Journal of the National Academy of Forensic Engineers®

http://www.nafe.org
ISSN: 2379-3252

Vol. 32 No. 2 December 2015

Forensic Engineering Evaluation of Utility Compressor Truck Explosion/Fire

By Christopher B. Shiver, P.E. (NAFE 661S)

Abstract

A compressed air system installed as a package on a utility company truck experienced a pressure boundary rupture in service, resulting in burning lubricant discharge onto an employee. Numerous design and component defects were alleged, and a series of expert group examinations of the truck, compressor system, and components occurred over the course of approximately three years. The author was retained by one of more than 20 component suppliers involved in this evaluation. Key issues included design of the compressor system and individual components in the pressure boundary, control system, and cooling system. Based on inspection and analysis, there were several causes for this incident that involved individual component and system design deficiencies, installation deficiencies, and operator training inadequacies.

Keywords

Forensic engineering, truck, air compressor, fire, explosion, safety system, controls

Introduction

A severe injury involving a utility company work truck occurred when the operators attempted to restart a power take off (PTO) driven air compressor after it shut down due to high temperature during heavy use and in hot weather conditions. During the restart attempt, while the operator was at the compressor control position, a pressure boundary component ruptured, resulting in discharge and ignition of hot oil onto that person. Reports that the injured operator restrained the system reset push button at the reset (in) position during the restart attempt (overriding the automatic high temperature shutdown) proved to be important in this case. The evaluation of the compressor system — and its numerous components from various sources — included focus on system pressure and temperature control/limitation, integrity of pressure boundary components, overall system design for safety and human factors, original assembly and maintenance of the truck and compressor system, and operational and maintenance information/instructions provided to persons responsible for those activities.

Background

The truck involved in the incident was used frequently by utility work crews for accessing and maintaining underground facilities. The truck included an air compressor system (mounted under the truck rear body) that was intended mostly for powering pneumatic excavation and other heavy tools (**Figure 1**). The compressor was driven by the truck engine through an electrically engaged PTO unit, and was rated for approximately 185 standard cubic feet/minute (scfm) output at 110 pounds/square inch – gage (psig). The compressor system maximum operating pressure and temperature were 175 psig and 250°F, respectively. The compressor system included provisions for separating the screw-type compressor lubricating oil from the output air in two stages prior to discharge to the working tools (by means of a sump/receiver tank and oil coalescer/separator), and recirculation of that oil back to the compressor after passing through a filter and forced draft air flow oil cooler.

Compressor control features included operator-adjustable automatic regulation of output air pressure in response to tool demand and automatic blowdown of the system, whenever a manual or automatic shutdown of the compressor occurred. The oil cooler fan was designed to be cycled by a temperature sensor to maintain the oil between 160°F to 200°F. Safety control features included separate high pressure (150 psig) and temperature (240°F) shutdowns and a pressure relief valve set to discharge at 175 psig. The system included a manual reset push button switch for restart after an automatic shutdown.

Christopher Shiver, P.E., 1200 Trailmore Drive, Roswell, GA 30076; (770) 587-5054; chrisshiverpe@bellsouth.net

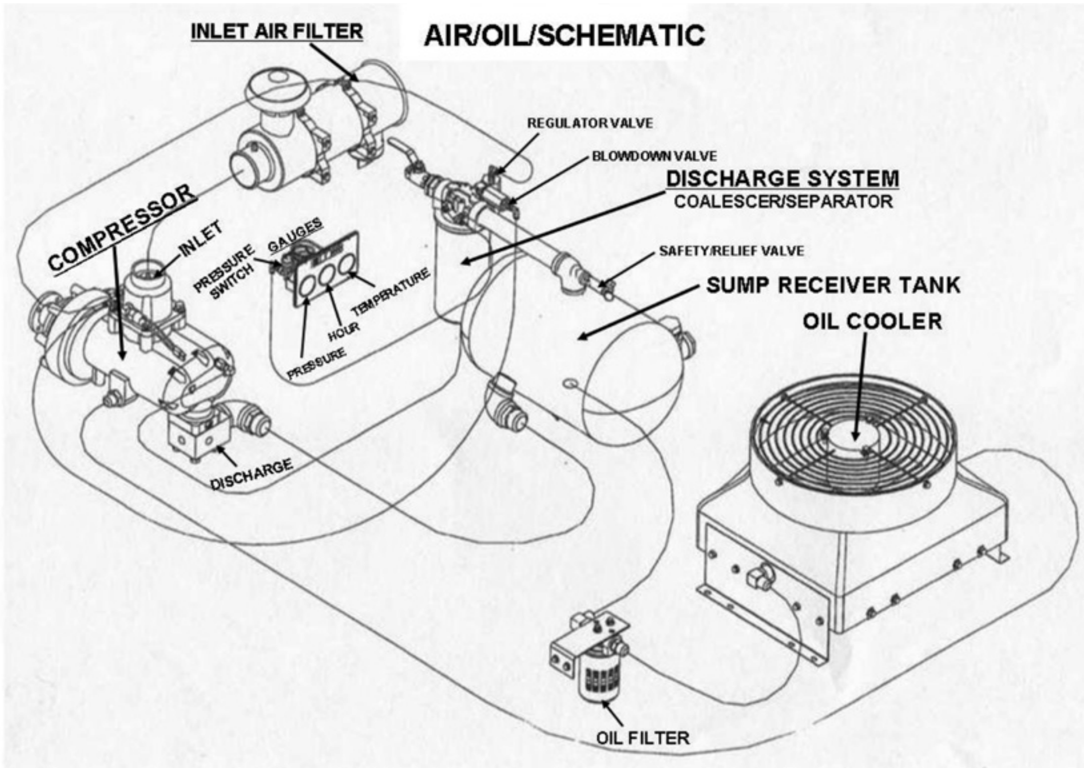


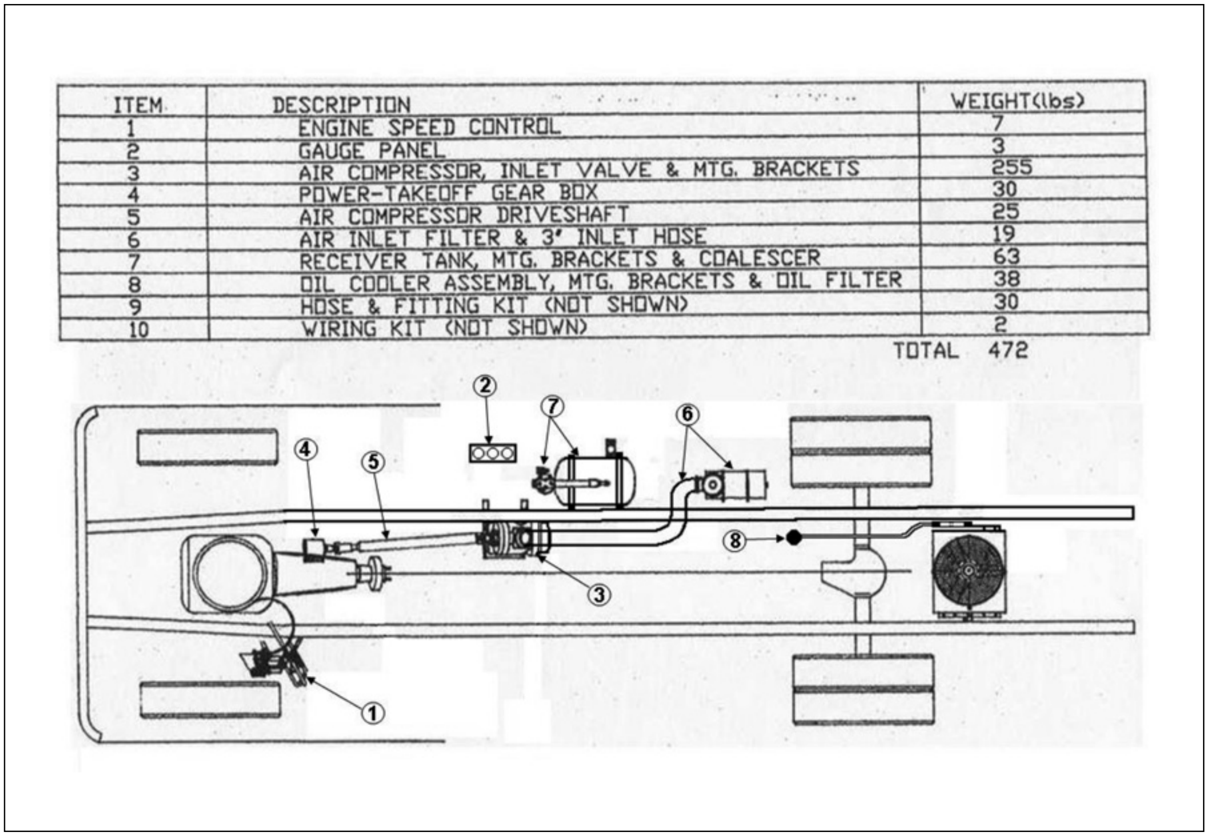
Figure 1
Air/oil schematic for compressor system.

Information and documentation provided by the manufacturer of the compressor system (operations, installation, and parts manual for the subject system as well as competitors' compressor systems, system drawings, component lists, and sworn depositions of manufacturer management personnel) indicated that the model of system installed on this truck was not actually "designed" by this particular manufacturer. Rather, the manufacturer sold a rough copy of other similar systems that had been manufactured by possible competitors. There was no record of any independent design analysis or review of the system design having been conducted by the subject compressor system manufacturer. Instead, the component selection decisions were based on what had been done at other companies that key managers (at the compressor manufacturer) had worked with in the past. There was no apparent evidence of a Failure Modes and Effects Analysis (FMEA) or some other type of safety evaluation of the system operation (including possible abnormal or adverse situations) by the compressor system manufacturer. In addition, the testimony of those same managers revealed that the installation, operation, and maintenance manual contents, instructions, and warnings were also mostly based on literature produced by other competitor manufacturers rather than being an original document written to specifically encompass the subject system, including some of its unique features.

Truck & Compressor System Inspection

Over a three-year period, approximately two dozen parties involved in the evaluation conducted at least eight inspections of the truck, compressor system, individual system components, and exemplars for this equipment. The examinations started with inspection of the truck and compressor in the post-incident condition and then systematic removal of the complete compressor system for further laboratory examination and testing. During this process, examination and testing of exemplars occurred, including a similar complete truck and compressor system assembly used by the same utility company as well as various exemplar assemblies and components for the subject model compressor system.

Initial examination indicated that the compressor system was installed under the truck with the screw-type compressor installed behind the engine and transmission with the compressor drive shaft connected to the PTO on the transmission (**Figure 2**). The air inlet filter, air/



ITEM	DESCRIPTION	WEIGHT(lbs)
1	ENGINE SPEED CONTROL	7
2	GAUGE PANEL	3
3	AIR COMPRESSOR, INLET VALVE & MTG. BRACKETS	255
4	POWER-TAKEOFF GEAR BOX	30
5	AIR COMPRESSOR DRIVESHAFT	25
6	AIR INLET FILTER & 3' INLET HOSE	19
7	RECEIVER TANK, MTG. BRACKETS & COALESCER	63
8	OIL COOLER ASSEMBLY, MTG. BRACKETS & OIL FILTER	38
9	HOSE & FITTING KIT (NOT SHOWN)	30
10	WIRING KIT (NOT SHOWN)	2
	TOTAL	472

Figure 2
Compressor system component locations diagram on truck frame.

oil sump/receiver tank, and oil coalescer/separator were all installed from back to front, respectively, on the vehicle passenger side frame outboard side behind the cab access steps. Installed in a hole cut into the kick plate portion of those steps, just forward of the oil coalescer/separator, was the instrument cluster, which included the pressure/temperature gauges, limit controls, and manual reset switch (**Figure 3**). A separate hole with no apparent purpose was also present in the kick plate aft of the controls locations. The oil cooler was installed between the truck frame rails aft of the rear axle. It is important to note that after the subject incident occurred, the utility company modified similar work trucks that had this compressor system, relocating the instrument cluster from the cab passenger side steps to the rear bumper area (as noted on an inspected exemplar truck).

Figure 3
Damage to passenger side steps and control gauges.
Note unused extra hole in steps.

The burn damage to the truck and compressor system indicated that a limited explosion and fire had initiated between the truck passenger side frame rail and cab step in the vicinity of the oil coalescer/separator, which uses gravitational and inertial effects to separate the compressed air and oil. The cylindrical coalescer/separator's thin-walled metal casing evidenced a rupture due to internal overpressure on the side toward the vehicle front (**Figure 4**). Burning oil discharge toward the vehicle front and passenger side step was evident, which caused destructive fire/heat damage to the instrument cluster and passed outward through the cluster hole cut in the step's kick plate as well as the other nearby similar hole. Beyond the instrument cluster and coalescer/separator — and their hose and wiring connections — the compressor system was generally intact with limited or negligible fire effects.

Figure 4
Damage to oil coalescer/separator, including rupture.

Inspection and testing of compressor system components also revealed that the mounting loops for the steel wire grill (located under the oil cooler fan) had fractured in three of four locations, causing the grill to sag downward (**Figure 5**). The center of the fan grill directly supported the fan motor such that this sagging was causing the fan blade tips to make contact with the fan shroud under the oil cooler. The blade tips and shroud evidenced abrasion damage from this contact. Detailed metallurgical examination of the failed mounting loops indicated fatigue fracture over time with possible initiating damage from road debris impacts.

Figure 5
Fan grill support fracture (one of three).

Detailed inspection and testing indicated that the following other compressor system components were in acceptable condition or functioning properly, based on the original manufacturer's specifications and maintenance requirements (both the subject compressor system manufacturers' literature, and literature provided by component suppliers/manufacturers where available):

- Compressor modulating control valve and air inlet valve
- Timer, relays, and switches that control truck engine speed during compressor operation
- Cooling fan temperature switch and relay
- Solenoid-actuated PTO
- Inlet air filter
- Oil filter
- Blowdown valve
- Pressure relief valve
- Electrical control system circuit breaker
- Electrical push button reset switch/relay

Where practical, the proper working condition of each of the items listed above was confirmed by functional testing — both individually and when connected to other interactive components.

Metallurgical analysis of the ruptured oil coalescer/separator cylindrical shell was performed, including computerized tomography x-ray scanning and scanning electron microscope viewing of the failure region with energy dispersive analysis for materials characterization (**Figure 6**). The findings of this analysis revealed that the material had been overheated from within, resulting in rupture by normal operating pressure forces. In addition to the rupture location, the shell had also bulged outward in several other locations due to overheating while at or below system design pressure. It was determined that the system was below the design pressure based on no evidence of relief valve or high pressure shutdown control actuation prior to the coalescer rupture.

Compressor system temperatures and pressures were sensed and limited by pressure and temperature gauges with integral switch contacts that were reportedly set to the design shutdown limits by the compressor system manufacturer. Both of these gauge and switch assemblies were severely disrupted by the fire damage — such that their functional conditions and settings prior to the incident could not be determined. Both of the gauge and switch assemblies were found wired to the control system reset switch/relay — such

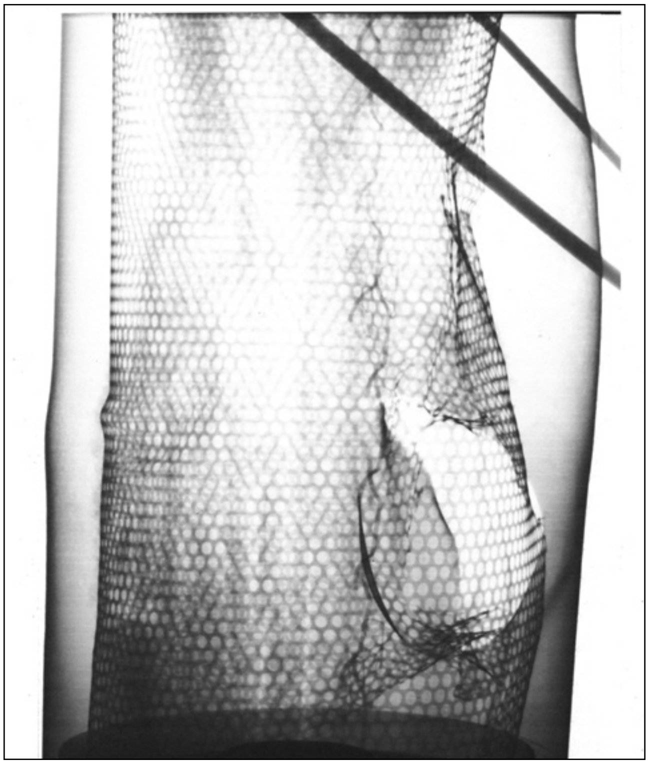


Figure 6
Oil coalescer/separator x-ray image in rupture zone.

that the opening of either set of switch contacts on high pressure or temperature would have shut down the compressor. The compressor could be restarted after a shutdown by momentarily pressing the button on the reset switch/relay. However, if an excessive pressure or temperature condition had still been present, shutdown would recur upon release of the button. Testing of this control system using the same model of exemplar components in place of the damaged components indicated that holding down the reset button would allow continued compressor operation — even if one or both of the gauge switch contacts had opened in response to an excessive pressure or temperature condition. It was observed that the reset switch/relay installation on the subject truck included a still-legible compressor system manufacturer's label at the button stating: "Push Button to Restart Engine or Compressor" with no other instructions or warnings.

Functional testing of the oil cooler fan assembly was performed, including the shroud and grill with three out of four supports fractured. The testing demonstrated that the fan rotation was significantly impeded by the contact between the blade tips and shroud, with intermittent stoppage occurring. This contact and rotation interference was found to be affected by the changing vibration as the fan speed varied due to this abnormal condition. It was also observed that with the fan motor connected to a DC power supply (in the same manner as found on the truck) the curved fan blades were rotating in reverse from the component manufacturer's design intent. Comparison of the air flow in reverse rotation to intended normal rotation indicated overall flow reduction was approximately one-third below normal in the reverse direction. Calculations for axial fan air flow based on established fan engineering principles[1] further confirmed these findings.

Analysis was also performed on residual oil remaining within the compressor system oil filter casing, the air/oil sump/receiver tank, and the oil coalescer/separator casing. The oil quantity recovered was approximately 15 percent of the compressor system manufacturer specified operating quantity, though some oil was still left on system component internal surfaces. This oil was still liquid, evidencing moderate usage conditions and normal viscosity. This analysis was important because some documentation provided by the compressor system manufacturer indicated that, in some instances, oil usage beyond the recommended replacement intervals (based on engine hours and time) in high ambient temperature and humidity conditions could result in severe thickening and color change (to a pink tone) of the compressor oil. This severe oil deterioration was reportedly determined to have been a cause for some previous pressure boundary failures involving compressor systems manufactured by the subject company.

Exemplar Truck & Compressor System Studies

Inspection and testing were performed on the same model compressor system mounted on a similar model truck owned by the same utility company as the subject truck. More-involved testing was also performed on a separate similar model truck and compressor system that had been purchased in a used condition solely for testing purposes. Tests were primarily oriented toward evaluating the potential for compressor system overheating in hot weather conditions similar to those documented at the time of the incident. The tests included normal operation with the compressor discharge air driving the tool reported in use at the time of the incident and also with abnormal operation of the oil cooler fan, including impeded rotation and reverse flow. The tests results indicated that with normal function of the oil cooler, the compressor system did not reach the high temperature shutdown level, but it did shut down in several instances where the oil cooler fan operation was impaired.

One of the parties in this evaluation proposed a modification to the electrical control safety shutdown circuit for the compressor system, which was intended to prevent the system from restarting or running with the reset button held down by an operator, if the system pressure and/or temperature was above the high shutdown limit values (**Figure 7**). Based on input from the other parties involved, the proposed control circuit was assembled using new exemplar components (same model components as specified by the compressor system manufacturer) for comparative testing to the original control circuit. The modified circuit included addition of a single-pole/double-throw relay and two diodes as well some wiring connection modifications (**Figure 8**). The testing demonstrated that it was possible to have designed and installed an electrical control safety shutdown circuit on the compressor system that would have prevented the system from restarting or running with the reset button held down by an operator, if the system pressure and/or temperature was above the high shutdown limit values. The expense and effort required for this modification was determined to be negligible in comparison to the total system cost.

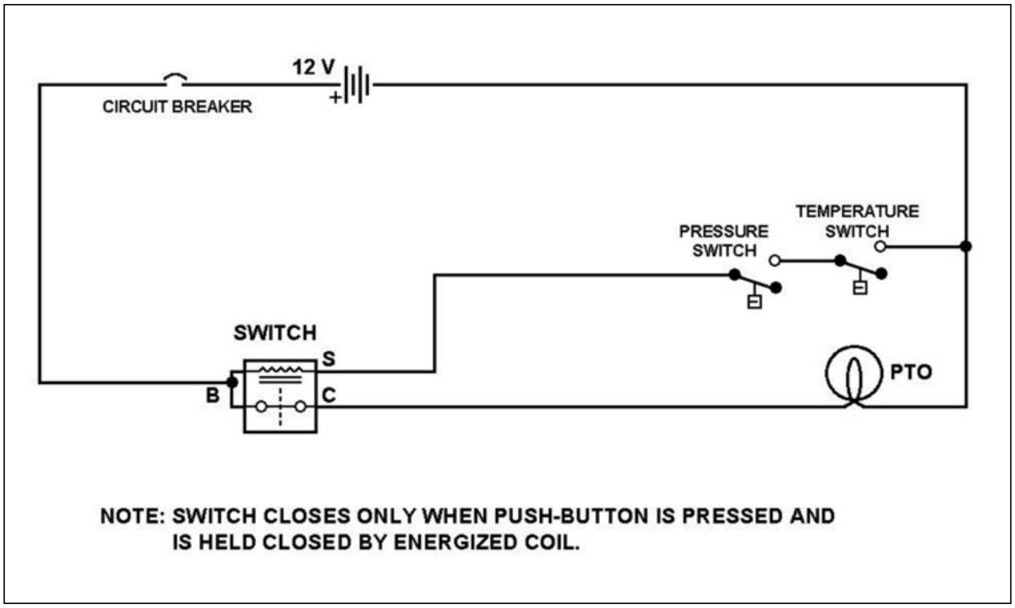


Figure 7
Original safety shutdown circuit.

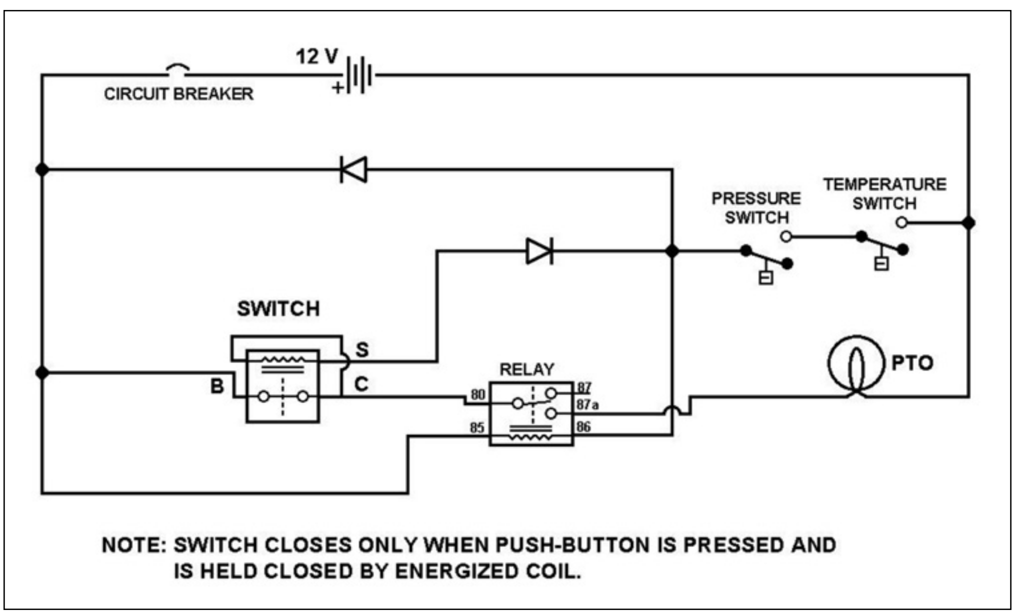


Figure 8
Modified safety shutdown circuit.

Research

Review of two American National Standards for compressor systems of the subject type[2,3,4] indicates that manual restart capability is permitted only if this does not create a hazard or cause damage to the equipment. The compressor system manufacturer must also provide the user with startup and shutdown procedures, where an improper procedure could create a hazard to personnel or cause damage to the equipment. In addition, the compressor system user had to maintain the equipment in accordance with the manufacturer's instructions to promote continuous operator safety.

Review of federal regulations applicable to worker safety during use of compressor systems[5,6] indicates that safety appliances, including control devices, shall be constructed, located, and installed so that they cannot be readily rendered inoperative by any means.

International Standards Organization publications[7,8] that generally applied to the design of the subject compressor system outlined general systematic methods for establishing appropriate levels of safety and hazard reduction in equipment designs. In particular, they indicate that such analysis should include an assessment of safety function and component reliabilities, the consequences of failure or defeat of a safety critical component/system (including control circuits), and the ability of critical safety components to function reliably in the intended usage environment/application. These principles were further covered in additional engineering papers presented at international design and safety conferences[9,10] and in an engineering society design guide[11].

Similar compressor systems from the subject manufacturer and other manufacturers that had been mounted on work trucks owned by other entities were also reviewed, as was installation literature provided by other manufacturers. It was found that control locations for truck-mounted compressor systems were typically well away from high-pressure components on these systems. In addition, many manufacturers specifically instructed or warned installers against locating the control components in a position that might expose an operator to hazards caused by either a failure in the high-pressure portions of the system or by possible discharge from the pressure relief valve.

Conclusion

Evaluation of the entire subject compressor system clearly indicated that a breach had occurred due to an over-temperature condition in the oil coalescer/separator. The damage observed to the compressor and truck further indicated that this breach had resulted in discharge of hot compressed air mixed with compressor oil into the area where the compressor controls had been located. The report that a system operator was manipulating those controls at that time is consistent with the reported severe burn injuries he reportedly sustained. The detailed examination performed on the ruptured oil coalescer/separator casing indicated that its rupture was due to normal internal pressurization in an overheated condition, and was not related to any material or fabrication defect in that component.

Inspection and testing of the subject compressor system oil cooler assembly indicated that several functional conditions likely impeded the cooler's performance. The cooler fan grill support fractures were resulting in probable intermittent slowing or stopping of the fan rotation. Analysis of these fractures indicated that thrown debris from the truck rear axle tires was a probable contributor — in combination with expected vehicle road vibration. Also noted in the installation manual for this system (provided by the manufacturer) was that the subject under-truck rear installation location for the cooler was one of several options for positioning it — with the other optional locations in areas less vulnerable to road hazards. In addition, during the cooler installation, incorrect wiring connections resulted in reverse rotation, which caused reduced air flow even when the fan was rotating unimpeded. Therefore, it was determined that installation deficiencies had resulted in compromise of the oil cooling system on the subject vehicle, which was the probable cause for the compressor system overheating, leading to the incident. In addition, the system design, which permitted installation in an area under the truck where damage due to road debris was an expected condition, was deficient and also contributed to the oil cooler conditions.

The subject compressor system design and installation included automatic shutdown controls in the event of either an air/oil over-temperature or over-pressure condition. However, the control system also included a manual reset push button, which would allow the operator to not only restart the system if an over-temperature or over-pressure condition existed, but would also override those automatic shutdown features if the button were held in. During the evaluation, it was proven that with minimal additional design effort and expense, the control system could have been configured to prevent operator override of the automatic shutdown features. In addition, the manufacturer's labeling and instructions did not provide any specific directions on how to properly use that reset switch or identify possible hazards of pushing the button (or holding it in) during over-temperature or overpressure conditions. These design deficiencies were not compliant with the governing national standards applicable to design and safety of air compressor systems of this type. They were also not in accordance with the "standard of care" for design of commercial/industrial equipment.

Also noted during the evaluation was that the truck passenger side cab access step assembly had been cut out in at least one location to accommodate the location of the compressor control components. The locating of the controls in this position was not in accordance with potential locations recommended by the system manufacturer's installation manual. Further, at least one additional cutout had been made for reasons the equipment installer could not explain. The presence of this extra cutout and the controls in close proximity to the oil coalescer/separator contributed to the operator suffering serious injury when that component ruptured.

Extensive documentation was provided by the utility company regarding regular maintenance and inspection of the subject truck compressor system, mostly by outside contractors. It was noted that none of these inspections identified the fan grill failure conditions, which had likely occurred over time because three separate supports had failed. On this basis, it was determined that a failure to perform proper inspections of the compressor system was a probable contributor to overheating of the system and the subject incident.

Review of the training procedures for the injured operator and other members of the same work crew indicated a lack of a systematic approach and an overreliance on "on-the-job" learning methods by the utility. In particular, no means were documented for assuring that workers received complete operational and safety instruction on the equipment they were using. During sworn statements by these workers, it was apparent that many misunderstood how the subject compressor system functioned and should be operated. Of critical importance was the fact that many of the operators also did not understand the potential safety consequences of restarting the compressor system while it was in an overheated condition or holding down the reset switch to prevent an automatic shutdown. It also became clear that certain supervisory personnel (who did understand those safety consequences) had not taken the proper steps to assure that their subordinates understood those concepts or knew how to operate the equipment safely. As a result, improper and incomplete training of the injured operator was determined to be an important contributing factor to the incident. These training deficiencies were potentially compounded by the lack of safety guidance or instruction regarding operation of the reset control provided by the compressor system manufacturer.

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Acknowledgement

Figures 1, 2, 7, and 8 were prepared with the valuable assistance of professional graphics specialist Monica Helms of Marietta, GA.