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# 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.

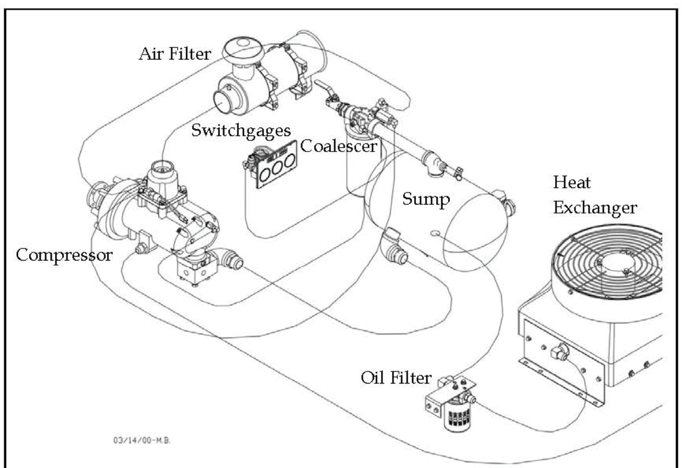


**Figure 1**
Diagram of air compressor system showing the major components.

## 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.

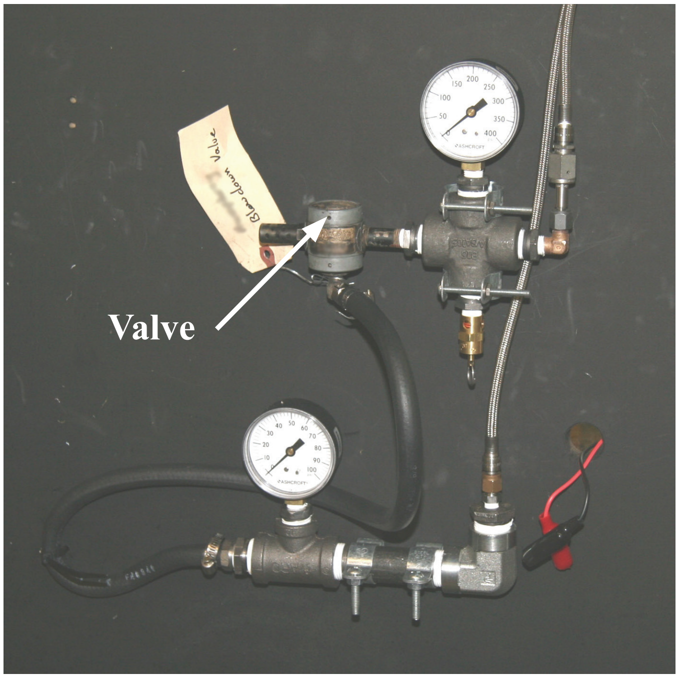



**Figure 4**
Test apparatus used to test the automatic blowdown valve and the pressure switches. The system is shown with the automatic blowdown valve installed.

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

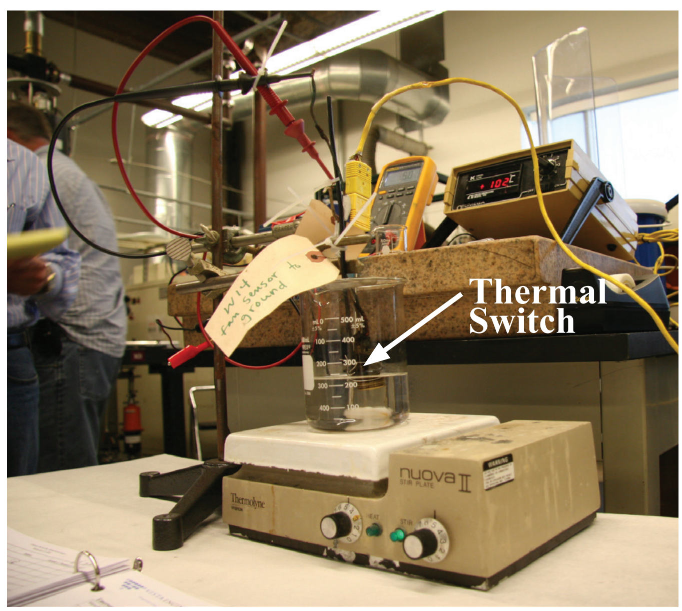



**Figure 5**
Test apparatus to measure the high and low temperature threshold of the thermal switch used to energize the relay controlling the heat exchanger fan motor.

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"

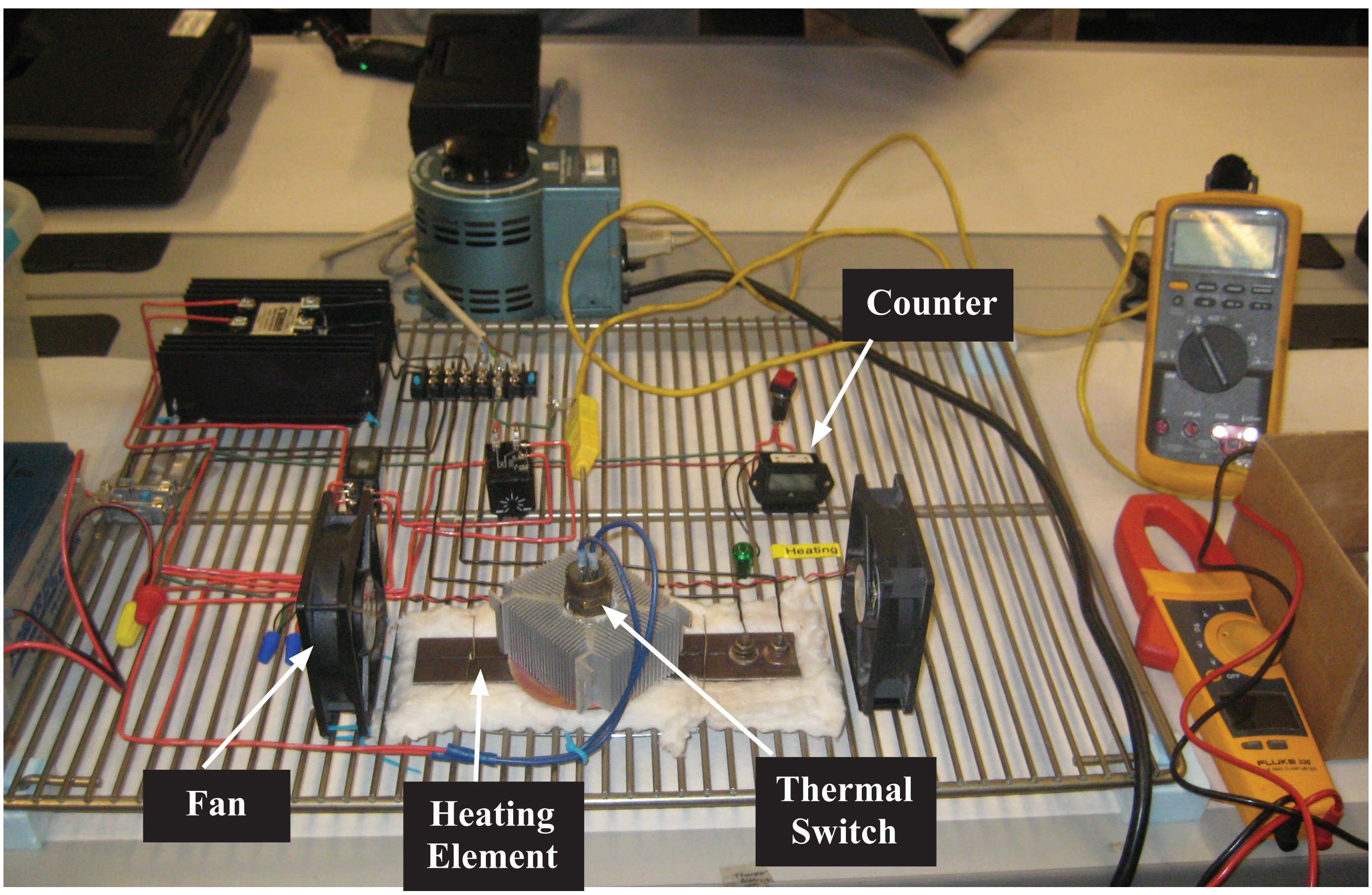



**Figure 6**
Test apparatus to measure cyclic temperature performance of thermal switch.

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**.

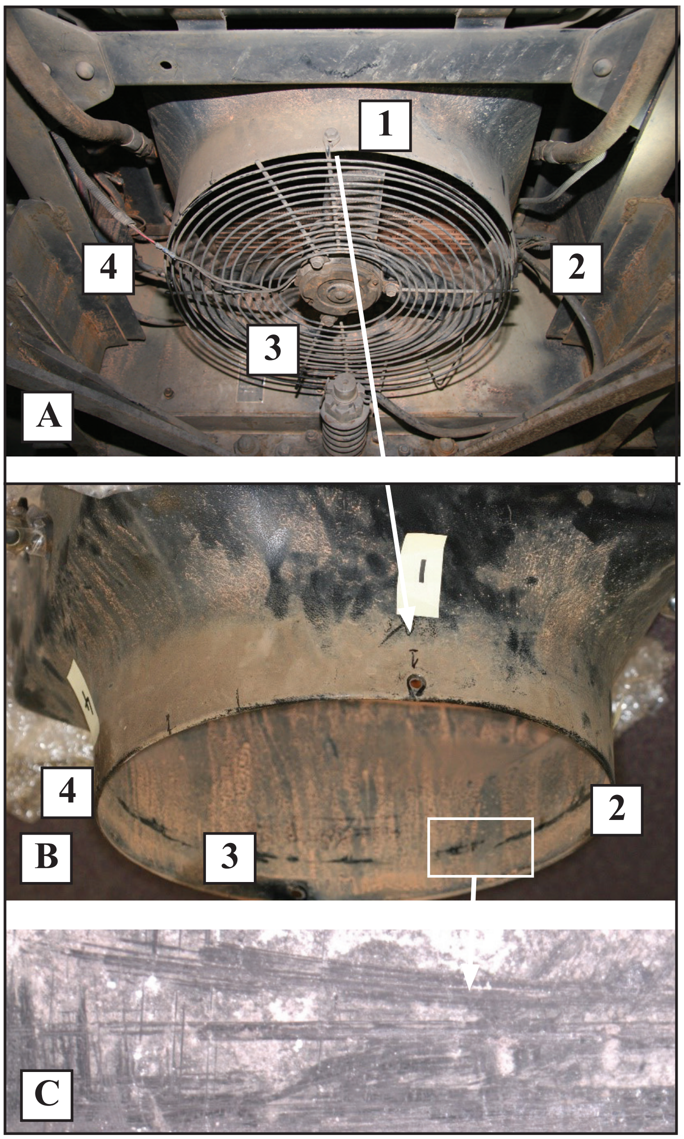



**Figure 7**
Subject fan shown at top (A) with its four grill support wires identified as shown (1 – 4). Witness marks on the inside surface seen in B and C of the heat exchanger shroud showing that the fan ran against the shroud for short time before binding. The grill was held in place at wire [1] 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.

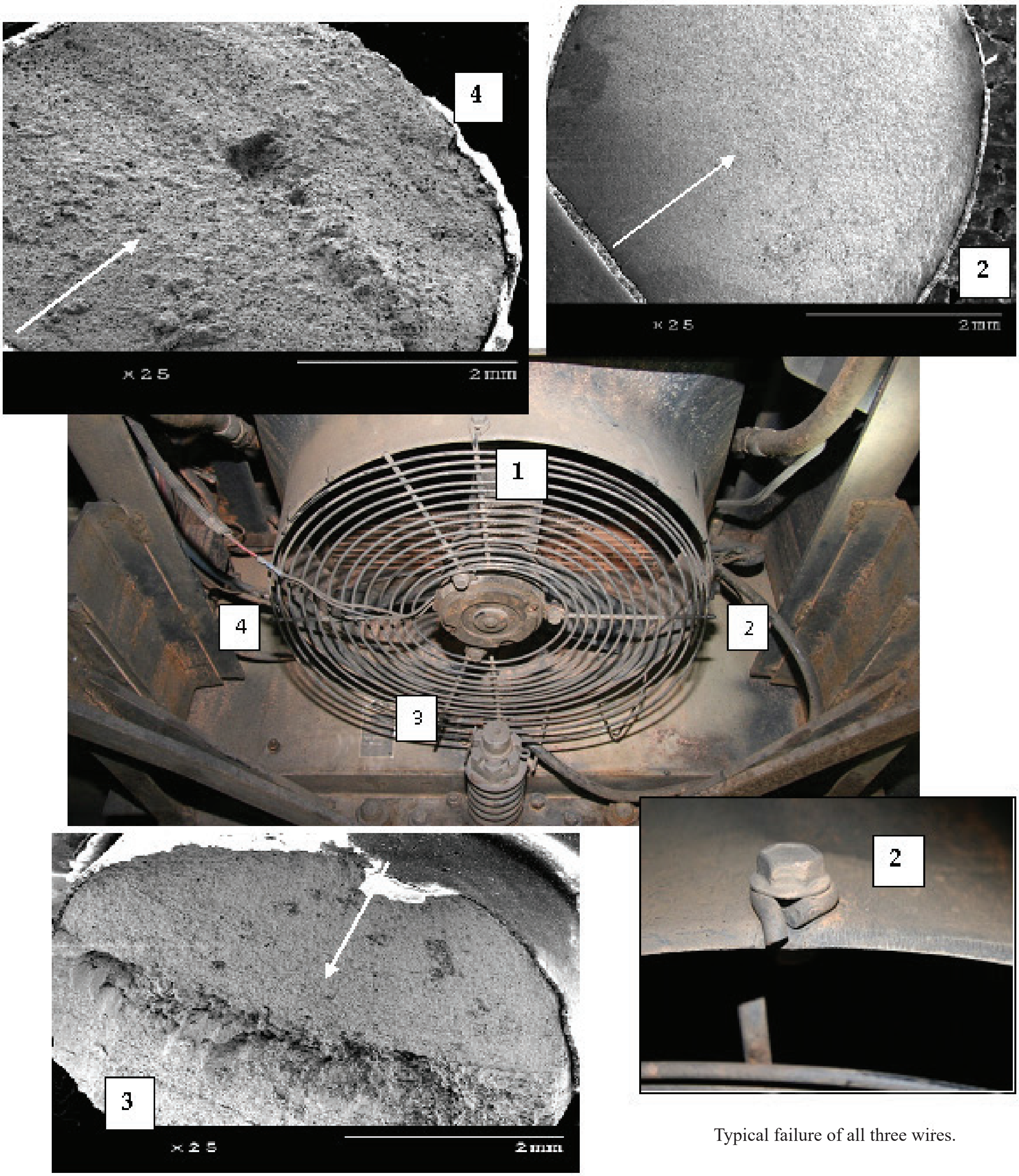
Scanning electron microscope (SEM) examination of the broken wires showed they had failed in fatigue — and failed progressively in order 2 – 4 – 3 (**Figure 8**). The root cause of the fan failure was fatigue of the grill support wires. The wires were overloaded by the weight of the fan motor and blades 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.

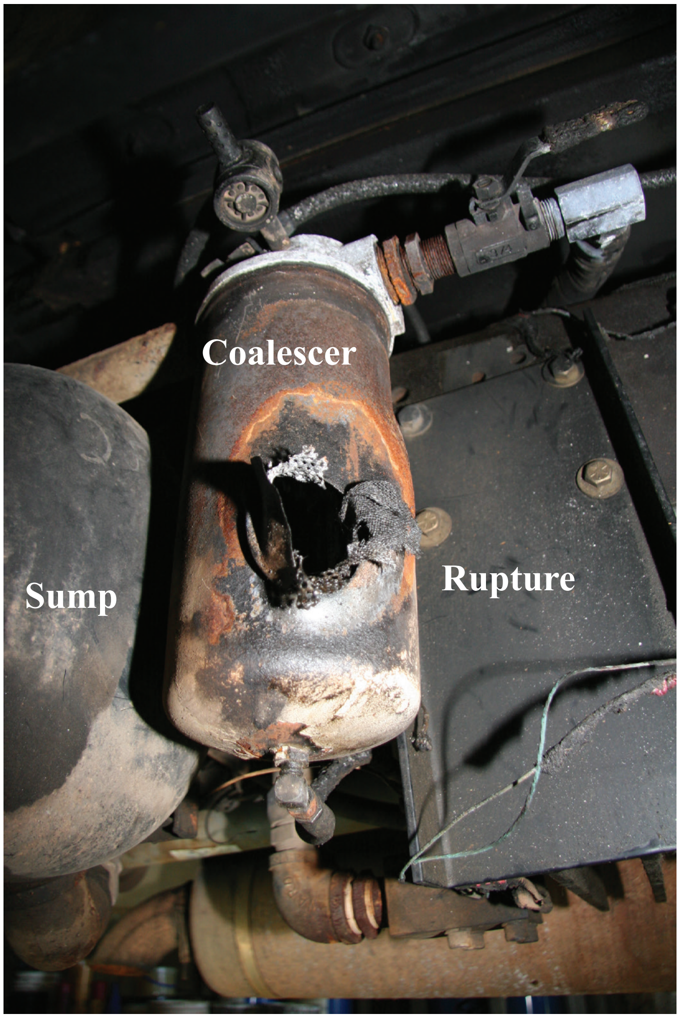



**Figure 9**
Image of the coalescer rupture after the step was removed.
The coalescer is located forward of the sump
directly behind the rear hole in the passenger side step.

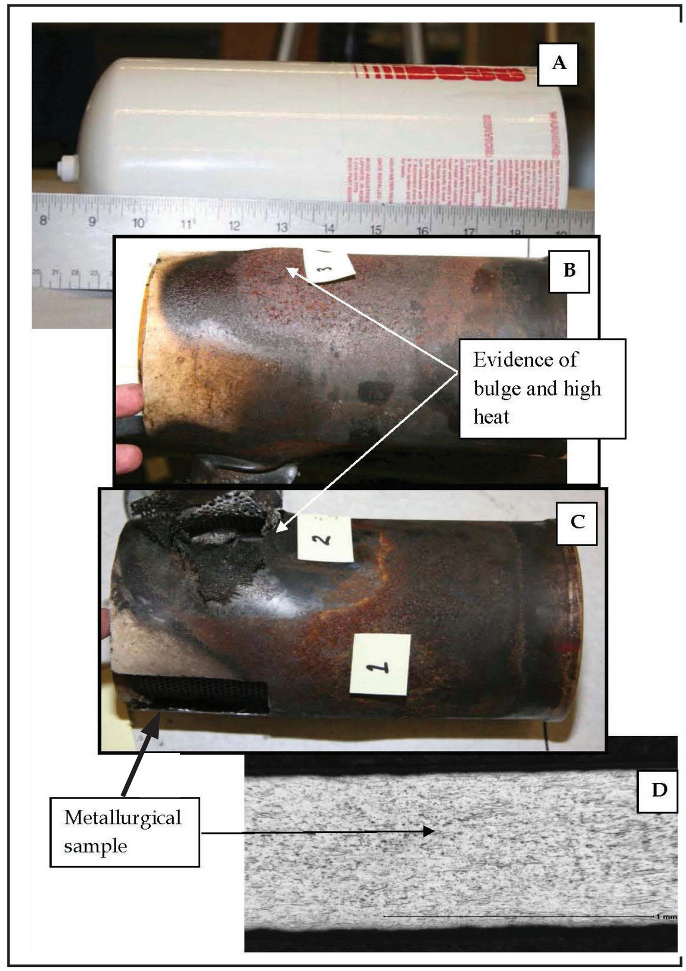



**Figure 10**
Subject coalescer seen in B and C exhibits bulging
at the location of highest heat. The rupture occurred in the bulged
area. The metallurgical structure of the thin-walled coalescer is cold-worked low carbon steel. Exemplar A shown for pre-cut comparison.

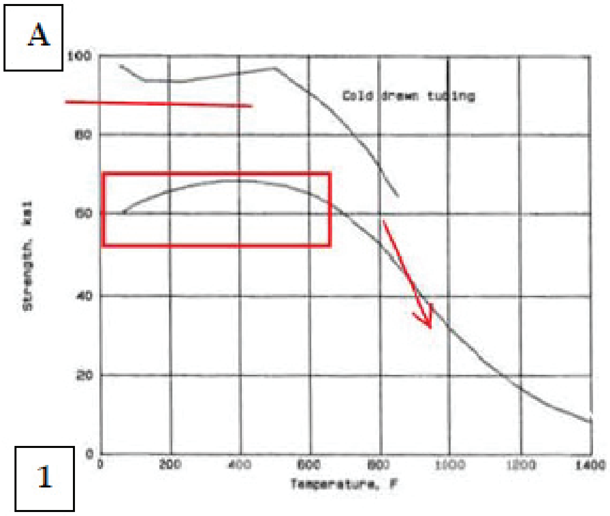
a coalescer to remove oil vapor from the air supply upon exit and return the reclaimed oil to the compressor. The coalescer contained a large rupture, as shown in **Figure 9**, which allowed rapid depressurization and the instantaneous release of burning oil at high pressure. The location of the rupture 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.

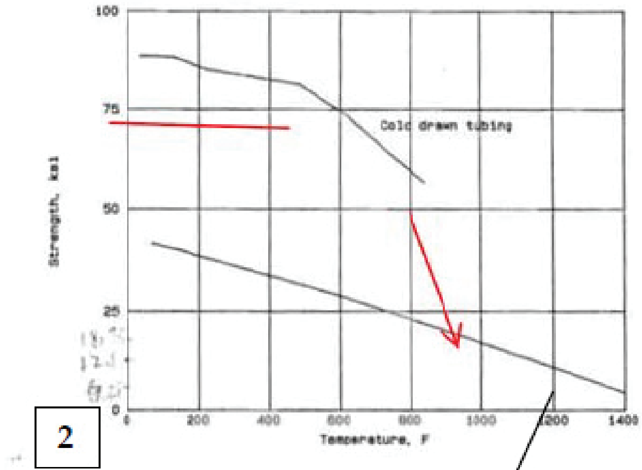
The bulged coalescer was evidence that the internal heat occurred while the coalescer was pressurized, thus the fire started in the coalescer prior to rupture. The source of the ignition is unknown. The heat produced was enough to soften and weaken the metal as shown in **Figure 10**. This would have 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




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




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

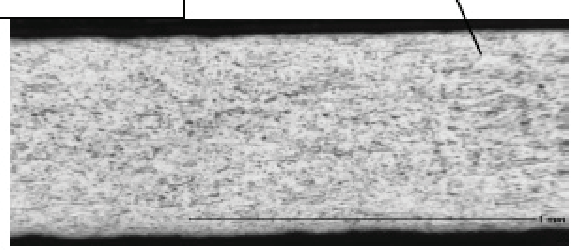


**Figure 11**
Subject coalescer had an as-manufactured hardness of 180 HV corresponding to a tensile strength of over 80,000 psi (D). The hoop stress on the coalescer (B, E) as a function of the compressor pressure shows a safety factor of 2-4 at temperatures up to 400°F. At temperatures of 1000 - 1400°F (A, C, B) the coalescer will plastically yield (bulge) and rupture within the normal operating range of the compressor (B).

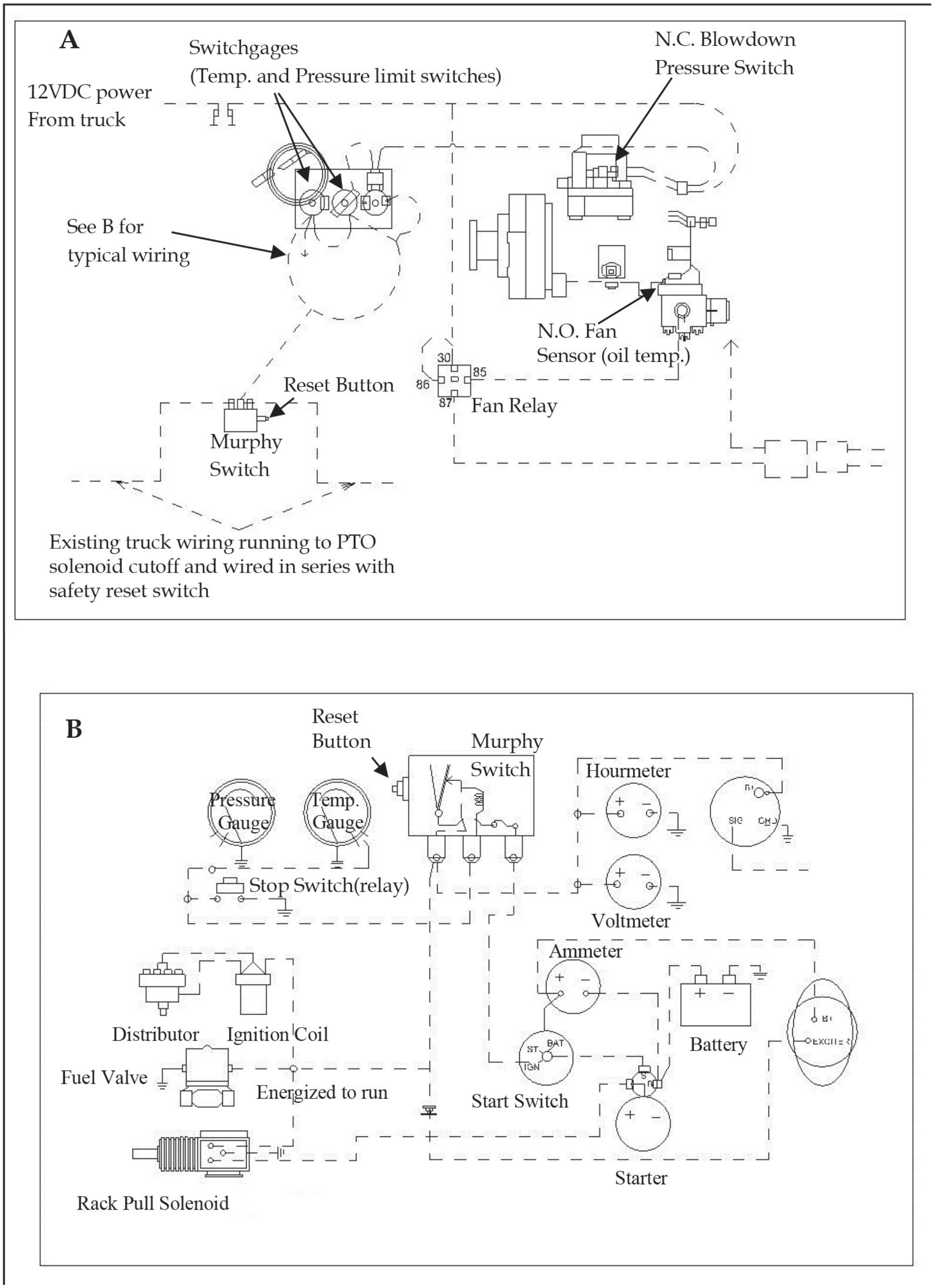



**Figure 12**
A. Diagram showing the air compressor manufacturer's subject safety shutoff circuit that allows the operator to manually override the out-of-limit condition and continue operating the air compressor system. B. Component manufacturer's design of a typical circuit (stop switch [relay] and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

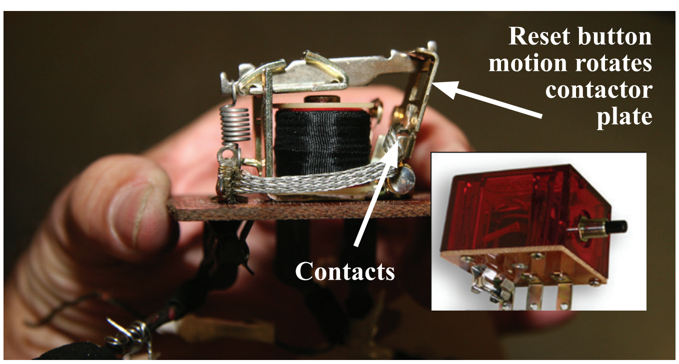



**Figure 13**
The subject safety shutoff switch in the unlatched position.
To reset, push the spring-loaded contactor to the left and lock it in place on the hook. When the electromagnet is energized, the hook is pulled down, causing the contact linkage to unhook and rotate to the unlatched position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

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>

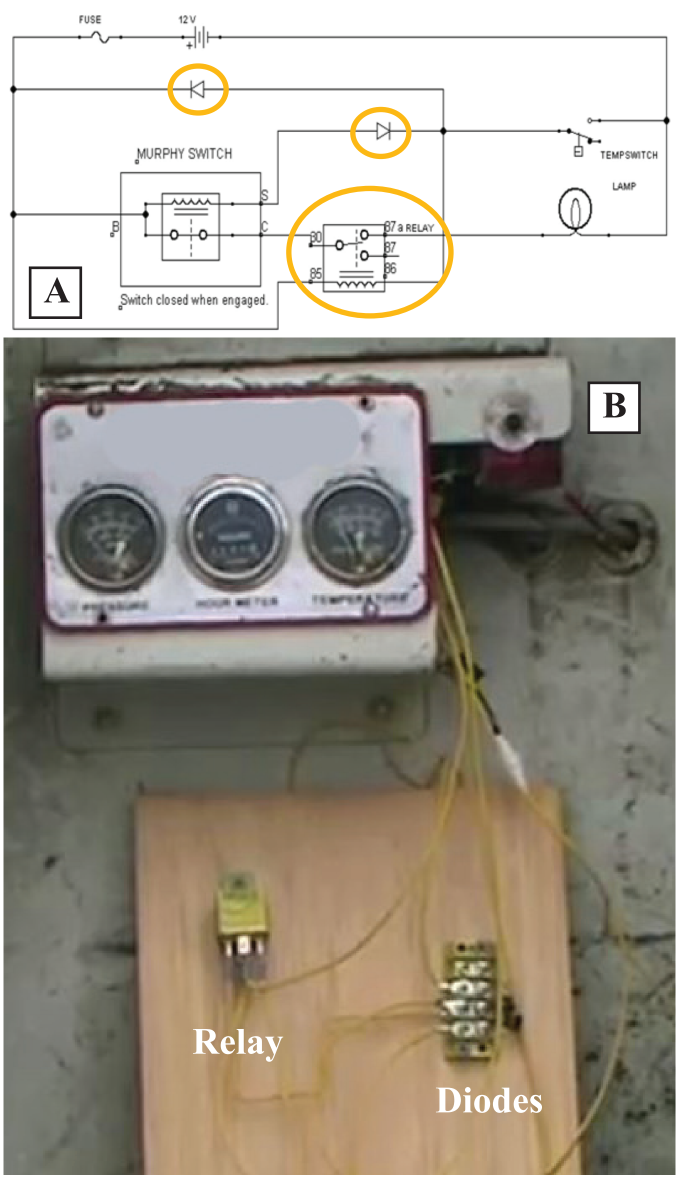



**Figure 14**
A) The authors' safety shutoff circuit that deactivates the system and prevents the operator from energizing the air compressor while an out-of-limit condition exists.
B) The revised safety shutoff circuit installed and tested on the exemplar truck and air compressor. The out-of-limit condition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

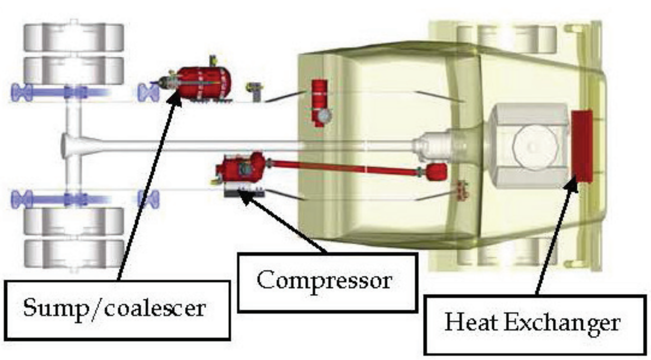



**Figure 15**
Typical system installation presented by system manufacturer. Heat exchanger vertically mounted.

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

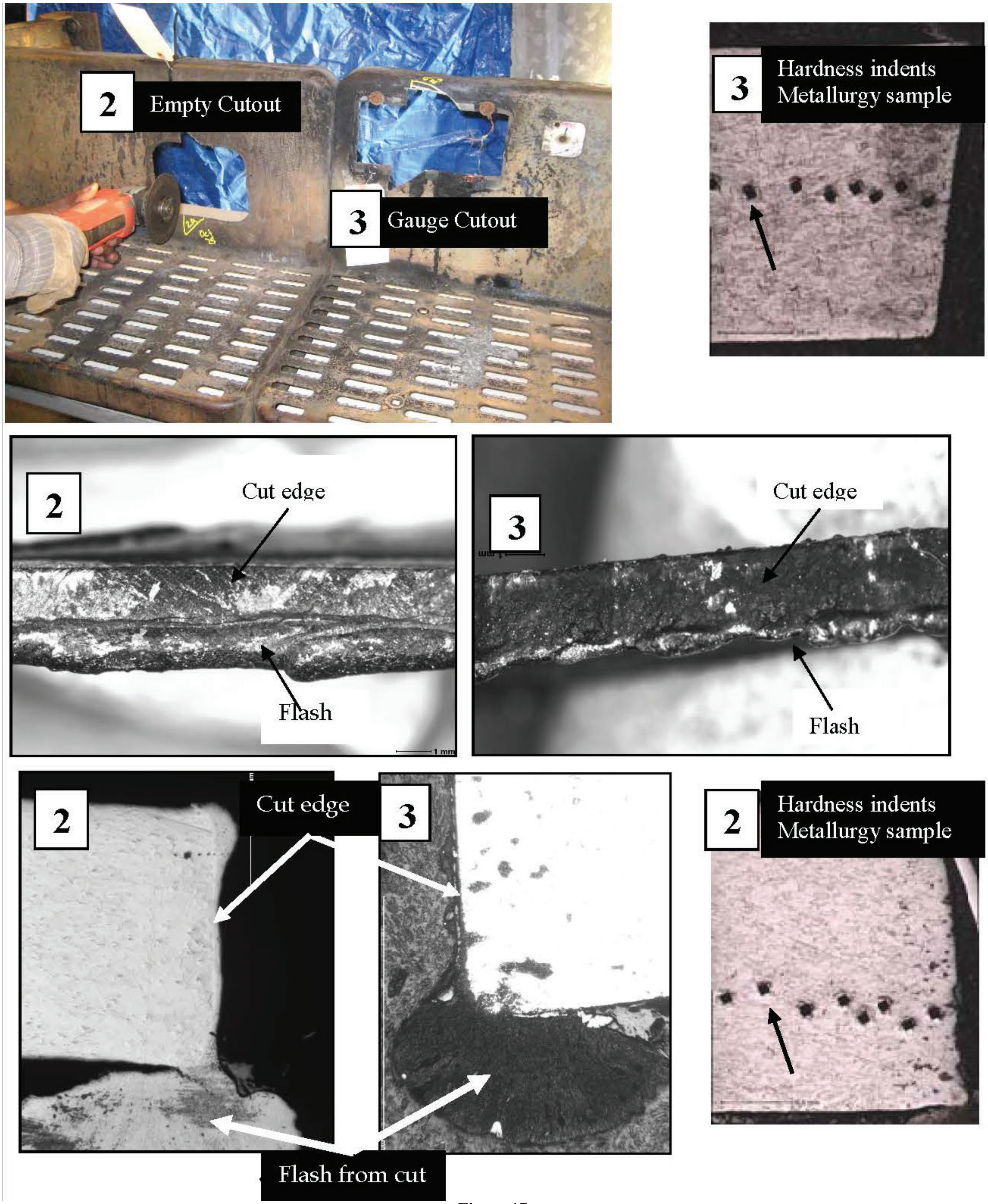



**Figure 17**

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.

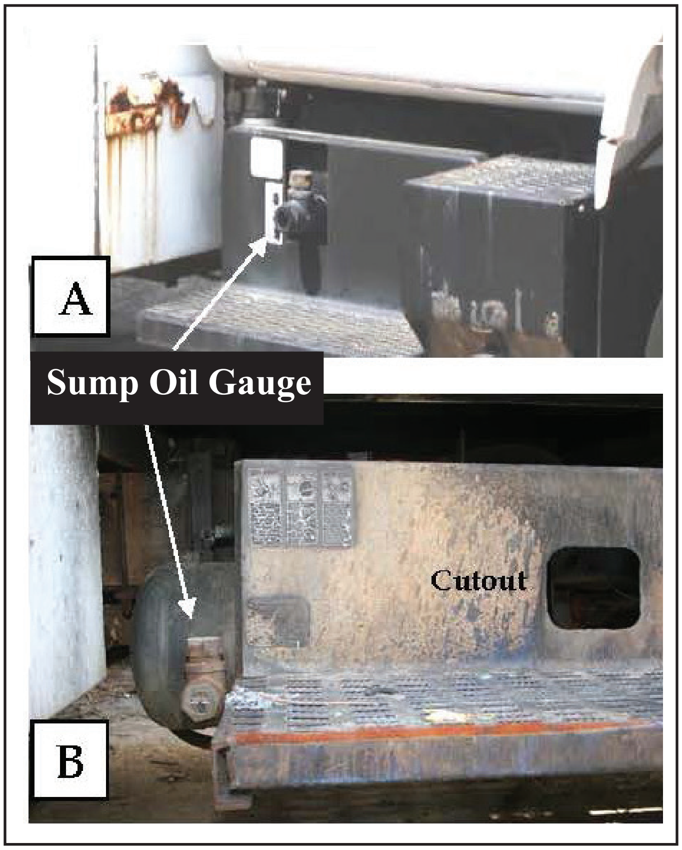



**Figure 18**
Exemplar truck oil gauge location. B.
Subject truck oil gauge location and open cutout.

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.

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