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Voice in Healthcare

November 16, 2022

Dr. James Ireland, MD
Emergency Medical Services Director
Honolulu Emergency Medical Services
3375 Koapaka, Suite 450
Honolulu, HI 96819

Via E-mail: James.Ireland@honolulu.gov

Re: Investigation of a Fire within an Ambulance

Dear Dr. Ireland:

I am writing to present our findings and conclusions to date regarding a fire within one of Honolulu's Emergency Medical Services' (EMS) ambulances that occurred on August 24, 2022, leaving one patient dead and a paramedic seriously injured. You requested that we perform an independent examination of the associated ambulance and equipment in partial fulfillment of Honolulu's EMS's quality assurance/risk management process. The findings and conclusions presented in this report are to a reasonable degree of biomedical and scientific certainty related to the technology involved in this incident. This report may be modified if further testing is performed at a later date.

Onsite Investigation

ECRI's Director of Accident and Forensic Investigations, Chris Schabowsky, PhD, CCE, arrived at Honolulu on August 30 and performed a two-day investigation on August 31 and September 1. The following activities were performed during the investigation:

Day 1

1. Kick-off meeting with Honolulu EMS leadership including agenda review, gathering of general information related to the incident and investigation efforts to date as well as requesting pertinent documentation for future review.
2. Presentation and review of exemplar equipment, medical devices, and supplies commonly found within EMS ambulances.
3. Review of oxygen (O_2) cylinders storage at EMS and discussions related to the delivery of supplemental O_2 to patients during emergency calls.
4. Visit to Honolulu Fire Department for introductions, viewing of photographs taken during the initial steps of the department's investigation, and discussions about the current state of the ambulance, evidence, and findings to date.

Day 2

1. Thorough inspection of both the incident ambulance and exemplar (identical) ambulance for comparative purposes.
2. Photographs and video footage were taken to document all aspects of the incident ambulance, salvaged equipment, and medical devices. No equipment was tested, dismantled, or taken from the scene.
3. EMS and Fire Department leadership and investigators were debriefed with ECRI's initial findings and preliminary conclusions.

Received Materials and Reviewed Documentation

In preparation for this investigation, Honolulu EMS provided the following documentation:

1. Braun Northwest Inc. 2192 thur 95-1 C&C of Honolulu Electrical Schematics (11/24/2015)
2. American Medical Response Compressed Gas Safety Policy (version 2.0, effective 07/08/2011)
3. National Fire Protection Association Recommended Practice on Materials, Equipment, and Systems Used in Oxygen-Enriched Atmospheres (NFPA 53, 2004)
4. National Registry of Emergency Medical Technicians Psychomotor Examination (Oxygen Administration by Non-Rebreather Mask)
5. Honolulu EMS Memorandum re: previous O_2 fire (02/23/2011) involving the main Y size O_2 tank including recommended operator best practices
6. Federal Specification for the Star-of-Life Ambulance, US General Services Administration (KKK-A-1822F, August 1, 2007)
7. United States Fire Administration/Technical Report Series Special Report: Fires Involving Medical Oxygen Equipment (USFA-TR-107, 03/1999)
8. Emergent PortO$_2$VENT CPAP$_{OS}$ Operator's Manual, Emergent Respiratory (1900-140 Rev L, undated)
9. Pulmodyne GO-PAP Disposable CPAP specification sheet, in-service outline and order form
10. United States Food and Drug Administration (FDA) Manufacturer and User Facility Device Experience (MAUDE) database search results

ECRI also reviewed documents and video footage produced by government agencies, professional societies and other organizations to perform the investigation. These organizations include:

1. United States Food and Drug Administration (US FDA)
2. National Institute of Occupational Safety (NIOSH)
3. National Fire Protection Association (NFPA)
4. Compressed Gas Association (CGA)
5. Occupational Safety and Health Administration (OSHA)
6. WHA International
7. American Medical Response (AMR)
8. United States Fire Administration
9. ECRI

Reported Circumstances

The following summary of events is based on interviews with the paramedic and emergency medical technician (EMT) who experienced the ambulance fire, discussions with Honolulu Fire Department leadership and investigators, as well as review of available evidence.

On August 24, 2022, a 91-year-old male [redacted] and an ambulance was summoned. Upon arrival, the paramedic provided the man supplemental O_2 via a non-rebreather mask. For the non-rebreather mask to supply pure O_2, it was connected to a portable medical O_2 cylinder (size jumbo-D) via its low-pressure outlet.

[redacted] portable monitor/defibrillator (PhysioControl Lifepak 15) that was placed on a bench located at the opposite side of the gurney. Oxygen administration [redacted] was changed from the non-rebreather mask to a continuous positive airway pressure (CPAP) device (Emergent Respiratory, PortO_2Vent $CPAP_{OS}$), which was set at 8 cmH_2O. Oxygen provided to the patient via the CPAP device was supplied from a 50 psi Ohmeda "quick-connect" wall outlet located in the ambulance wall next the gurney and "captain's chair," which is positioned behind the head of the gurney and where the paramedic was seated.

During the ride to Adventist Health Castle in Kailua, the patient received CPAP O_2 treatment without complications and the paramedic did not use any other medical or electronic devices during patient treatment.

As the ambulance approached the emergency department bay, the paramedic intended to switch the CPAP device's O_2 supply from the wall outlet to the jumbo-D portable O_2 cylinder in order to transfer the patient from the ambulance to the emergency department while still providing supplemental O_2. However, the moment the CPAP hose's male Ohmeda quick connect contacted the female connector of the hose attached to the portable O_2 cylinder, the paramedic heard a "pop" noise. This was immediately followed by a flash of bright light and a fire. The box quickly filled with fire and black smoke and the paramedic heard a continuous sound similar to the "noise of an activated propane blowtorch."

Concurrently, the EMT had stopped the ambulance at the street near the emergency department when he noticed the fire while he was still in the vehicle. At the time of ignition, he heard a loud "boom" that left his ears ringing afterwards. Plexiglass that was positioned against the passthrough between the driver's cabin and the box had blown into the driver's cabin and black smoke filled the cabin. Like the paramedic, the EMT reported that he also heard a loud "hissing" noise.

The paramedic was able to exit the ambulance; however, the patient died. It was reported that it took fire fighters nearly 10 minutes to extinguish the fire because it continued to reignite.

Technical Background

This section describes two key concepts that should be understood before the presentation of ECRI's findings and conclusions. These concepts include 1) the fire triangle and 2) the design and use of O_2 cylinders and gas regulators in the healthcare setting.

Fire Triangle

A fire will occur when an ignition source, an oxidizer, and combustible material (i.e., fuel) come together in the proper proportions and under the right conditions. These three basic elements constitute the fire triangle (see Figure 1) and without one or more of these elements, a fire will not occur.

Oxygen is the most common oxidizer and ambient air consists of 21% O_2 with the remaining predominantly nitrogen. Many materials, for example wood and cloth, are considered combustible while exposed to ambient air and an ignition source (e.g., a butane lighter). While other materials, such as glass and stone, will not combust under these conditions. However, increasing the concentration of O_2 above 21% in a surrounding area drastically changes the conditions and behavior of fire. This situation is often called an oxygen enriched atmosphere. As the concentration of O_2 increases, materials not combustible in ambient air will easily combust and the resulting fire will burn much more intensely and quickly. Fire within an oxygen enriched atmosphere will cover a large area within seconds and set materials not thought combustible ablaze (e.g., aluminum) along the way.

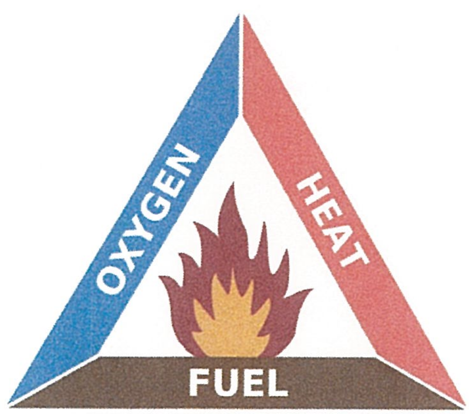

Figure 1: Fire triangle

Design and Use of O_2 Cylinders and Regulators

Providing patients with supplement medical O_2 has been a longtime and successful treatment method. Supplying more O_2 to patients often improves blood O_2 saturation and provides more

O_2 to vital organs. Delivering concentrated medical O_2 is a treatment commonly used by first responders when an individual is suffering respiratory distress.

Since first responders often administer supplemental medical O_2 to patients before transferring them inside an ambulance, the O_2 source must be both portable and controllable. Typically, pure medical O_2 is contained in specialized cylinders of various sizes. The most common portable cylinders are constructed of aluminum, contain very high purity levels (99.5% O_2) and typical sizes are D (425 liters), jumbo-D (647 liters), and E (684 liters). These O_2 cylinders are easily carried in a bag and are capable of providing a patient with enough pure O_2 while transferring the patient to and from an ambulance. In order for O_2 to flow out of the cylinder when it is opened, the O_2 is stored in a highly pressurized atmosphere, typically 2,000 psi. In comparison, ambient air at sea level is approximately 14.7 psi (absolute).

Since the pressure of O_2 coming out of an open cylinder is so high, a regulator is needed to lower the output pressure and then reliably control that pressure. For medical purposes, a regulator should reduce the output pressure to about 50 psi. Some regulators also have a low-pressure output for use with an integral or attached flowmeter. The low-pressure output is typically used with nasal cannula and facemasks.

Figures 2 and 3 illustrate the different components of a medical O_2 cylinder and regulator. The depicted devices are the same manufacturer and model as the equipment involved in this ambulance fire. The O_2 cylinder is a size jumbo-D, and the regulator is a Cramer Decker AREG8725-B2D, which is a fixed pressure, variable flow regulator with two diameter-safety system (DISS) threaded connectors operating at 50 psi and one nipple adapter with flow rates that can be adjusted by the flow regulator knob (0 lpm to 25 lpm). The regulator has an aluminum body, a brass core, and chrome plated brass bodies. As of 2021, Cramer Decker rebranded to ProRack Gas Control Products.

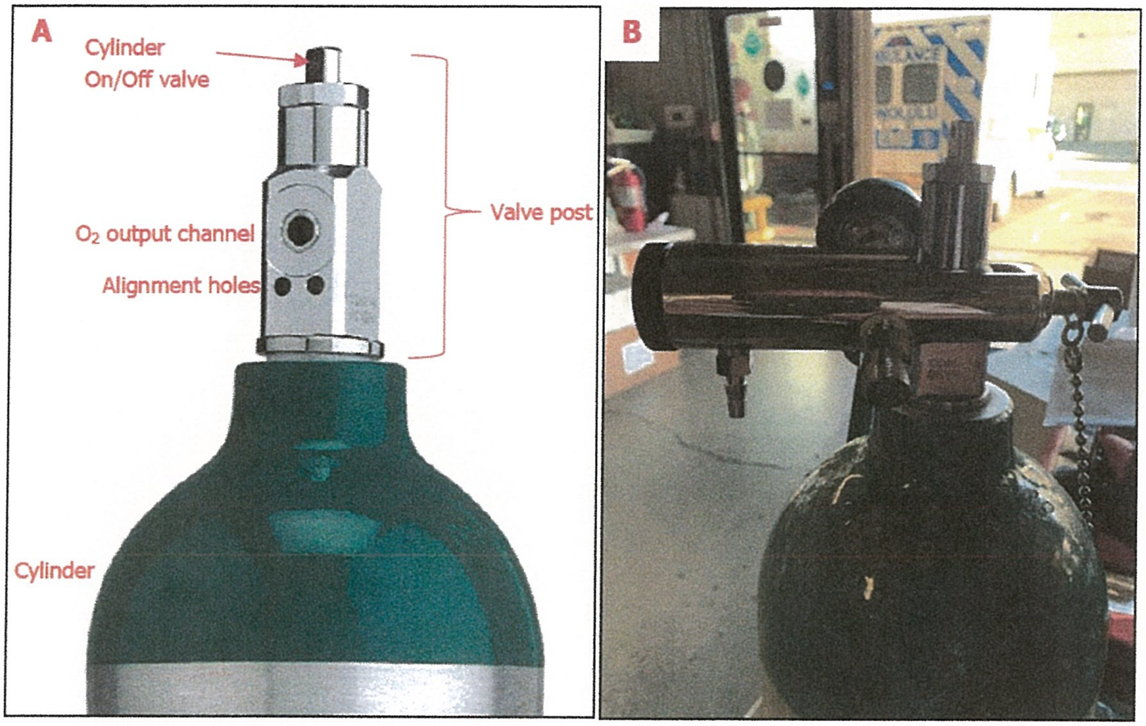

Figure 2A) Medical O_2 jumbo-D cylinder and valve post **2B)** Assembled cylinder and regulator

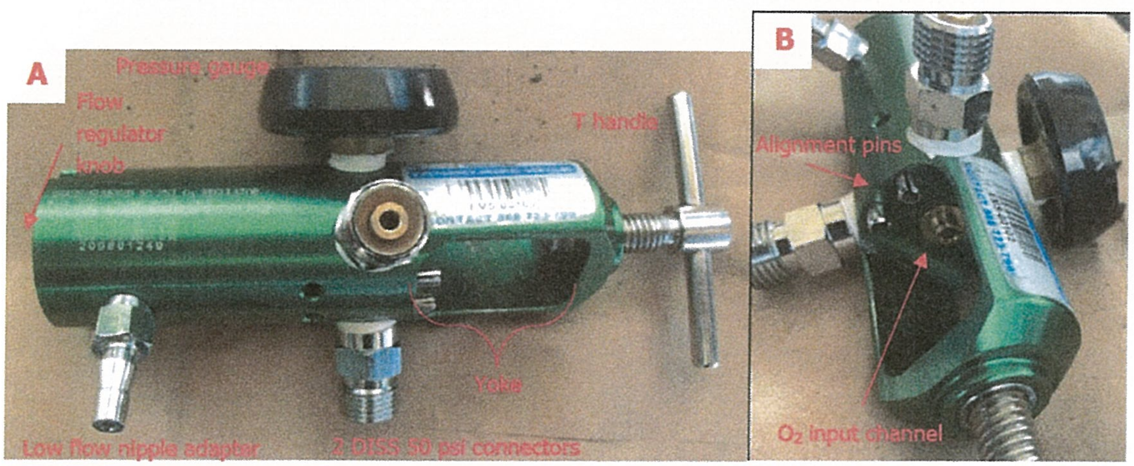

Figure 3A) and 3B) Different components of an O_2 regulator

The regulator is assembled onto the O_2 cylinder by placing the regulator's yoke around the O_2 cylinder's valve stem and positioning the alignment pins adjacent to the O_2 cylinder's alignment holes. Then, the yoke screw is turned until the regulator is flush against the valve post and the regulator O_2 input hole is aligned with the cylinder O_2 output hole with one washer positioned in between to avoid leakage.

Once the regulator is assembled to the O_2 cylinder, the O_2 cylinder can be opened by turning the on/off valve, which will pressurize the regulator. The regulator's pressure gauge will display the current capacity of the cylinder while the regulator reduces the incoming pressure to 50 psi for the two DISS connectors and further reduces the pressure for the low flow nipple adapter, depending on the chosen flow rate as adjusted by turning the knob.

At this point, O_2 can be administered to the patient through the low flow nipple adapter or high pressure DISS connector using various types of devices (e.g., CPAP) or masks (e.g., non-rebreather mask).

Investigation Findings

The investigation scene was set up so that the incident ambulance and an exemplar ambulance of the same make and model (Braun Northwest Ford 350 2192/3/4/5-1) were parked parallel to each other. Before my arrival, the Honolulu Fire Department had already spent seven days recreating the incident ambulance while salvaging damaged equipment and organizing them along the side of the ambulance from the back of the box to the driver's cabin. The amount of damage to the incident ambulance was extensive compared to the exemplar model (see Figures 4, 5, and 6).

Based on the widespread damage within the ambulance's box, it was quickly determined that this fire originated from an O_2 source. Additionally, the paramedic explained that no other devices (e.g., defibrillator) were used when the fire initiated and the investigation did not uncover any other readily identifiable ignition sources (e.g., malfunctioning lithium-ion battery or faulty electronic equipment). Further, he noted that the fire began immediately after he attached the female Ohmeda connector of the portable O_2 cylinder adapter (i.e., pigtail) to the CPAP's male Ohmeda O_2 hose connector. (The "pigtail" is a short length of compressed O_2 hose having an O_2 DISS fitting and a female Ohmeda O_2 quick connect.) Accordingly, the investigation focused on the O_2 cylinder and regulator as the potential source of the fire.

When the paramedic connected the quick connects of two O_2 hoses, he was seated at the captain's chair and the yellow bag containing the portable O_2 cylinder was likely positioned behind the head of the gurney with the regulator facing either the ceiling or the closest wall to the paramedic's right. The CPAP device was likely positioned near the patient's side or hooked around the head of the gurney (see Figure 7, 8, and 9).

Figure 4A) Incident ambulance damage perspective behind the ambulance **4B)** Exemplar ambulance from the same perspective

Figure 5A) Gurney inside the incident ambulance **5B)** Gurney inside the exemplar ambulance

Figure 6A) Incident ambulance damage side perspective **6B)** Exemplar ambulance from the same perspective.

Figure 7) Photograph taken from exemplar ambulance's side door showcasing the most likely locations of the CPAP device, portable O_2 cylinder bag, the captain's chair, and the O_2 wall ports.

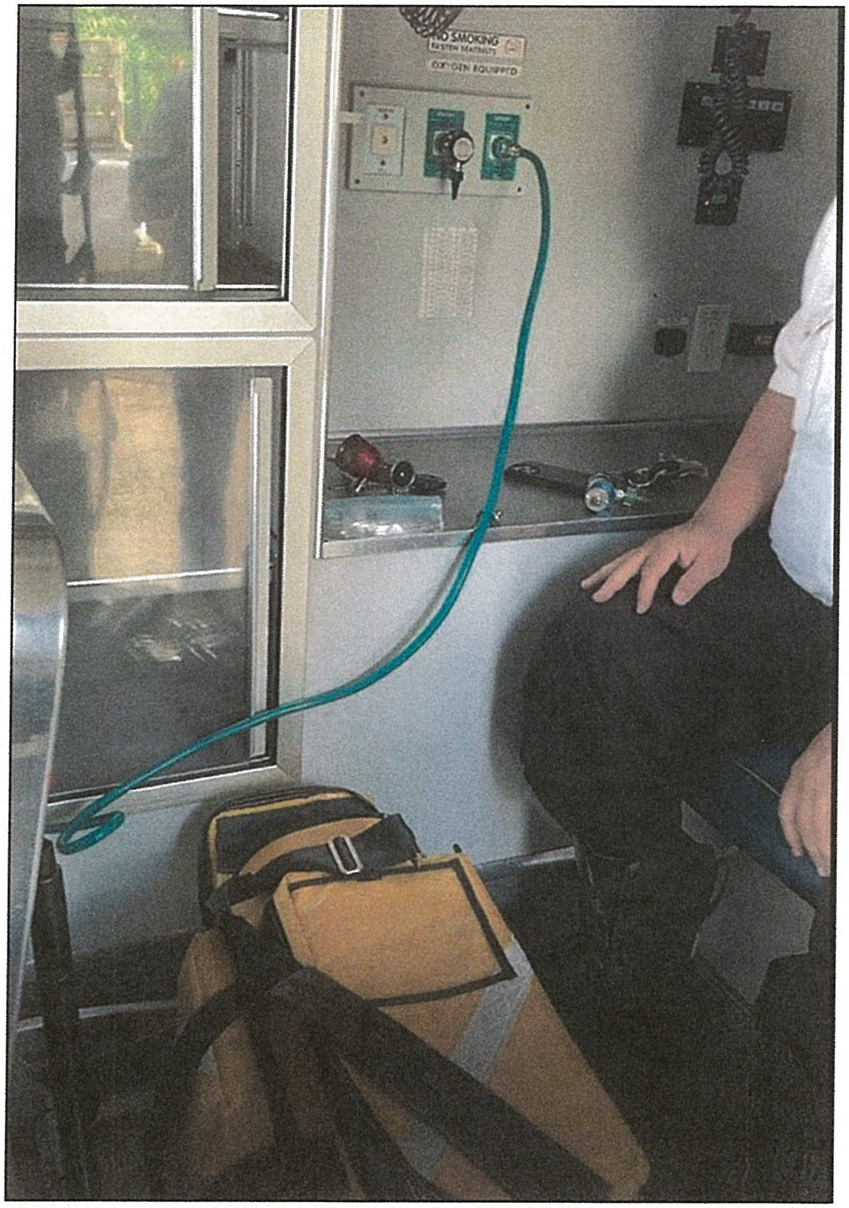

Figure 8) Seat location of the paramedic relative to the wall O_2 port and portable O_2 cylinder bag. Note the regulator is facing toward the wall beside the paramedic.

Figure 9) Possible position of the CPAP device and the position of the O_2 cylinder bag with the green O_2 hose connected to the pigtail linking the two pieces of equipment together (within the red circle) to enable O_2 flow to the patient via the CPAP device.

The incident regulator displayed signs of significant physical damage. The area surrounding the two vent holes was completely blown out. The "pigtail" female DISS connector was fused to the regulator's male connector and the hose component was entirely gone. Additionally, there is another small hole at the location of one alignment pins. Figures 10A, 10B, and 10C illustrate the damaged regulator compared to an exemplar regulator of the same model.

Determining that no other external ignition source was close to the regulator and assessing the significant structural damage to it, it is most likely that the fire initiated within the regulator as the two Ohmeda connectors were pushed together. Given that these connectors were not recovered, it is unknown if the connectors latched. Nevertheless, initiation of O_2 flow begins prior to the spring-loaded latching of the connection. At this time, the O_2 cylinder valve was open, and the gas regulator was pressurized. This is supported by the paramedic's recollection of hearing an audible "pop" right before the fire occurred. Fires within an oxygen enriched atmosphere commonly make an audible noise because of rapid gas expansion.

Due to high internal pressure and pure O_2 within the regulator, the fire burned very quicky (i.e., milliseconds) leading to an explosion that created the holes in the aluminum body. This action is probably the moment the paramedic was forced to close his eyes because of the bright flash and intense heat. Afterwards, the holes in the regulator allowed the fire to escape. Now amplified by 100% O_2 under high pressure acting as the oxidizer, the O_2 cylinder and regulator assembly acted like large flamethrower igniting surrounding materials easily and quickly. Materials that do not burn in ambient air would begin to burn under these circumstances, particularly aluminum, which comprised the regulator body and was present among most of the equipment in the ambulance. The continuous flow of O_2 out of the regulator most likely created the loud hissing noise recounted by both the paramedic and EMT. This was confirmed during the investigation by opening an exemplar jumbo-D size O_2 cylinder inside the ambulance box that could be easily heard in the driver's cabin.

These findings are further supported by the damage to the paramedic's clothing [redacted]

Above the burning regulator was a very thin, plastic roof with on-board O_2 system compressed gas hose positioned almost directly over the captain's chair and reaching across the length of the ambulance. This tubing connects the larger Y size O_2 tank to the O_2 wall port on the other side of the ambulance. It is possible that the "flamethrower from the roof" seen by the EMT was the moment the flaming portable O_2 tank burned through the roof and the on-board O_2

system tubing. At that point, there were two sources of oxygen-enriched fire, the portable O_2 tank and the line along the roof attached to the Y size cylinder. Upon inspection, there was no sign of the O_2 tubing above the roof or along the wall next to the main Y size O_2 cylinder. This would also explain why it took the fire department several minutes to extinguish the blaze. As long as the O_2 cylinders were expelling oxygen enriched flames, it would be very difficult to keep the fire extinguished. Both O_2 cylinders were empty after the fire was extinguished.

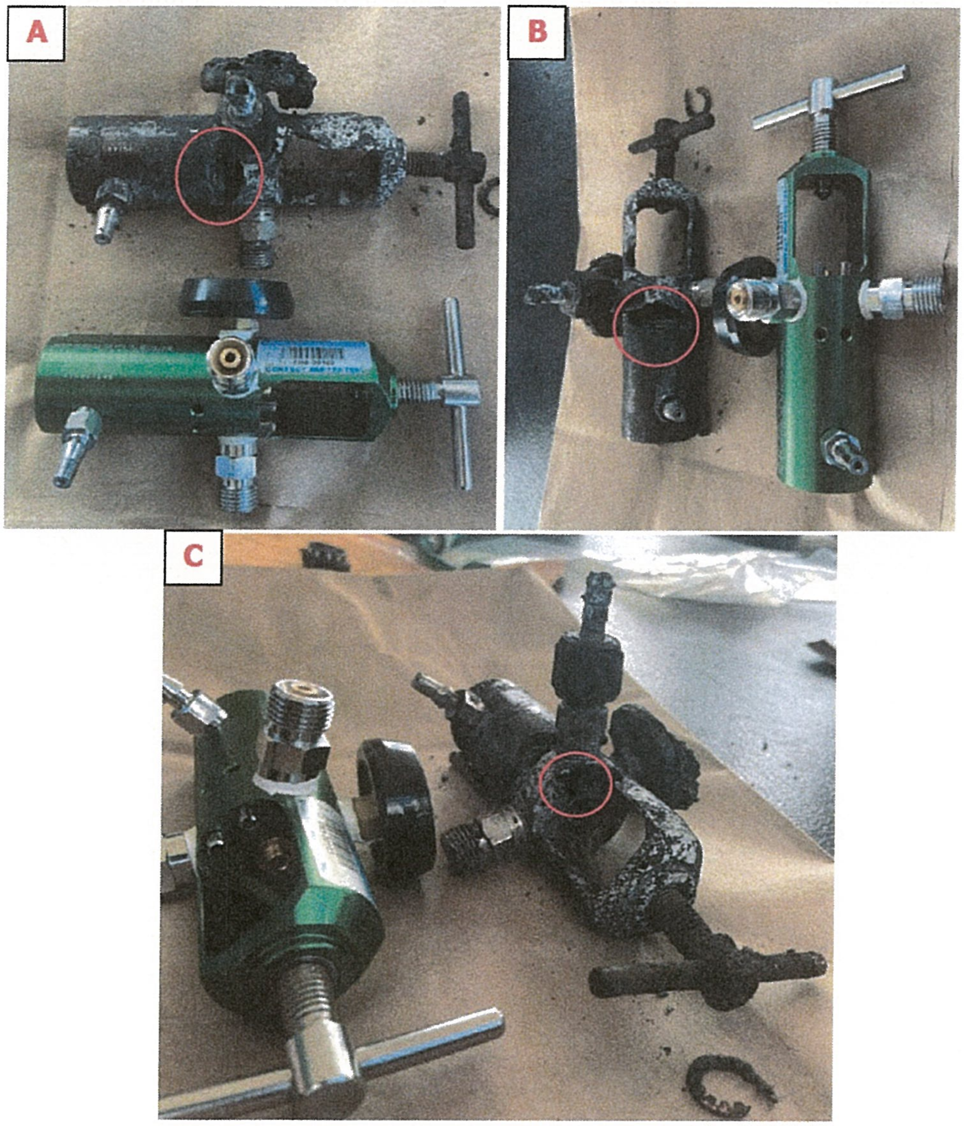

Figure 10A) Incident regulator (top) with large hole at the location of the two vent holes (within red circle) **10B)** alternative perspective of the regulators more clearly showing the fused DISS connectors (within red circle), **10C)** longitudinal view showing a small hole at the location of one alignment pin (within red circle)

Figure 11A) The frontside of the paramedic's clothes worn during the fire with significant burns on the right side and noticeable less damage on the left side. **11B)** The backside of the paramedic's clothes showing a distinct difference in damage between the right and left side as well as extensive thermal damage to the back of the shirt.

Conclusion

At the time of this report, the precise mechanism that caused the fire within the regulator is not known. Additional testing may provide more evidence to definitively determine the cause of the fire, but there is also a chance that it will not deliver enough information to offer more clarity. However, there are two mechanisms known to cause regulator fires both of which involve contaminants, such as small amounts hydrocarbons (e.g., oil and grease), organic, and metallic substances, within the O_2 cylinder and regulator assembly that burn when exposed to high pressure and heat in an oxygen enriched atmosphere. These ignition mechanisms are known as adiabatic compression (colloquially known as a gas hammer effect) and particle impact. If these two mechanisms are coupled with promoted ignition (fire propagation along the flow of O_2 burning other material downstream), they can cause a catastrophic failure of the gas regulator.

Based on the evidence described above, it is likely that the regulator fire was the result of one of these phenomena.

Adiabatic compression can occur when O_2 rushes into the regulator stem or high-pressure hose causing the local pressure to be much higher than the pressure of the O_2 cylinder. This transient pressure spike can increase local heat devoid of any external heat sources. Without heat transfer, the system experiences a sudden and severe increase in both temperature and pressure within a highly oxygen enriched atmosphere. These conditions can ignite contaminants within the system. The incident regulator has an aluminum body and brass components. Brass components were promoted by professional and government organizations in the early 2000s to reduce regulator fires because the metal requires much higher pressure (8,000 to 10,000 psi) than aluminum (25 to 35 psi) to ignite in an O_2 enriched atmosphere. Doing so will reduce, but not entirely eliminate, the potential for such ignition. However, aluminum and other contaminants, such as oils and dirt, can easily combust during adiabatic compression within a high-pressure O_2 enriched atmosphere. Once ignited, fire under these conditions can consume a hose and its connector or explode inside a regulator.

Particle impact occurs when O_2 flows extremely fast out of the O_2 cylinder and regulator assembly. This action can propel contaminants and even metal flakes from within the O_2 cylinder with enough force to generate energy capable of igniting the foreign objects when they slam into rigid surfaces potentially resulting in a flash fire within the system. Aluminum O_2 cylinders are particularly susceptible to this phenomenon because flakes from the interior body of the cylinder can burn at pressures much lower than within the system.

Further, the ignition caused by adiabatic compression and particle impact can be exacerbated by promoted ignition causing more material to burn with explosive force downstream of the initial ignition site.

Although O_2 regulator fires are rare, they have garnered the attention of government agencies, professional societies, and other organizations over the years.

Animated video footage displaying the effects of adiabatic compression (10:35) and particle impact (9:06) can be seen in a video produced by the US FDA in 2000 titled "Hidden Danger: Oxygen Regulator Fires." This video also contains testimonies of paramedics, EMTs, and firefighters that were injured after experiencing similar regulator fires.

WHA International has studied medical O_2 regulator fires extensively. This organization analyzed 11 regulator fires attributed to adiabatic compression, particle impact, and the presence of contaminants within and around the assembly. Not surprisingly, this organization showcases photographs of damage to an ambulance and gas regulator on its website that are nearly identical to the ambulance and regulator involved in this incident.

Thank you for the opportunity to assist you in this matter. An encrypted USB drive will also be shipped to you along with this correspondence. This drive will contain images taken during the investigation. If you have any questions, I can be reached at (540) 272-2740 or at cschabowsky@ecri.org.

Sincerely,

Chris Schabowsky

Chris Schabowsky, PhD, CCE
Director
Accident and Forensic Investigation Services