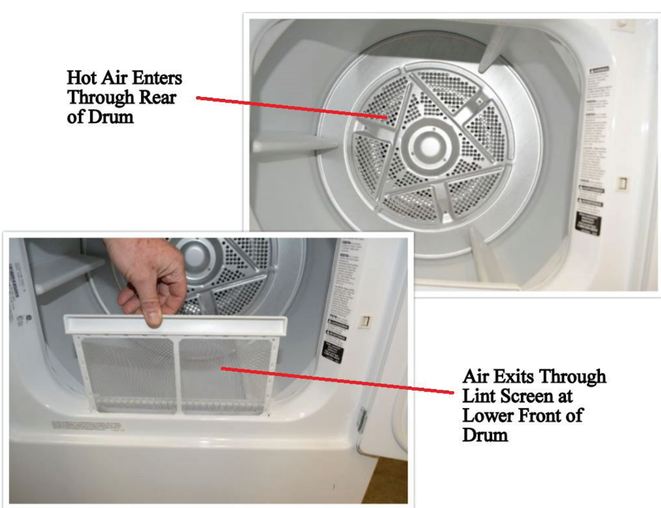

Figure 12
Ball hitch dryer drum.

residential clothes dryers. It is recommended to obtain a control schematic and parts list for the dryer model involved in an investigation before performing a detailed examination of the dryer.

In a normally operating dryer, the drum temperature will be slightly higher than the thermostat setting, likely somewhere between 150°F and 180°F. When the exhaust duct is restricted, airflow through the dryer is reduced. Since heated air is not being effectively moved through the drum, the drum temperature will actually be lower in a blocked vent condition. The temperature upstream of the drum, in the heater pan or heat duct, will increase. Instead of the heater cycling on and off in response to the operation of the operating thermostat, it cycles on and off in response to the operation of the safety thermostat (high temperature limit switch).

Airflow through the dryer can also be reduced by a large load or by leaks in dryer seals, upstream of the blower. Those conditions can also cause a dryer to cycle on the safety thermostat instead of the operating thermostat, even in a properly vented dryer.

Examination of the safety thermostat switch contacts will indicate if the switch has been cycling. The contacts on the high temperature limit switch from a gas dryer will generally have less damage, since the switch interrupts the low current from the gas valve coils. The switch contacts on a high temperature limit for an electric dryer will show relatively greater damage due to interrupting the larger current of the electric heating elements. **Figures 14** and **15** show the high temperature limit contacts from a

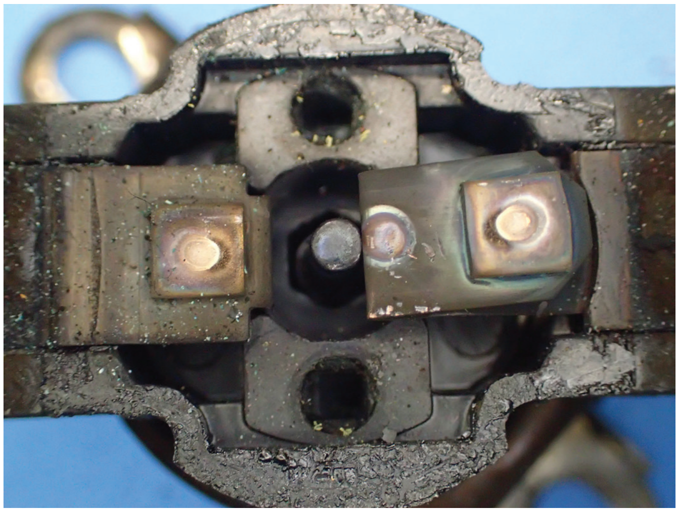

Figure 14
Contacts of gas dryer safety thermostat.

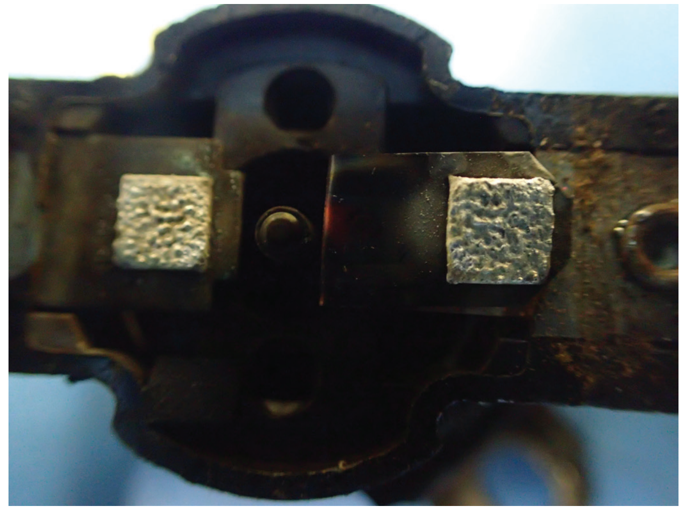

Figure 15
Contacts of electric dryer safety thermostat.

gas and an electric dryer.

Clothes Dryer and Related Standards

Residential clothes dryers are constructed and tested to comply with voluntary consensus standards. Electrically heated dryers fall under the scope of UL 2158 – Electric Clothes Dryers[4]. Gas-heated dryers fall under the scope of ANSI Z21.5.1 – Gas Clothes Dryers[5].

The March 2009 version of UL 2158 incorporated requirements for fire containment tests for electric dryers. The compliance date was March 20, 2013. Four separate fire containment tests are necessary to meet the requirements of the standard, including a drum load fire containment test with the dryer in operation, a drum load fire containment test with the dryer stopped, a base fire containment test with the dryer in operation, and a base fire containment test with the dryer stopped.

The ANSI Z21.5.1 standard incorporated similar fire containment testing requirements in the 2015 edition of the standard including four separate fire containment tests for each dryer design.

UL 2158A – Clothes Dryer Transition Ducts[6] contains requirements for the transition ducts used to connect a dryer exhaust to the permanent duct system in a residence. The first edition of this standard was published in 2011. Transition ducts were previously listed under UL Subject 2158A, Outline of Investigation for Clothes Dryer Transition Ducts[7], which was first published in 1996.

UL 94 – Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances[8] provides a method for rating the ignition characteristics of plastic materials. Flame class ratings range from the minimum of HB through the maximum of 5VA and 5VB. UL 2158 requires that plastic materials in clothes dryers meet one of three flammability classifications in UL 94, including the horizontal burn classification of HB or the more stringent vertical burn classifications of 5VA or 5VB.

Building Code Requirements for Residential Clothes Dryers

In most locations, residential clothes dryers are required to be installed in compliance with local building codes. UL 2158 requires that the installation instructions include a statement to install the clothes dryer according to the manufacturer's instructions and local codes. ANSI Z21.5.1 requires that the installation instructions include a statement that the installation must conform with local codes, or in the absence of local codes, with the National Fuel Gas Code, ANSI Z223.1/NFPA 54[9].

One frequently adopted model code is the International Residential Code (IRC)[10]. Requirements in the IRC for clothes dryers include the following:

- Clothes dryers shall be exhausted in accordance with the manufacturer's instructions;
- Dryer exhaust systems shall be independent of all other systems;
- Exhaust ducts shall terminate outside the building and be equipped with a backdraft damper;

- Terminations shall not contain screens;

- Exhaust ducts shall be constructed of metal and shall have a smooth interior finish;

- Clothes dryer transition ducts shall be metal, be limited to a length of 8 feet and shall be listed and labeled for the application;

- The maximum exhaust duct length shall not exceed 25 feet;

Exception: Where the make and model of the dryer is known the length shall be in accordance with the manufacturer's instructions;

- Installations exhausting more than 200 cfm shall be provided with a source of air for combustion and ventilation (make-up air).

- Closet installations require an opening with an area not less than 100 square inches.

ANSI Z223.1/NFPA 54 includes the following requirements for residential clothes dryer installations:

- Clothes dryers shall be exhausted to outdoors;

- Make-up air shall be provided in accordance with the manufacturer's installation instructions;

- Dryer exhaust ducts shall be independent from other vents and shall not be connected to an attic, crawl space or similar concealed space;

- Exhaust ducts shall be constructed of rigid metallic material. Transition ducts shall be listed for that application or installed in accordance with the manufacturer's installation instructions.

Clothes Dryer Exhaust Duct Systems

The exhaust duct system for a residential clothes dryer will generally contain a permanent duct system and a transition duct, which connects the dryer exhaust outlet to the permanent duct system. The permanent exhaust duct system is often installed during the construction of the residence and is concealed within the construction. The transition duct is often installed at the time the dryer is installed or may be re-used from a previous dryer.

Clothes dryer installation instructions contain recommendations for the exhaust duct system. Most instructions recommend that the duct system be constructed of 4-inch-diameter (minimum) rigid metal or flexible metal duct. The instructions will include one or more charts indicating maximum duct length and number of 90 degree elbow combinations for each type of duct. Maximum duct length is also dependent on the type and size of exhaust hood used in the system.

Many manufacturers include an alternate method of determining if a duct system is acceptable. That method is to measure the back pressure in the exhaust duct where it connects to the dryer with a manometer. The back pressure is measured with the dryer operating in a non-heat mode. Maximum allowable back pressure differs between manufacturers and dryer models. For example, Frigidaire permits a maximum back pressure of 0.75 inches of water column for most of its clothes dryer models. Samsung permits a maximum back pressure of 0.83 inches of water column for some of its dryer models.

The installation instructions provided with many newer dryers have more limitations for the use of flexible metal duct. For example, a 2010 installation instruction manual for a Whirlpool clothes dryer eliminates a flexible metal length chart and does not permit flexible metal vent to be installed in concealed spaces. Newer Frigidaire instructions limit flexible metal vent to a maximum length of 8 feet.

Transition ducts can be found constructed of rigid metal duct, flexible metal duct, or flexible plastic duct. Each type of transition duct has advantages and disadvantages. Although manufacturers recommend using rigid metal duct or flexible metal duct, a large portion of dryers are installed with flexible transition ducts, including UL-listed transition ducts, flexible foil ducts, and flexible vinyl ducts. According to a U.S. Consumer Product Safety Commission Survey, 42% of respondents indicated that their dryer duct was "flexible accordion type foil," and 16% reported that their dryer duct was constructed of "accordion-type white plastic"[11]. Transition ducts are not permitted to be installed in concealed spaces.

While rigid metal duct is preferred for dryer exhaust, it has some disadvantages when used for transition duct. It is difficult to obtain a good seal between the dryer exhaust outlet and the first transition duct fitting. It can be very difficult (if not impossible) to access both ends of the transition duct when installing the dryer. This is particularly true for under-counter installations, closet installations, and

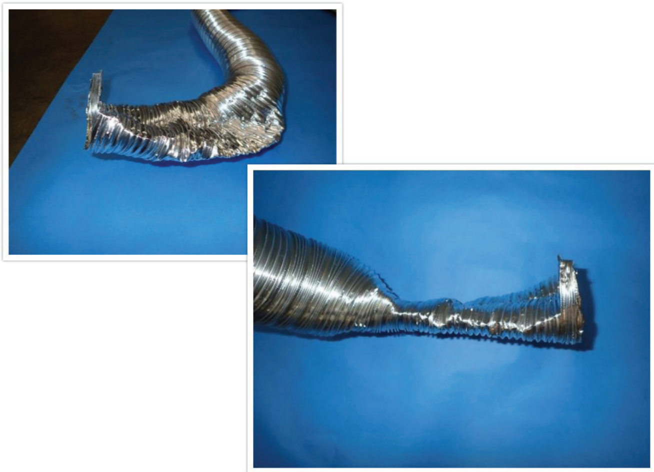

Figure 16
Crushed flexible metal duct.

alcove installations.

Flexible metal duct also has disadvantages. The interior surface has ridges that can collect lint. It has limited puncture resistance and poor resilience. When crushed or kinked during installation — or when the dryer is moved for cleaning — it will not return to its original shape (**Figure 16**). Recall that building codes, such as the International Residential Code and National Fuel Code, require clothes dryer transition ducts be listed for the application. Most flexible metal duct is not listed as clothes dryer transition duct.

UL 2158A contains requirements for clothes dryer transition duct. The standard includes tests for surface burning, flame resistance, bending, corrosion resistance, puncture resistance, impact resistance, tension, and torsion. Most UL-listed transition ducts that are currently available are flexible foil style ducts. UL-listed flexible foil transition ducts are also subject to being crushed or kinked but have a better ability to return to their original shape when repositioned.

UL-listed flexible foil clothes dryer transition duct is permitted by the installation instructions of many clothes dryer manufacturers for some of their models, including Whirlpool, Frigidaire (Electrolux), GE, Samsung, and LG. **Figure 17** contains a list of some dryer manufacturers that permit the use of UL-listed flexible foil transition ducts.

Lint

Lint is generated from laundry items such as clothing, bedding and towels. During use, movement and abrasion breaks down the fibers of the laundry items. Washing creates lint through mechanical agitation of the laundry load and the action of temperature, detergents and other additives. Additional lint is created in the dryer by the mechanical tumbling action with heat and air flow. Lint particles that become separated from the laundry items become airborne in the dryer. Those lint particles can be collected in the lint trap, discharged through the exhaust duct, and/or deposited within the dryer. Dryer lint can also contain pet hair and other contaminants from the load. Fabric abrasion tests have shown that 100 percent cotton fabrics experience a greater mass loss than 50/50 cotton/polyester fabrics[12]. **Figure 18** shows ignition temperatures for various textile fibers and textiles.

Dryer Manufacturer	Transition Duct Instructions
Whirlpool	If flexible metal (foil type) duct is installed, it must be a of a specific type identified by the appliance manufacturer as suitable for clothes dryers.
Frigidaire	In Canada and the United States, if metal (foil type) duct is installed, it must be of specific type identified by the appliance manufacturer as suitable for use with clothes dryers and in the United States must also comply with the Outline for Clothes Dryer Transition Duct, UL standard 2158A.
GE	In Canada and the United States, only the flexible metal (foil-type) ducts that comply with the "Outline for Clothes Dryer Transition Duct Subject 2158A" shall be used.
LG	Rigid or semi rigid metal ducting is recommended for use between the dryer and the wall. In special installations when it is impossible to make a connection with the above recommendations, a UL-listed flexible metal transition duct may be used between the dryer and wall connection only.
Samsung	In the United States, only those foil-type flexible ducts, if any, specifically identified for use with the appliance by the manufacturer and that comply with the Outline for Clothes Dryer Transition Duct, Subject to 2158A, shall be used.

Figure 17
Clothes dryer instructions (summarized from user manual) permitting UL-listed flexible foil transition duct.

Material	Ignition Temperature °F	Source
Wool	1112	Plastics Flammability Handbook[13]
Cotton Fibers	500	Ignition Handbook[14]
	490-750	NFPA Handbook - 19th Edition – Table 8.5.5[15]
Cotton	662	Plastics Flammability Handbook
	662	Khattab[16]
Polyester Fibers	680-750	NFPA Handbook - 19th Edition – Table 8.5.5[23]
Polyester	896	Plastics Flammability Handbook
Cotton/Polyester 50/50 Blend	842	Khattab

Figure 18
Textile fiber ignition temperatures.

Cotton has a heat of combustion of 19 KJ/g (8169 Btu/lb) and polyester has a heat of combustion of 24 KJ/g (10,318 Btu/lb)[13]. However, lint density is very low, and the resulting fuel load created by accumulated lint is low.

Lint Accumulation

Lint begins to accumulate in clothes dryers upon first use, even when the dryer is properly vented, and the lint screen is cleaned after each usage[17]. Lint also accumulates in the base of the dryer cabinet, on component surfaces and on wiring harnesses (**Figure 19**). In ball hitch dryers, lint also can accumulate in the heater pan and on the rear side of the drum. Reduced airflow through the dryer is likely to cause increased accumulation of lint. As lint accumulates in the internal air flow passages of a dryer and exhaust system it creates additional restriction to air flow. Lint accumulated on gas burner air intake openings can alter the size and shape of the burner flame.

Multiple potential paths are available for lint to travel from the laundry load to the interior of the dryer. During each cycle of the dryer, lint accumulates on the lint screen. As the lint screen becomes blocked, airflow through the dryer decreases. A significant amount of lint bypasses the lint screen and accumulates in the air duct, blower, exhaust tube, and external exhaust duct. Recall that the upstream of the blower, the dryer air flow path is at a negative pressure and downstream of the blower, the air flow path is at a positive pressure. Any leaks at internal seals within the dryer, downstream of the blower, will result in leakage of lint-laden exhaust into the base of the dryer. This leakage will increase with increased exhaust duct restriction. One such seal is between the blower discharge and exhaust tube (**Figure 20**).

The exhaust duct external to the dryer also operates at a positive pressure. A leak in that exhaust duct can leak lint-laden exhaust from the duct. On most dryers, cabinet

Figure 19
Accumulated lint in base of dryer.

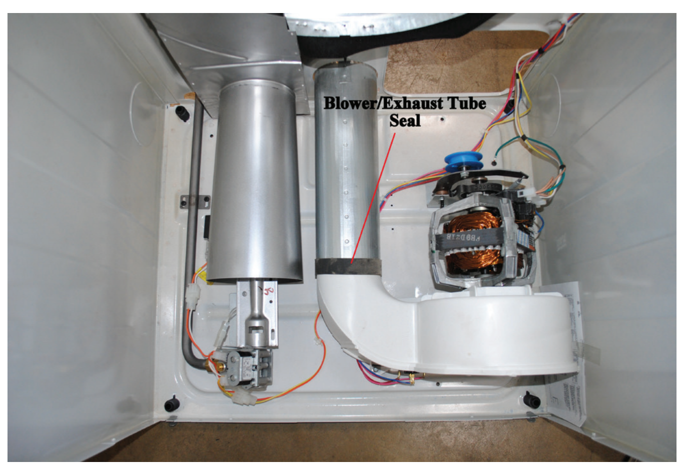

Figure 20
Positive pressure blower exhaust seal.

Figure 21
Exhaust tube and air intake louvers.

Figure 22
Non-crushed seal.

air intake openings are located on the back of the dryer near the first exhaust duct connection to the dryer. This has the potential to draw lint-laden exhaust back into the dryer cabinet through the air inlet louvers (**Figure 21**).

Air leaks at seals on the negative pressure side of the blower (upstream of the blower) can also lead to additional lint accumulation within the dryer and alter the patterns of lint accumulation within the dryer. For example, a leak at the front drum seal will permit air from the dryer cabinet to enter the front end of the drum. This air leaking into the drum will displace air that is normally pulled through the burner or heater box and through the rear of the drum. A large leak could result in increased temperatures upstream of the drum. In ball hitch dryers, this reduced airflow can cause additional lint accumulation behind the drum. A leak at the seal between the air duct (lint chute) and blower will have a similar effect. A leak at seal on the negative pressure side of the air stream will also act like a vacuum, pulling lint laden air to the leak. That can result in an abnormal accumulation of lint around the seal.

Figure 23
Crushed seal.

For example, in ball hitch dryers, the rear of the drum is supported by a single shaft in a bearing. The front end of the drum is supported by the front drum seal. During use, the seal can become crushed and create a gap to open at the lower end of the drum (**Figures 22, 23** and **24**).

Ball hitch-style dryers are equipped with a heater pan behind the drum. Lint can accumulate in the heater pan of ball hitch dryers. Larger accumulations occur in gas ball hitch dryers than in electric ball hitch dryers due to the presence of a seal between the heater pan and rear of the drum on the gas dryers (**Figure 25**).

Exemplar dryers can be examined to determine lint accumulation patterns and the amount of lint accumulated in a dryer. The gas dryer shown in **Figures 19** and **25** was in operation for eight years by a family of four. In that time, the interior of the dryer cabinet was not cleaned. The total weight of accumulated lint in the dryer at the end of that eight years was 0.256 pounds. In a similar model gas dryer operated for more than 10 years, with no

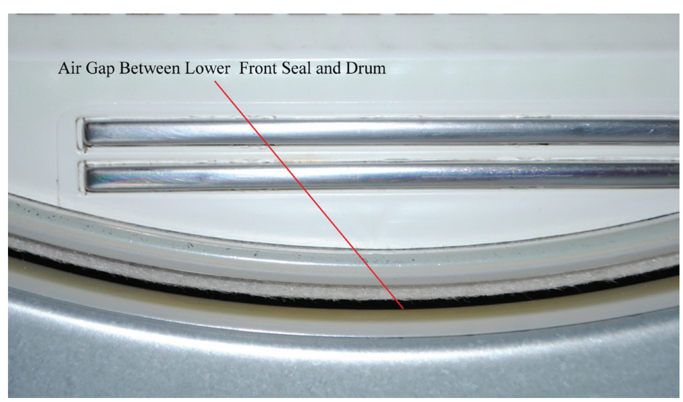

Figure 24
Gap created by crushed seal.

Figure 25
Charred lint in the heater pan of a ball hitch dryer.

cleaning of the interior of the dryer cabinet, the weight of the accumulated lint was 0.086 pounds. The fuel loads provided by the lint in those dryers, assuming 100 percent cotton, would be only 2091 Btu and 702 Btu, respectively.

Accumulated lint in a clothes dryer creates a risk of fire. Even though the lint provides a relatively small fuel load it can spread fire to other combustible materials in the dryer such as the load and/or combustible plastic components.

Cleaning and Maintenance

The UL 2158 standard for electric clothes dryers and the ANSI Z21.5.1 standard for gas clothes dryers contain requirements for the content in dryer instruction manuals. The UL standard requires that the instruction manual contain an instruction to clean the lint screen before or after each load and that the interior of the appliance and the exhaust duct should be cleaned periodically by qualified service personnel. The ANSI standard requires that the maintenance instructions include instructions for cleaning of lint screens and for periodic examination of exhaust systems. Many manufacturers recommend that cleaning should be performed "periodically." Other manufacturers recommend that cleaning be performed at intervals ranging from 12 to 18 months.

Cleaning of the interior of a clothes dryer is intended to remove accumulated lint. It requires partial disassembly/opening of the dryer cabinet and removal of the drum. Paying qualified service personnel to perform this procedure creates a significant expense over the life of the dryer. According to a U.S. Consumer Products Safety Commission Survey only 20% of respondents indicated that the inside of their dryers were ever cleaned.

Self-Heating of Dryer Load

According to NFPA 921, self-heating is the result of exothermic reactions occurring spontaneously in some materials under certain conditions, whereby heat is generated at a rate sufficient to raise the temperature of the material. Self-ignition is ignition resulting from self-heating, synonymous with spontaneous ignition.

In the context of clothes dryer fires, the mechanism of spontaneous ignition is generally the following:

- The laundry load consists of combustible materials.
- The load is contaminated by vegetable oils, certain animal fats or petroleum products.
- An exothermic oxidation reaction of the contaminant generates heat.
- Heat is trapped in the load, increasing the internal temperature,
- The increased temperature increases the rate of the reaction, further increasing the temperature.
- Smoldering ignition occurs inside the load.
- Possible transition to flaming ignition.

A number of factors must be present for spontaneous ignition to occur:

- The contaminant substance must be capable of self- heating.
- There must be enough contaminant so that self-heating is not limited by depletion of the contaminant before ignition occurs.
- The load must be large enough to contain the heat yet permit sufficient air to continue the reaction. The heat generation must exceed the heat loss.
- The load must be sufficiently porous to permit air into the interior of the load.
- There must be sufficient time after the dryer has stopped operating for self-heating to progress to ignition (hours).

Under normal circumstances, the airflow through an operating dryer will remove the heat generated by an exothermic reaction occurring in the load. Therefore, a fire caused by self-heating of the load will not occur while the dryer is in operation.

The potential for a laundry load to self-heat to ignition is greatly enhanced by heating the load during the dryer operating cycle. Most dryers have a cool-down period at the end of the drying cycle. The benefits of this cool down cycle are often eliminated when the load is too large to be adequately cooled during the cool down cycle, when the drying cycle is interrupted before the cool down cycle is started or completed (for example when a user opens the dryer door to remove one article before the dryer cycle is complete) or when the heated load is removed from the dryer before cooling and placed in a clothes basket or a pile on the floor or counter. Even the act of folding and stacking the laundry may not permit it to cool sufficiently.

When self-heating, progressing toward ignition occurs, large amounts of acrid smoke are likely to be produced[18, 19]. It is likely that smoke would be observed by any occupants present.

Tests were performed by Sanderson and Schudel[20] to determine if dryer lint self-heated when exposed to elevated temperatures. No self-heating of dryer lint was observed in their tests.

When a suspected cause of a clothes dryer fire is self-heating, it may be possible to collect a sample and have it analyzed to check for materials prone to self-heating. It may also be possible to collect a sample of water from the clothes washer drain hose for analysis.

Fuel Analysis

According to NFPA 921 – 2017, "Fuel analysis is the process of identifying the first (initial) fuel item or package that sustains combustion beyond the ignition source and identifying subsequent target fuels beyond the initial fuel."

In many residential clothes dryer fires, the first fuel ignited is lint. However, ignition of lint alone is unlikely to pose a significant fire hazard in a clothes dryer. To become a significant fire hazard, likely to create large amounts of smoke or spread the fire beyond the dryer, the lint must ignite secondary fuels such as leaking fuel gas, combustible components of the dryer or the laundry load. In many circumstances, ignition of the load by lint ignition alone is difficult, such as in the early part of the cycle when the load is still wet or damp.

The potential for fuel gas feeding the fire, after the dryer has stopped operation, can be evaluated by leak testing the gas supply pipe and control valve assembly. If a leak is found, the flow rate should be measured.

The use of plastics in dryer components can provide a significant fuel load in a dryer. As mentioned, UL 2158 requires that plastic components meet one of three of the UL94 flammability classifications. Those classifications include HB (horizontal burn) or the more stringent vertical burn classifications of 5VA and 5VB. Components constructed of HB rated plastics may ignite more quickly when exposed to ignited lint or an ignited load. HB plastic will continue to burn even if the initial ignition source is removed and produce hot molten plastic that can spread in the base or flow out of the dryer cabinet and continue to burn outside the dryer[21]. A material classified as 5VA or 5VB is subjected to a flame ignition source that is approximately five times more severe than that used in an HB test. Also, the 5V specimens may not drip any flaming particles. 5V materials tend to self-extinguish when the ignition source is removed[22].

The fuel load provided by combustible plastic components within the dryer can be determined several ways. Information may be available directly from the manufacturer or through the discovery process. Another approach is to obtain exemplar parts from an exemplar dryer or purchase replacement parts. The parts can then be weighed, and data regarding heat of combustion of the material can be used to determine the maximum available fuel load provided by the component. Consideration should be given to non-combustible mineral fillers used in the material, which may reduce the fuel load. The UL 94 flame class ratings for the components should be determined.

For example, the plastic components in an exemplar dryer were removed and weighed. The combined weight of the blower, air duct, lint trap housing and lint trap was about 3.4 pounds. The material used for the parts was polypropylene filled with 20 percent non-combustible material. Polypropylene has a heat of combustion of 18,917 Btu/lb and the filled material had a heat of combustion of 15,134 Btu/lb. This would provide and available fuel load from the plastic components of 51,456 Btu[13]. In comparison, the accumulated lint in the dryer shown in **Figures 19** and **25** provided a fuel load of about 2091 Btu.

Replacement of plastic materials with metal would completely eliminate the fuel load provided by the plastic materials regardless of the flammability classification of the plastic materials. For example, some manufacturers utilized steel in the construction of lint trap ducts and blower housings.

If the unburned load is removed from the dryer at the initial discovery of the fire — or if the load is minimally fire damaged — it is obvious that the load would have provided little or no fuel for the fire. If the load is involved in the fire, it should be examined to determine what was in the load. The users may be able to provide information regarding the contents of the load. If the load contents can be determined, the available fuel load can be determined using published heat of combustion values for the materials involved.

In most residential clothes dryers not caused by self-heating of the load, the first fuel ignited is lint. However, ignition of lint alone is unlikely to pose a significant fire hazard in a clothes dryer. Therefore it is important to identify and analyze subsequent target fuels beyond the initial fuel.

Case Studies

Case Study 1 – Ignition of Lint in an Electric Dryer

A fire occurred in a four-year-old electric dryer during operation about 15 minutes after a drying cycle was started. The fire was witnessed by the user. The dryer vent system complied with the manufacturer's installation instructions. The dryer load consisted of a twin size fleece blanket. The blanket was minimally damaged by the fire. From a detailed lab exam of the dryer and other artifacts, it was determined that lint was ignited by the energized electric heating element and spread the fire to the plastic components. Most of the combustible plastic components, including the blower and air duct, were consumed (**Figures 26** and **27**).

Case Study 2 – Ignition of Lint in a Gas Dryer

A fire occurred in a four-year-old natural gas fueled clothes dryer during operation (**Figure 28**). The fire was discovered and witnessed by the user several minutes after it had been placed in operation. Upon discovery of the fire, the user stopped the dryer and removed the unburned, wet load from the dryer. From a detailed lab exam of the dryer and other artifacts, it was determined that the fire resulted from ignition of lint within the dryer (**Figure 29**). The source of the ignition was the gas burner. The fire spread to the combustible plastic components, including

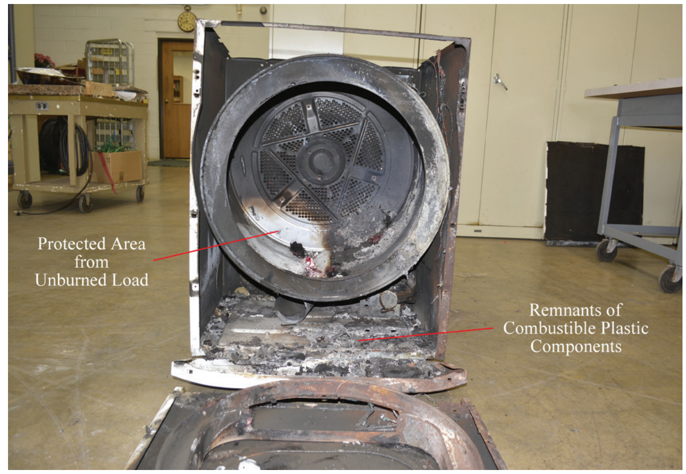

Figure 26
Front of partially disassembled electric dryer.

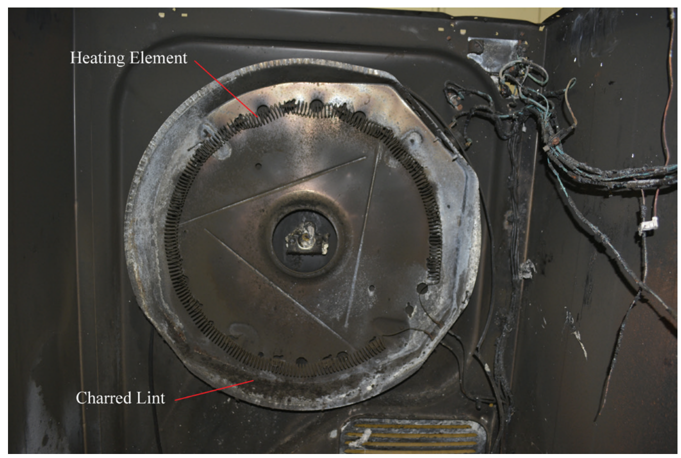

Figure 27
Heater pan of electric ball hitch dryer showing heating element and accumulated lint.

Figure 28
Dryer cabinet showing thermal damage from plastic fuel load.

the blower and air duct, and most of those components were consumed (**Figures 30** and **31**).

Figure 29
Heater pan of dryer showing accumulated lint.

Figure 30
Base of dryer showing mostly consumed combustible plastic components.

Figure 31
Base of dryer showing mostly consumed combustible plastic components.

Case Study 3 – Rear Drum Bearing Failure in An Electric Dryer

A 10-year-old electric ball hitch dryer started on fire while in operation. The homeowners witnessed the fire. Examination of the dryer determined that the rear drum support bearing had worn, permitting metal-to-metal contact between the rear drum support shaft and the bearing bracket (**Figure 33**). Eventually, the shaft was severed (**Figure 32**), and the rear of the metal drum baffle contacted the energized heating element. The resulting arcing

Figure 32
Severed ball hitch.

Figure 33
Wear on bearing bracket.

Figure 34
Load with minimal fire damage.

event and dispersal of molten metal into the dryer ignited lint within the dryer. The load had minimal fire damage (**Figure 34**). Most of the combustible plastic components burned (**Figure 35**).

Case Study 4 – Bra Underwire Contact with Energized Electric Heating Element

A nine-year-old electric dryer started on fire while in operation. A homemaker doing laundry heard a "clank" noise from the dryer and investigated. She opened the dryer door and did not initially observe anything wrong but could smell smoke. She removed the laundry load from the dryer, which was not burning or damaged. She got down low and saw flames under the dryer. Examination of the dryer revealed that a loose underwire from a bra had worked its way through the air holes in the rear of the drum and had contacted the energized heating element directly behind the drum. The underwire was welded to the element, and a large portion of the element was damaged (**Figures 36** and **37**). The resulting arcing event and dispersal of molten metal into the dryer ignited lint within the dryer. Most of the combustible plastic components burned. The dryer exhaust vent complied with the installation instructions.

Figure 35
Consumed plastic components.

Figure 36
Bra underwire welded to heating element.

Case Study 5 – Self-Heating of Laundry Load (Kitchen Towels)

Two identical laundry centers (washer/dryer combination machines) were in use in a high school home economics department (**Figure 38**). Both machines were less than one-year-old at the time of the fire. The laundry centers were used to wash and dry kitchen towels from cooking classes. This activity likely contaminated the towels with vegetable oils. Multiple brands and varieties of vegetable oils were found in the kitchen areas. On the day of the fire, both dryers were started with loads of kitchen towels after the last class of the day. A fire was discovered in one of the dryers several hours later, when the fire sprinkler system activated. Fire damage was limited to the one dryer. The other dryer was not fire damaged (**Figures 39** and **40**). Both dryers were examined in detail. In the fire damaged dryer, the damage was mostly limited to the drum. Minimal lint

Figure 37
Bra underwire welded to heating element.

Figure 38
Two identical model laundry centers.

Figure 39
Fire-damaged dryer.

Figure 40
Undamaged dryer and load.

Figure 41
Front of dryer.

was found in both dryers. No testable remnants of the load remained in the fire damaged dryer. However, the towels in both dryers had been used in the same manner with the same kitchen products. A sample of the towels of the unburned dryer was sent out for chemical analysis. The presence of unsaturated vegetable-type oils was detected in the sample. It was concluded that the fire was likely caused by self-heating of the vegetable oil-contaminated towels.

Case Study 6 – Dryer Drum Failure

A user discovered a fire in an operating gas clothes dryer (**Figure 41**). When the fire was discovered, the load was not burning. A detailed lab exam of the dryer found a large amount of charred clothing items in the base of the dryer (**Figure 42**). A large section of the dryer drum at the

Figure 42
Dryer base.

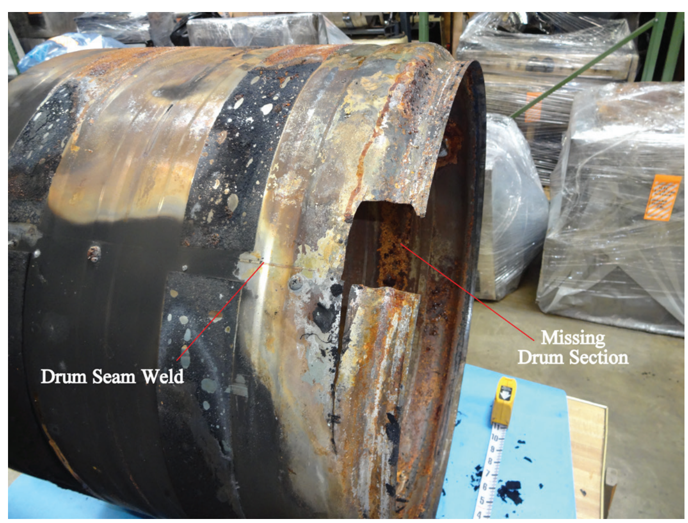

Figure 43
Rear edge of drum showing missing portion.

rear edge had detached from the drum (**Figures 43** and **44**). This missing section permitted small laundry items to fall into the dryer base near the burner assembly and onto the top of the burner tube where they were ignited. One edge of the fractured section was part of the longitudinal drum seam weld.

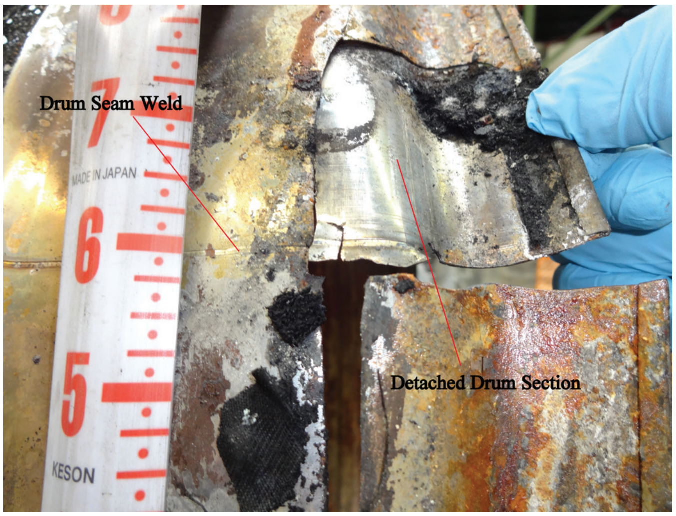

Figure 44
Rear of drum showing separated section of drum.

References

1. NFPA 921 - 2017. "Guide for Fire and Explosion Investigations". Quincy, MA: National Fire Protection Association, 2017.

2. "Clothes Dryer Fires in Residential Buildings (2008-2010)". FEMA Topical Fire Series Report, vol. 13, no. 7, 2012. U.S. Department of Homeland Security, U.S. Fire Administration. Emmitsburg, MD: National Fire Data Center.

3. "AHAM Analysis of Industry Data on Clothes Dryer Fire Incidents". Washington, DC: Association of Home Appliance Manufacturers, 2002.

4. UL 2158. "Electric Clothes Dryers". Northbrook, IL: Underwriters Laboratories, 2014.

5. ANSI Z21.5.1-2015. "Gas Clothes Dryers". Cleveland, OH: ANSI/CSA Group, 2015.

6. UL 2158A. "Clothes Dryer Transition Ducts". Northbrook, IL: Underwriters Laboratories, 2011.

7. UL 2158A. "Outline of Investigation for Clothes Dryer Transition Ducts". Northbrook, IL: Underwriters Laboratories, 1996.

8. UL 94. "Standard for Tests for Flammability of Plastic Materials for Parts in Devices and Appliances". 6th Edition. Northbrook, IL: Underwriters Laboratories.

9. NFPA 54. "National Fuel Gas Code". Quincy, MA: National Fire Protection Association, 2012.

10. International Residential Code, Country Club Hills, IL: International Code Council, 2006.

11. "Consumer Opinion Forum". Survey #3, Consumer Product Safety Commission, Bethesda, MD: 2010.

12. T. Vigo, "Abrasion and Lint Loss Properties of Fabrics Containing Crosslinked Polyethylene Glycol". Textile Research Journal, pp. 169-176, U.S. Consumer Product Safety Commission, 1991.

13. J. Troitzsh, "Plastics Flammability Handbook". Munich: Hanser, 2004.

14. V. Babrauskas, "Ignition Handbook". San Diego: Fire Science Publishers, 2003.

15. "Fire Protection Handbook - 19th Edition". Quincy, MA: National Fire Protection Association, 2003.

16. M. Khattab, "Spontaneous Ignition Behavior of Cotton Fabric Having Different Amounts of Polyester". Journal of Applied Polymer Science, vol. 62, pp. 1503-1507, 1996.

17. U.S. Consumer Products Safety Commission, "Final Report on Electric Clothes Dryers and Lint Ignition Characteristics". Bethesda, MD: US Consumer Products Safety Commission, 2003.

18. K. Gaw, "Autoignition Behavior of Oiled and Washed Cotton Towels". Fire and Materials. London, UK: Interscience Communications, LTD, 2005.

19. J. DeHaan, "Spontaneous Ignition Part II". Fire & Arson Investigator. Crofton, MD: International Association of Arson Investigators, Inc., 1996.

20. J. Sanderson, "Clothes Dryer Lint: Spontaneous

Ignition Does Not Occur in 16 Tests". Benton Harbor, MI: Fire Findings, 2006.

21. "Reducing Injury and Damage Related to Electric Dryer Fires: Fire Containment Tests for the Second Edition of UL 2158". Northbrook, IL: Underwriters Laboratories, 2011.

22. Underwriters Laboratories, "Plastics Testing". [Online]. Available: https://bit.ly/2StDb88. [Accessed 11 12 2018].