U.S. Chemical Safety and Hazard Investigation Board

Investigation Report
One Killed
Report Number: 2016-04-I-FL
Issue Date: February 2017

Nitrous Oxide Explosion

Key Issues:

- Process Safety Management System
- Inherently Safer Design
- Reactive Hazards
- Hazard Analysis
- Ineffective Safeguards

Airgas (Air Liquide)

Cantonment, Florida
August 28, 2016

> "The chemical industry has a continuing problem with reactive chemical accidents. This problem is due to the complex nature of chemical reactivity."
>
> "[W]e cannot avoid reactive chemical hazards; however, chemical plant accidents involving reactive hazards are unacceptable. The technology and the management systems do exist to produce these products safely."
>
> — Daniel Crowl

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Dedication

The United States Chemical Safety and Hazard Investigation Board dedicates this report to ***Jesse Folmar***, who was killed by the nitrous oxide explosion at the Airgas (Air Liquide) facility in Cantonment, Florida on August 28, 2016.[1]

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[1] *See* Jesse Folmar Obituary [121].

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Acronyms and Abbreviations

AGA	American Gas Association
ACGIH	American Conference of Governmental Industrial Hygienists
AIGA	Asia Industrial Gases Association
API	American Petroleum Institute
API RP	American Petroleum Institute Recommended Practice
ARA	Accident Risk Assessment – see page 103
CAL/OSHA	California Division of Occupational Safety and Health
CCPS	Center for Chemical Process Safety
CDT	Central Daylight Time
CFR	Code of Federal Regulations
CGA	Compressed Gas Association
CSB	U.S. Chemical Safety and Hazard Investigation Board
DOT	U.S. Department of Transportation
EIGA	European Industrial Gases Association
EPA	U.S. Environmental Protection Agency
FDA	U.S. Food and Drug Administration
FL	The State of Florida
FMEA	Failure Modes and Effects Analysis
FTC	U.S. Federal Trade Commission
GMP	Good Manufacturing Practice
HAZOP	Hazard and Operability Study
HIRA	Hazard Identification and Risk Analysis
IChemE	Institution of Chemical Engineers
ISA	International Society of Automation
ISO	International Organization for Standardization
JIMGA	Japan Industrial and Medical Gases Association
LOPA	Layers of Protection Analysis
LLC	Limited Liability Company
MAWP	Maximum Allowable Working Pressure
MOC	Management of Change
NIOSH	National Institute for Occupational Safety and Health
NO	Nitric oxide
NO_2	Nitrogen dioxide
N_2O	Nitrous oxide
NFPA	National Fire Protection Association
NPSH	Net Positive Suction Head
NTSB	U.S. National Transportation Safety Board
OSHA	U.S. Department of Labor Occupational Safety and Health Administration
PHA	Process Hazard Analysis
PHMSA	U.S. Pipeline and Hazardous Materials Safety Administration
PRD	Pressure Relief Device
PSI	Process Safety Information
psi	Pounds per Square Inch
psia	Pounds per Square Inch Absolute
psig	Pounds per Square Inch Gauge
PSM	Process Safety Management
PSMS	Pipeline Safety Management System (see API RP 1173)
PTFE	Polytetrafluoroethylene also known as Teflon
RAGAGEP	Recognized and Generally Accepted Good Engineering Practice

RMP	Risk Management Plan Rule
SDS	Safety Data Sheet
SIS	Safety Instrumented System
SMS	Safety Management System
TEFC	Totally Enclosed Fan-Cooled (motor)
TFE	Tetrafluoroethylene
U.S.	United States of America
USA	United States of America
USP	U.S. Pharmacopeial Convention

I. Executive Summary

1. On Sunday, August 28, 2016, at approximately 12:10 pm, a nitrous oxide trailer truck exploded at the Airgas manufacturing facility in Cantonment, Florida. The explosion killed the only Airgas employee present and heavily damaged the facility, halting nitrous oxide manufacturing at Cantonment indefinitely.

2. The U.S. Chemical Safety and Hazard Investigation Board (CSB) determined the most probable immediate cause of the incident was that during initial loading of a trailer truck, a pump heated nitrous oxide above its safe operating limits. Exceeding these critical safety limits appears to have started a nitrous oxide decomposition reaction that propagated from the pump into the trailer truck, causing the explosion. The CSB has documented its causal determination throughout this report based on a review of the evolution of corporate activities related to nitrous oxide production at the Cantonment site and other relevant facilities, a history of nitrous oxide decomposition explosions in the industry, and an analysis of all available physical, documentary, and testimonial evidence.

3. A definitive determination of the event that started the explosive decomposition of nitrous oxide is not possible due to the force of the explosion, the extent of damage to the facility, the minimal available process data, the absence of surviving eyewitnesses, and the lack of safety controls needed to prevent other potential sources of nitrous oxide decomposition. This report examines other theoretical causes of the explosion, including possible contamination of the nitrous oxide and the lack of an electrical bonding and grounding system needed to prevent static electricity, both of which could contribute to or cause nitrous oxide explosions.

4. Federal regulations require many types of chemical facilities that manufacture highly hazardous substances to have process safety management systems in place to protect their workforce and the public. The majority of these specialized rules do not apply to nitrous oxide facilities; specifically, neither the Occupational Safety and Health Administration's Process Safety Management standards, nor the Environmental Protection Agency's Risk Management Plan rule apply to the Airgas Cantonment facility. This is true despite the fact that since 1973, the nitrous oxide industry has averaged one major explosion about every seven years. These incidents killed six workers and injured 21 other people. In addition, since 2001 these explosions have occurred more frequently with an average of one explosion every four years during that timeframe.

5. The CSB investigation found that Airgas lacked a safety management system to identify, evaluate, and control nitrous oxide process safety hazards, which led to the explosion. Although not required by Federal regulations, good practice guidance recommends developing and implementing a robust safety management system to manage the hazards relating to manufacturing, transferring, and shipping nitrous oxide. The contributing causes of the explosion that killed the Airgas employee all stemmed from the company's lack of an effective overall process safety management system. These causes include:

    - Airgas did not evaluate inherently safer design options that could have eliminated the need for the pump;

- Airgas never evaluated its process to identify and control process safety hazards;
- Airgas did not effectively apply the hierarchy of controls to the safeguards that the company used to prevent a possible nitrous oxide explosion;
- Airgas installed equipment that increased the likelihood of an explosion without performing a management of change safety review;
- Airgas did not apply an essential industry safety instrumentation standard, or key elements of a voluntary safe storage and handling standard, both of which are intended to prevent nitrous oxide explosions;
- Airgas safeguards that failed to prevent the explosion include an automatic shutdown safety control and an explosion prevention device;
    - ➢ The automatic shutdown safety control Airgas relied on required the Airgas worker to be physically present – and located immediately adjacent to the trailer truck – in order to bypass the shutdown at a time when an explosion was most likely to occur; and
    - ➢ The Airgas explosion prevention device – a flame arrestor – was never tested or inspected to ensure it could protect workers from an explosion.
- Airgas failed to apply lessons from previous nitrous oxide explosions; and
- Airgas did not provide its Cantonment facility with an appropriate level of technical staffing support.

6. Through its subsidiaries, Air Liquide is the current owner of the nitrous oxide manufacturing facility in Cantonment, and the facility is one of three sites operating under the Airgas name. At the time of the incident, Air Liquide owned and operated all five nitrous oxide manufacturing facilities in the United States and Canada. Each of the nitrous oxide manufacturing plants is equipped with trailer truck loading facilities. Air Liquide ships nitrous oxide throughout North America by trailer truck and unloads it into storage tanks at customer facilities. Nitrous oxide customers include industrial users, universities, and hospitals, where workers and members of the public face additional exposure to potential explosions during liquid nitrous oxide transfers.

7. As a result of its investigation, the CSB is issuing safety recommendations to Air Liquide (Airgas), the Compressed Gas Association, and to both ACD and Cryostar (two nitrous oxide pump manufacturers).

II. Background Information

A. Industry and Corporate Overview

1. The corporate headquarters for Air Liquide is in Paris, France, and the company employs about 68,000 people in 80 countries.[2] On August 28, 2016, the day of the incident, Air Liquide owned and operated all five nitrous oxide manufacturing facilities in the United States and Canada. As shown in Figure 1, these facilities are located in:[3]

    1) Richmond, California
    2) Yazoo City, Mississippi
    3) Cantonment, Florida
    4) Donora, Pennsylvania
    5) Maitland, Ontario

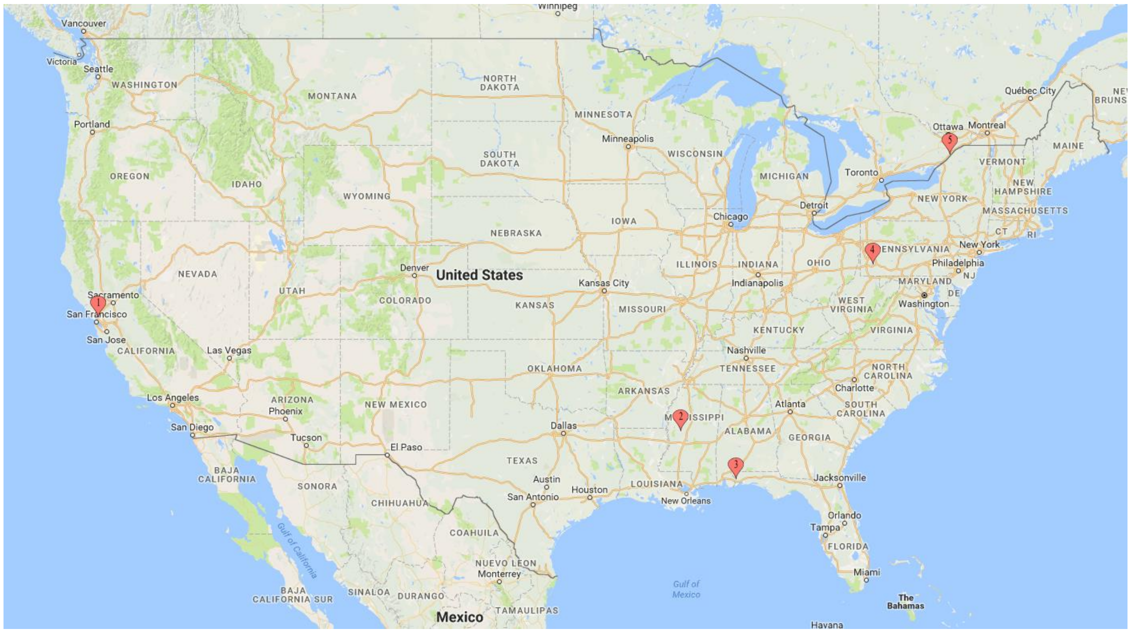

Figure 1. Map showing the five nitrous oxide manufacturing facility locations in the United States and Canada. Map created from www.mapcustomizer.com using Google Maps.

2. On May 23, 2016, American Air Liquide Holdings, Inc. ("Air Liquide") acquired Airgas, Inc. ("Airgas"), the largest producer of nitrous oxide in North America, making Airgas a subsidiary of Air Liquide.[4, 5] Before the acquisition, at the beginning of 2016, Air Liquide owned and operated

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[2] Air Liquide is an industry leader in the production of nitrous oxide, among many other products, technologies, and services. *See Air Liquide in brief* [111].

[3] *See* FTC document detailing nitrous oxide manufacturing locations [224].

[4] *See* Airgas is the largest nitrous oxide manufacturer in North America [112].

[5] *See* Air Liquide press release announcing completion of Airgas acquisition [214].

only two of these plants – Richmond and Donora. Airgas, at the time a separate company, owned and operated the other three sites – Yazoo City, Cantonment, and Maitland.[6]

3. As part of this transaction, the United States Federal Trade Commission (FTC) accepted a consent agreement that, among other things, called for Air Liquide to divest the Richmond and Donora nitrous oxide manufacturing plants.[7, 8] As a result of the agreement, Air Liquide sold the Richmond and Donora facilities to Matheson Tri-Gas on September 8, 2016.[9]

4. Currently, Airgas operates three nitrous oxide manufacturing facilities in North America – Cantonment, Yazoo City, and Maitland. The Cantonment facility is the only North American nitrous oxide manufacturing location that does not use ammonium nitrate decomposition technology. At Cantonment, Airgas produces nitrous oxide from the co-product gas of an adjacent chemical manufacturing facility.

B. Cantonment Nitrous Oxide Manufacturing Plant Overview

1. Facility History

5. Puritan-Bennett began design of the Cantonment, Florida facility in 1980, initiated construction in 1982, and started manufacturing nitrous oxide at the site in 1983. At the time, Puritan-Bennett was the largest supplier of nitrous oxide in North America. In 1996, Puritan-Bennett merged with Nellcor and the facility operated under the Nellcor Puritan Bennett name. This merger lasted until 1998, when Mallinckrodt purchased the Cantonment facility.

6. In 2000, Airgas acquired the facility from Mallinckrodt and the company name changed to Nitrous Oxide Corp.[10] Air Liquide then acquired the Airgas nitrous oxide business in May 2016.[11] As a subsidiary of Air Liquide, the Cantonment facility remains under the Nitrous Oxide Corp. ownership name, but Airgas is the more common name used by employees, the community, and on signs at the facility.[12] (Figure 2)

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[6] The three Airgas nitrous oxide facilities operate as part of Nitrous Oxide Corp.

[7] *See* FTC Analysis of Consent Agreement [4].

[8] The FTC ordered a similar divestiture of the Richmond, California and Donora, Pennsylvania sites in 2001 following the Airgas acquisition of all nitrous oxide manufacturing facilities in the United States and Canada in January 2000. See Federal Trade Commission Decision at page 717 [7].

[9] *See* Matheson news release [5]. Matheson is an industrial gas and equipment company with over 9,000 employees in 16 countries. See Matheson web site [6].

[10] *See* 2001 FTC News Release [7].

[11] *See* Air Liquide press release announcing completion of Airgas acquisition [214].

[12] *See* Delaware Department of State: Division of Corporations: File Number 2049053 [145]. Although Air Liquide owned the Cantonment facility at the time of the incident, this report will use the trade name, Airgas, to refer to the Cantonment facility unless required to identify the facility with respect to Air Liquide's current ownership. The CSB is also directing safety recommendations to Air Liquide in its capacity as the parent company.

Figure 2. Post-incident photo of the administrative and operations building at the Airgas nitrous oxide manufacturing facility in Cantonment, Florida nitrous oxide manufacturing facility. Although the official corporate name is Nitrous Oxide Corp., the Airgas name is more commonly used.

2. Process Description

7. As noted above, the feed to the Airgas nitrous oxide process is a co-product gas from a chemical manufacturing facility adjacent to the Airgas facility.[13] (Figure 3) This feed gas contains primarily nitrous oxide, nitrogen, oxygen, and carbon dioxide.

Figure 3. Overhead photo of the Airgas manufacturing facility shown in purple. The larger facility located to the north is the neighboring chemical manufacturing facility. Photo from Bing Maps.

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[13] Airgas receives a portion of the nitrous oxide co-product gas from a neighboring chemical manufacturing facility.

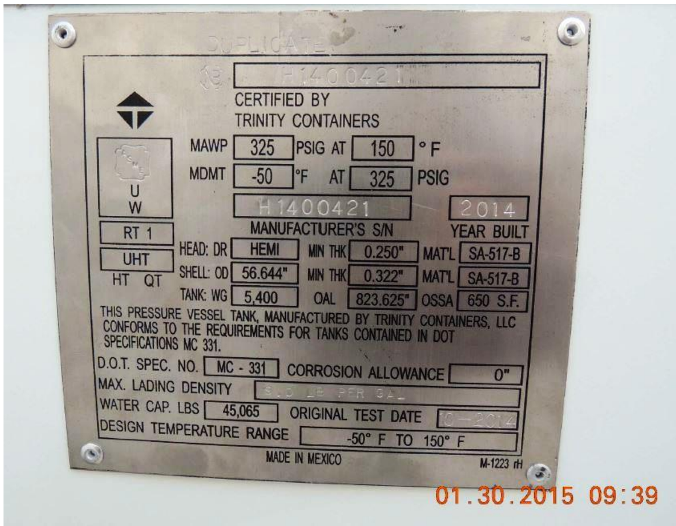
8. The Airgas process separates the nitrous oxide from the other components. Next, the nitrous oxide is compressed, condensed, and stored in one of three 50-ton horizontal storage tanks. (Figure 4) The liquid in these tanks is stored at its boiling point, typically 0 to -10 degrees Fahrenheit (°F).

Figure 4. Post-incident photo showing one of the three 50-ton nitrous oxide storage tanks.

9. From storage, Airgas pumps the cold liquid nitrous oxide into insulated trailer trucks or shipping containers. After loading, Airgas transports the nitrous oxide trucks and shipping containers to its many North American customer distribution sites, which include industrial facilities, hospitals, and universities. (Figure 5)

Figure 5. Photo showing a typical trailer truck used at Airgas to transport nitrous oxide to customers.

10. Airgas uses U.S. Department of Transportation (DOT) MC-331 trailers to transport nitrous oxide.[14] (Figure 6)



DUPLICATE

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TRINITY CONTAINERS

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MAWP 325 PSIG AT 150 ° F
MDMT -50 °F AT 325 PSIG
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MANUFACTURER'S S/N YEAR BUILT
RT 1
UHT
HT QT
HEAD: DR HEMI MIN THK 0.250" MAT'L SA-517-B
SHELL: OD 56.644" MIN THK 0.322" MAT'L SA-517-B
TANK: WG 5,400 OAL 823.625" OSSA 650 S.F.

THIS PRESSURE VESSEL TANK, MANUFACTURED BY TRINITY CONTAINERS, LLC CONFORMS TO THE REQUIREMENTS FOR TANKS CONTAINED IN DOT SPECIFICATIONS MC 331.

D.O.T. SPEC. NO. MC - 331 CORROSION ALLOWANCE 0"
MAX. LADING DENSITY 8.0 LB PER GAL
WATER CAP. LBS 45,065 ORIGINAL TEST DATE 10-2014
DESIGN TEMPERATURE RANGE -50° F TO 150° F
MADE IN MEXICO
M-1223 rH

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Figure 6. Trailer 182 design. This is a pre-incident photo of the Trailer 182 nameplate. Manufactured in 2014, Trailer 182 was built to the MC-331 specification. The trailer volume is 5,400-gallons with a maximum allowable working pressure (MAWP) of 325 pounds per square inch gauge (psig).

11. Although Airgas ships both trailer trucks and shipping containers, trailer trucks are more common and were involved in the August 28, 2016, incident. Figure 7 shows a simplified schematic of the equipment Airgas used to transfer liquid nitrous oxide from storage to a trailer truck.

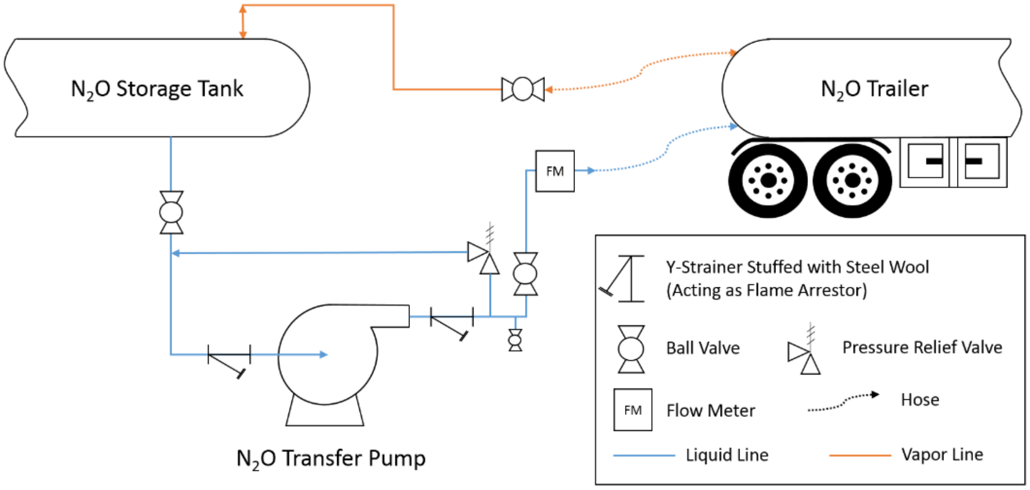

Figure 7. Simplified flow diagram of Airgas equipment used to load trailer trucks with nitrous oxide. This approach to loading a truck is called the "two-hose method," in reference to the two separate hoses (one vapor and one liquid) connected to the truck. "N_2O" is the chemical formula for nitrous oxide and serves as an abbreviation.

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[14] *See* Texas Trailer website [8] and 49 C.F.R. § 178.337 (accessed December 22, 2016).

12. Airgas used the “two-hose method” for truck loading at Cantonment. One hose connects the nitrous oxide pump outlet (discharge) to the bottom (liquid inlet) connection of the trailer truck. The second hose connects the top (vapor) of the trailer truck to the top (vapor) of the nitrous oxide storage tank to equalize or “balance” the pressure between the storage tank and the trailer truck.

13. Airgas employees informed CSB investigators that there is no level indicator on the trailer truck to indicate how much nitrous oxide is loaded. To prevent overfilling, U.S. Department of Transportation (DOT) regulations require MC-331 nitrous oxide trailers to be equipped with a method to prevent completely filling a trailer.[15]

14. From the storage tank, liquid nitrous oxide flows to a transfer pump. The pump provides additional pressure needed for liquid to flow into the trailer truck, because the storage tank sits close to the ground. (Figure 4) The trailer truck sits atop wheels (Figure 5) that elevate it approximately four feet above the bottom of the storage tank.

15. As shown in Figure 8, Airgas installed filtration strainers (y-strainers) on the pump inlet and outlet. To improve the strainer’s utility as a flame arrestor, the company filled these strainers with steel wool to prevent a nitrous oxide decomposition reaction from causing an explosion in either the storage tank or the trailer truck.

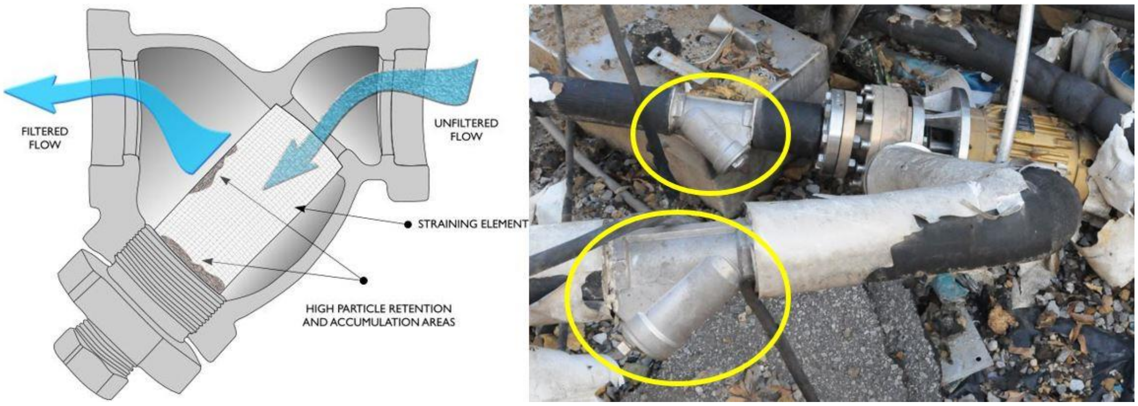

Figure 8. The left graphic is a generic depiction showing a typical application for a y-strainer – removing solid particles from a liquid stream.[16] The photo on the right shows one of the nitrous oxide pumps at Airgas, the ACD centrifugal pump. The y-strainers are circled in yellow. Airgas installs steel wool into the open cylinder of the y-strainer to function as a flame arrestor.

16. Airgas installed a flow meter between the pump and the trailer truck.[17] This flow meter allowed the operator to monitor the total amount of liquid nitrous oxide transferred to the trailer truck and

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[15] 49 C.F.R. § 173.315. Airgas uses a fixed length dip tube to prevent completely filling a trailer.

[16] *See* y-strainer photo [9].

[17] *See* Turbine Flowmeter [10] and Sponsler T675 - Deliver System Totalizer [11].

provided an automatic shutdown (safety interlock) to turn off the pump motor when the meter detected a low-flow rate.[18]

17. This low-flow safety interlock is critical because at least three other nitrous oxide industry explosions appear to have started when pumps generated heat from loss of prime, low-flow rate, or dry running. An operating pump generates heat and without enough liquid flow the temperature of pump components increase. At times, nitrous oxide industry pumps have developed enough heat to initiate decomposition explosions.

18. The Airgas truck loading process required manual operation by on-site personnel, with no automatic controls other than the safety interlock associated with the pump.

19. Although not shown in Figure 7, Airgas installed two nitrous oxide transfer pumps configured in parallel. Having two pumps allowed Airgas to have a spare pump. The company installed the second pump because replacement pumps from the original manufacturer, Smith Precision Products ("Smith"), were no longer available.

20. In 2014, Smith stopped manufacturing this pump for nitrous oxide service. As a result, Airgas recognized the need to purchase a new nitrous oxide pump from a different manufacturer. The original Smith nitrous oxide transfer pump utilized a gear-type positive displacement technology.[19] After Smith notified Airgas that Smith would no longer produce its nitrous pumps, Airgas first installed a Cryostar and later an ACD pump (both centrifugal pumps) to load trailers at the Cantonment facility.[20, 21] The Smith pump remained installed as a backup.

21. The gear-type positive displacement Smith pump was equipped with a pressure relief device on the outlet (discharge) side of the pump with the outlet piping from the relief device routed to the inlet (suction) side of the pump as shown in Figure 7. Providing a relief device on the discharge of a positive displacement pump is common as this type of pump can generate pressure beyond equipment design conditions.

22. The new centrifugal pumps were also equipped with a pressure relief device on the outlet side of the pump with the discharge piping from the relief device routed to the suction side of the pump, as shown in Figure 7. Although Airgas does not have documentation showing the basis for this relief device, it is likely that the company copied the design for the centrifugal pump relief valve from the design of the relief valve installed on the positive displacement Smith pump. In addition, although recycling the outlet of the relief valve back to the pump inlet piping can protect against overpressure, it also recycles heat gained by the fluid from the pump and can lead to vapor formation. As discussed later in Section IV.D.2 (Pump Recycle Piping), good piping design

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[18] This automatic shutdown or safety interlock is also referred to as a low-flow or run-dry interlock. Run-dry, low-flow, and loss of prime all refer to the general condition of a pump operating without enough liquid flow.

[19] *See* Smith Precision Products company website [12].

[20] *See* Cryostar company website [13].

[21] *See* ACD company website [68].

practice suggests routing the recycle back to the storage tank, away from pump's liquid supply connection.

3. Nitrous Oxide Industry Safety Standards

23. The Compressed Gas Association (CGA) is an industry association that publishes a number of voluntary nitrous oxide safety standards.[22]

24. CGA standards concerning the handling and transfer of nitrous oxide include:

- CGA G-8.1–2013, *Standard for Nitrous Oxide Systems at Customer Sites*
- CGA G-8.2–2010, *Commodity Specification for Nitrous Oxide*
- CGA G-8.3–2016, *Safe Practices for Storage and Handling of Nitrous Oxide*
- CGA G-8.4–2016, *Safe Practices for the Production of Nitrous Oxide from Ammonium Nitrate*

25. Among these voluntary standards, CGA G-8.3–2016, *Safe Practices for Storage and Handling of Nitrous Oxide* is most applicable to the storage and liquid trailer truck loading operations at the Airgas facility in Cantonment, Florida.

26. Due to global coordination efforts by industrial gas associations, CGA G-8.3–2016 is effectively an international standard. Each equivalent gas association standard notes:

> This publication is intended as an *international harmonized publication for the worldwide use and application by all members* of Asia Industrial Gases Association (AIGA), Compressed Gas Association (CGA), [European Industrial Gases Association] (EIGA), and Japan Industrial and Medical Gases Association (JIMGA). Each association's technical content is identical, except for regional regulatory requirements and minor changes in formatting and spelling.[23] (Emphasis added.)

4. Nitrous Oxide Decomposition Reaction

27. The CGA notes in its standard that nitrous oxide is a stable compound under normal operating conditions:

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[22] *See* CGA publications [152].

[23] *See* AIGA - Safe Practices for Storage and Handling of Nitrous Oxide at page 2 [215]. Although this report makes many references to CGA G-8.3–2016, this CGA standard is not a public document and costs about $100. The AIGA version of this standard, AIGA 081/16, Safe Practices for Storage and Handling of Nitrous Oxide, is a public document and contains nearly the same language as CGA G-8.3–2016.

> Under normal operating conditions, nitrous oxide is a stable compound in both the liquid and gaseous states. Nitrous oxide is classified as a nonflammable gas, with oxidizer as a secondary classification.[24]

28. But the CGA also describes the self-reactive decomposition of nitrous oxide, including the hazard, chemistry, effects, and limitations of the reaction.[25] The standard explains that in certain gaseous conditions nitrous oxide can decompose violently:

> "Nitrous oxide can decompose explosively, into nitrogen and oxygen:"[26]
>
> $$2N_2O \xrightarrow{yields} 2N_2 + O_2 + \text{Heat}^{27}$$
>
> "Accidents and experiments have shown that nitrous oxide, as a result of its positive formation energy, can decompose exothermally. This decomposition reaction can be self-sustaining and violent. The theoretical pressure ratio at decomposition, final pressure/initial pressure, can reach 10 to 1."[28]
>
> "Laboratory results indicate that nitrous oxide can be safely handled in the liquid state, but decomposition hazards exist in the gaseous state at elevated pressure and/or temperature. The reaction can propagate through vapor with liquid present."[29]

29. Although it can be violent, the self-reactive nitrous oxide decomposition reaction is relatively slow. By comparison, the propagation speed of the nitrous oxide decomposition reaction is 30 times slower than the flame propagation speed for propane with air.[30] As a result, the CGA states that the decomposition reaction is "easily quenched."[31]

30. CGA provides a chart (Figure 9) showing conditions needed to propagate an explosive nitrous oxide decomposition reaction. In general, for each piping diameter, higher pressure results in lower propagation temperature. Smaller piping diameters also require a higher combination of temperature and pressure to sustain the decomposition reaction. CGA recommends operating "below the propagation threshold by controlling pressure, temperature, or line [piping] size."[32]

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[24] *See* [150], Section 4.3.2.
[25] A self-reactive chemical is a thermally unstable substance susceptible to undergo a strongly exothermic decomposition. See self-reactive definition [14].
[26] *See* [150], Section 4.3.2.
[27] The reaction is exothermic and liberates 800 British Thermal Units per pound of nitrous oxide. See [150], Section 4.3.2.
[28] *See* [150], Section 4.3.2.
[29] *Id.*, at Section 4.3.2.
[30] Propagation speed refers to the speed that the reaction travels through the piping. See definition of propagation speed [99].
[31] *See* [150], Section 4.3.2.
[31] *Id.*, at Section 4.3.2.
[32] *Id.*, at Section 4.3.3.3.

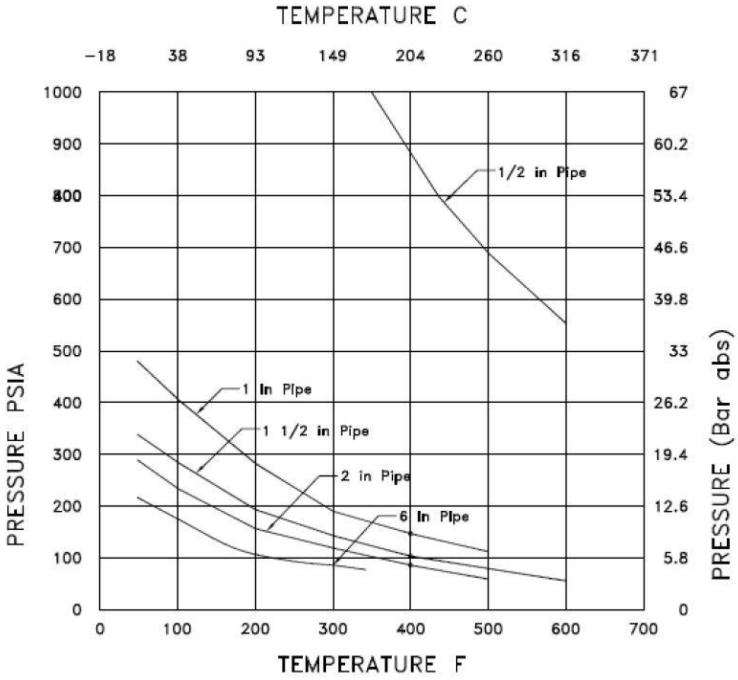

Figure 9. CGA Propagation threshold for nitrous oxide decomposition reaction.[33]

31. Contamination of nitrous oxide may lower the propagation threshold.[34] Nitrous oxide manufacturers do not fully understand the full range and effect of contaminants, but known contaminants include flammable hydrocarbons and combustible materials.[35] In addition, metal particles may act as a catalyst.[36] As a result, equipment in contact with nitrous oxide requires cleaning to oxygen service standards and "[v]isible particles, fibers, or drops of water shall not be accepted.[37]

32. Nitrous oxide decomposition explosions have occurred from, among other things, pumps running dry, hot work, and sudden or rapid compression of the vapor (adiabatic compression).[38] CGA provides a table of sources known to have initiated a nitrous oxide decomposition reaction.[39] (Figure 10)

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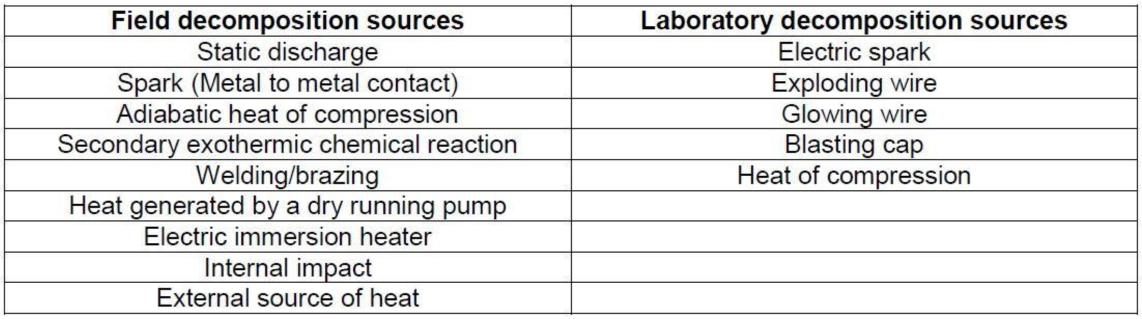
[33] *Id.*, at Section 4.3.3.3.
[34] *Id.*, at Section 4.3.3.4.
[35] *Id.*, at Section 4.3.3.3.
[36] *See* Scaled Composites Nitrous Oxide Safety Guidelines at page 3 [15].
[37] *See* [150], Section 5.5.
[38] Adiabatic means without heat transfer – without gain or loss of heat. See definition of adiabatic [16].
[39] *See* [150], Section 4.3.3.



Field decomposition sources	Laboratory decomposition sources
Static discharge	Electric spark
Spark (Metal to metal contact)	Exploding wire
Adiabatic heat of compression	Glowing wire
Secondary exothermic chemical reaction	Blasting cap
Welding/brazing	Heat of compression
Heat generated by a dry running pump	
Electric immersion heater	
Internal impact	
External source of heat	

Figure 10. Table of sources known to initiate the nitrous oxide decomposition reaction.

5. Trailer Loading

33. CGA recommends using a ground-mounted pump adjacent to the storage tank to fill trailers. The standard requires designing pump piping to meet the pump manufacturer's inlet liquid pressure requirements.[40]

34. To prevent the accumulation of static electrical charges, the standard recommends electrically bonding the trailer to the storage tank and ensuring the system is grounded.[41, 42]

35. For additional safety, CGA recommends filling operations enter the bottom of a tank to "allow a potential decomposition starting at the pump to be quenched in the liquid phase."[43] To accomplish this for trailer truck loading, CGA recommends using the two-hose method to load into the bottom of the trailer to prevent a decomposition reaction. The standard recommends:

> Transport tanks [trailers] should be filled by the two-hose filling procedure in order to minimize pressure differential and the hazard of decomposition. Filling shall be made through the bottom fill line and the gas phase shall be directed back to the stationary tank. Filling through the top equalizing line or any other line to the top is not recommended in order to avoid heat input into the gas phase by a hot running pump.[44]

6. Safeguards to Prevent Pumps from Causing Explosions

36. For a liquid nitrous oxide transfer system, such as the one used by Airgas at Cantonment, the transfer pump can be a source of heat. As noted in Figure 10, heat generated by a dry running pump can cause pump components to exceed the temperature needed to start a nitrous oxide decomposition reaction.

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[40] *Id.*, at Section 8.2.
[41] *Id.*, at Sections 5.7 and 8.2.
[42] *See* explanation of bonding and grounding [212].
[43] *See* [150], Section 6.4.
[44] *Id.*, at Section 8.2.

37. Although not defined in CGA G-8.3–2016, "dry running" is likely applicable to any condition that creates an insufficient liquid supply to the pump and generates heat, increasing the temperature of a pump component.

38. CGA G-8.3–2016 describes the potential for a pump to initiate a nitrous oxide explosion. The standard states, "Pumps shall not be allowed to operate with no flow or loss of prime. A number of serious incidents have been attributed to overheated equipment."[45]

39. The standard recommends piping configuration and suggests using strainers as a flame arrestor (Section IV.C.1).[46] The standard states:

> Best practice for liquid transfer pumps is to install the pump with a flooded suction line and a liquid return connection to help quench a decomposition reaction. Strainers should be installed on the suction and discharge of liquid pumps to provide a heat sink that assists in quenching a decomposition flame front ….[47]

40. To prevent nitrous oxide explosions from high pump temperature, CGA requires a nitrous oxide loading pump to be equipped with a protective interlock – "[n]itrous oxide transfer pumps shall be provided with an interlock to prevent dry running …."[48]

41. CGA further explains that the safety function of this protective interlock is to prevent the pump from operating during conditions that can generate extra heat:

> The primary hazard during pump operation is dry running, which leads to heating and damage of the pump. Nitrous oxide can over heat and cause a decomposition reaction, which can lead to an explosion. Dry running is most often experienced at startup of the pump and when loss of prime occurs during operation. Provide an interlock system that allows the pump to start only after it has been properly cooled down and filled with liquid product, which protects the pump from dry running.[49]

And:

> All pumps, compressors, or other equipment with rotating or sliding components shall be protected by automatic controls against loss of prime and excessive operating temperatures.[50]

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[45] *Id*., at Section 5.7.
[46] *See* Section IV.C.1 of this report for more information on flame arrestors.
[47] *See* [150], at Section 5.7.
[48] *Id*., at Section 4.3.3.5.
[49] *Id*., at Section 7.4.3. (Emphasis removed from original).
[50] *Id*., at Section 5.7.

C. History of Nitrous Oxide Explosion Incidents

42. The CSB identified six previous major explosion incidents in the nitrous oxide industry that occurred before the explosion at Cantonment. (Figure 11) Since 1973, the nitrous oxide industry has averaged one major explosion about every seven years. These incidents killed six workers and injured 21 other people.[51] In addition, since 2001 these explosions have occurred more frequently with an average of one explosion every four years during this timeframe.

Year	Location	Likely Initiation Source	Killed	Injured	Contamination Identified	Pump Involved
1973	West Palm Beach Florida, USA	Adiabatic Compression	—	—		
1980	Richmond California, USA	Pump Heat	—	—	✓	✓
1987	Reading Pennsylvania, USA	Hot Work	1	3		
2001	Eindhoven the Netherlands	Pump Heat	—	10	✓	✓
2007	Mojave California, USA	Adiabatic Compression	3	3	✓	
2012	Moncada Spain	Pump Heat	1	5	✓	✓
2016	Cantonment Florida, USA	Pump Heat	1	—	✓	✓

Figure 11. History of nitrous oxide explosions.

43. Of the six reactive chemical incidents prior to the Cantonment explosion, three reportedly occurred from a similar scenario – a nitrous oxide transfer pump created enough heat to trigger an explosive nitrous oxide decomposition reaction.

- In 1980, a pump initiated a nitrous oxide explosion at a Puritan-Bennett facility in Richmond, California. According to the investigation report: "Miraculously, the operator was not injured …";
- In 2001, a pump initiated a nitrous oxide explosion at a Linde facility in Eindhoven, the Netherlands. Linde concluded that the explosion would have likely killed a worker, but he left the area minutes before the explosion. The explosion also injured ten other people; and

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[51] Of the 21 injuries, at least two were members of the public.

- In 2012, a pump initiated a nitrous oxide explosion at an Air Liquide facility in Moncada, Spain that killed one worker and injured five others.

44. CGA G-8.3–2016 gives an overview of previous nitrous oxide explosions, stating:

> Most nitrous oxide decomposition incidents have occurred in large pressure vessels, such as a storage tank or cargo tank. As the vapor volume and temperature increase, the risk of disassociation increases…. The decomposition [reaction] can also be initiated by external heat (such as welding or brazing) on the vessel or vessel piping, or heat generated by a dry running pump. If initiated in the piping, the reaction front can travel through the piping and into the vessel, if operating above the propagation threshold. Once the reaction front is inside the vessel there is effectively no heat sink to quench the reaction. Since 1.5 moles of gas are created for each mole of decomposed nitrous oxide, the decomposing nitrous oxide compresses and heats the unreacted nitrous oxide as the reaction front moves into the vessel. Eventually, the unreacted nitrous oxide reaches high enough temperature and pressure to auto-initiate, resulting in an explosion [due to the rapid pressure increase].[52]

1. 1973 Pratt & Whitney Explosion – West Palm Beach, Florida

45. In July 1973, a nitrous oxide explosion and fire occurred at a Pratt & Whitney facility in West Palm Beach, Florida.[53] During preparations to test a chemical laser, a 550-gallon tank of gaseous nitrous oxide at a pressure of about 1,300 pounds per square inch (psi) and a temperature of nearly 400 °F exploded as the result of a violent nitrous oxide decomposition reaction.[54]

46. The explosion caused significant property damage, but there were no injuries. A Pratt & Whitney investigation report detailed the findings. The report showed that changes to previous operating conditions, including higher temperature and a faster rate of increasing the pressure, likely started a nitrous oxide decomposition reaction from rapid (adiabatic) compression.[55] The company also concluded that the higher temperature was not likely a direct cause of the explosion, but since lower ignition energy is required at higher temperature, the increased temperature increased the hazard.[56]

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[52] *See* [150] at Section 4.3.3.5. (Emphasis in original).
[53] *See* [18] at page 9. Also see Nitrous Oxide Explosive Hazards at pages 5 and 6 [17], as well as Nitrous Oxide Trailer Rupture at page 23 [1].
[54] *See* [18] at page 18.
[55] *See* [18] at page 17.
[56] *See* [18] at page 17.

2. 1980 Puritan-Bennett Explosion – Richmond, California

47. In November 1980, an explosion occurred when loading a trailer truck at a Puritan-Bennett nitrous oxide plant in Richmond, California.[57, 58] The explosion "blew out the walls of a plant building, shattered windows in a 10-block area and rocked communities as far as 10 miles away."[59] "Authorities in surrounding communities and in San Francisco across the bay from Richmond received hundreds of telephone calls from residents asking if an earthquake had occurred."[60]

48. In its investigation report, Puritan-Bennett stated: "Miraculously, the operator was not injured despite the complete destruction of the process building and the scatter of pieces of the … trailer, process piping and small equipment about the entire plant."[61]

49. The Puritan-Bennett incident report showed that the explosion occurred when the loading pump operated without enough liquid supply (running dry) and the resulting temperature increase from the pump propagated an explosive nitrous oxide decomposition reaction.[62] The report explained that the trailer was empty and the explosion occurred shortly after initiating a transfer of liquid into the trailer.[63] The report also noted that the presence of an excessive amount of sealant inside the pump might have acted as a contaminant, which "greatly enhances the propagation potential of the decomposition of nitrous oxide."[64]

50. Puritan-Bennett's post-incident recommended corrective actions included installing a new pump to provide five feet of elevation between the bottom of the storage tank and the pump to "assure pump priming and continued suction flooding."[65]

51. The company also recommended installing a safety interlock to prevent the pump from running dry. With the safety interlock installed, the Puritan-Bennett investigation report concluded, "ignition at the pump caused by frictional heat will not be possible now since the pump will be prevented from running dry because of the low [motor] load switch."[66]

52. Furthermore, as shown in Figure 12, the company developed a piping system standard that added metallic flame arrestors in addition to strainers on the pump suction and discharge piping to prevent propagation of a potential nitrous oxide decomposition reaction.[67] Puritan-Bennett also

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[57] *See* Richmond explosion news article - November 6, 1980 [203].

[58] At the time of the Cantonment explosion, August 28, 2016, the Richmond, California facility was owned and operated by Air Liquide.

[59] *See* Richmond explosion news article - November 6, 1980 [203].

[60] *Id.*

[61] *See* [20] at page 18.

[62] *See* [20] at pages 12-14.

[63] *See* [20] at page 12.

[64] *See* [20] at page 51. Contamination can lower the safe operating limit conditions for the nitrous oxide decomposition reaction. The exact effect of contamination on nitrous oxide decomposition is not fully understood. Possible contaminants were identified at Airgas during post-incident equipment evaluation. As a result, contamination may have contributed to the explosion at Airgas.

[65] *See* [20] at page 214.

[66] *See* [20] at page 215. Puritan-Bennett used the low motor load switch as a safety interlock to shut down the pump motor when the pump was running and a condition such as dry running may have caused the motor power to drop to an abnormally low amount of power.

[67] *See* [20] at page 216. The Puritan-Bennett investigation report shows that providing these metallic flame arrestors was in addition to the strainer on the pump inlet (suction) and outlet (discharge) piping.

recommended using flexible connectors to connect the piping to the pump, which reduced piping stress. Additionally, the company applied a startup bypass valve that circulated liquid back to the storage tank, yet away from the pump inlet piping. Because the storage tank would contain a protective inventory of liquid nitrous oxide, this configuration reduced the risk of an explosion while starting and cooling down the pump.

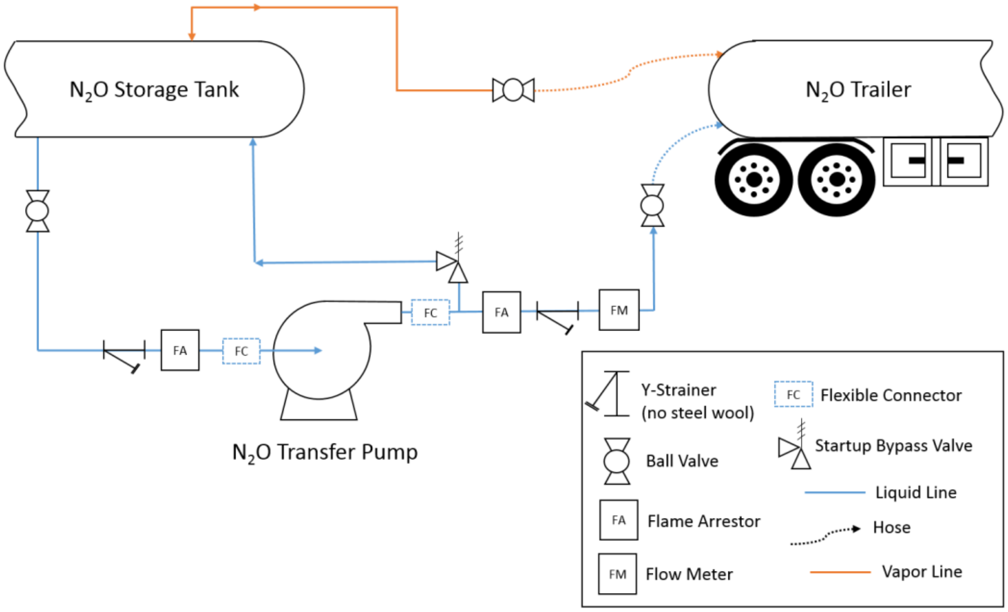

Figure 12. Simplified schematic of the recommended design standard for nitrous oxide transfers developed by Puritan-Bennett following the 1980 explosion at the Richmond, California facility. Post-incident, the company recommended both a strainer and a metallic flame arrestor on each side of the pump.

3. 1987 Butler-Amerigas Explosion – Reading, Pennsylvania

53. In May 1987, an explosion killed a welder working on a 6.5-ton nitrous oxide tank system at a Butler-AmeriGas facility in Reading, Pennsylvania.[68, 69] The explosion also injured three people including one plant worker and two members of the public.[70]

54. OSHA's accident investigation summary stated, "Employee #1 was using an oxyacetylene torch to heat a Freon pipeline during modification of and/or repair to a nitrous oxide storage tank. An explosion occurred and he was killed." In addition, a news article describing a subsequent lawsuit stated, "The official explanation of the explosion was that heat from the [welding] torch prompted the nitrous oxide to decompose which, in turn, created immense pressure in the tank."[71]

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[68] *See* OSHA inspection report [128].
[69] *See* Pennsylvania news article - May 12, 1987 [22].
[70] *See* Associated Press news article [21].
[71] *See* News article on Air Products lawsuit [23].

4. 2001 Linde Explosion – Eindhoven, the Netherlands

55. In July 2001, an explosion occurred when loading an empty trailer truck at a Linde nitrous oxide plant in Eindhoven, the Netherlands, injuring ten people.[72] (Figure 13) Linde concluded the explosion would have killed the driver, but he left the immediate area before the explosion.[73] The explosion resulted in heavy damage to the facility as well as neighboring businesses.[74]

56. A report by European authorities indicated that starting the loading pump without enough liquid supply (running dry) was causal to the incident.[75] A more detailed investigation report noted that carbon particles from a damaged bearing might have facilitated propagation of the explosive nitrous oxide decomposition reaction.[76] European authorities also stated that lessons learned include taking measures to prevent pump overheating and placing flame arrestors around the pump.[77, 78]

Figure 13. Photo of damage following the July 2001 nitrous oxide truck-filling explosion in Eindhoven, the Netherlands. Photo from [1].[79]

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[72] *See* Nitrous Oxide Trailer Rupture [1].
[73] *Id*.
[74] *See* [24] at page 5.
[75] *See* European Union Accident Profile [32].
[76] *See* [24] at page 21.
[77] *See* Major Accident Report [32].
[78] An alternate spelling for flame arrestor is flame arrester.
[79] *See* Nitrous Oxide Trailer Rupture [1].

5. 2007 Scaled Composites Explosion – Mojave, California

57. In July 2007, a nitrous oxide decomposition reaction exploded a storage tank during testing of a rocket engine nozzle by Scaled Composites in Mojave, California, killing three people and injuring three others.[80, 81, 82, 83] (Figure 14)

Figure 14. Photo of damage following the July 2007 nitrous oxide tank explosion in Mojave, California. Photo from parabolicarc.com[84]

58. Cal/OSHA investigated and issued citations totaling $25,870.[85, 86] Cal/OSHA reported that the explosion took place about three seconds into a 15-second test conducted by Scaled Composites. The Cal/OSHA investigation file showed that 10,000 pounds of nitrous oxide was held at 390 pounds of pressure at 70 °F.[87] To abate the citations, Cal/OSHA required Scaled Composites to

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[80] *See* California news article [202].
[81] *See* Evaluation of Cal/OSHA report on Scaled Composites accident [143].
[82] *See* NBC News Video [144].
[83] *See* News Article Covering Cal/OSHA Investigation [87].
[84] *See* Post-Incident photo of Scaled Composites Explosion [119].
[85] *See* Cal/OSHA Investigation File - Scaled Composites Explosion [117]. Although Cal/OSHA was not able to provide the CSB with investigation records because the agency only retains them for seven years, the website knightsarrow.com provides a link to its copy of the Cal/OSHA investigation file: Cal/OSHA Investigation File - Scaled Composites Explosion, [117].
[86] *See* space.com article on Scaled Composites Cal/OSHA citations [25]. "The citations, issued Thursday, faulted the Mojave, Calif.-based firm for failing to provide 'effective information and training of the health and physical hazards associated with nitrous oxide,' a compound used during a July 26 test that ended in an explosion, killing three employees and injured three others at the Mojave Air and Space Port."
[87] *See* Cal/OSHA Investigation File - Scaled Composites Explosion at page 13 [117]. The nitrous oxide conditions reported by Cal/OSHA may not be accurate as these are not equilibrium conditions. See Thermodynamic Properties of Saturated Nitrous Oxide [113].

apply several safety management system elements to its rocket motor programs including safety information, hazard analysis, mechanical integrity, and operating procedures.[88]

59. The cause of the incident was not publicly reported; however, post-accident safety guidelines published by Scaled Composites in June 2009 suggest the incident may have been caused by adiabatic compression with contamination of the nitrous oxide.[89]

60. The Scaled Composites safety guidelines also identified non-stainless steel metal as a possible contaminant that can significantly reduce the amount of heat needed to trigger an explosive nitrous oxide decomposition reaction.[90, 91] The guidelines stated, "remove all corrosion prone metals (non-stainless steels, etc.) from the N_2O [nitrous oxide] oxidizer flow path and/or storage, due to risk of catalytic reaction."[92] In addition, the safety guidelines addressed important nitrous oxide storage vessel design safety features:

> In the event that ignition prevention measures and deflagration wave mitigations fail, pressure vessel designs should allow for a controlled failure upon overpressure. In large oxidizer systems operated at high pressures, the energy released during a tank rupture for [whatever] reason (structural, overpressure, feedback, decomposition) is very high. This failure mode should be designed for with burst disk or other similar safety precautions that can safely reduce the PV [pressure volume] energy in the vessel without catastrophic failure.[93, 94]

61. The safety guidelines published by Scaled Composites include important information about potential ignition sources. The guidelines state:

> Design all components and assemblies so that they are incapable of releasing any substantial amount of energy into the oxidizer. No component or assembly should be capable of producing a temperature, for any length of time, on any surface, above 573 deg K [degrees Kelvin] (571 deg F) [degrees Fahrenheit].[95]

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[88] *See* Cal/OSHA Investigation File - Scaled Composites Explosion at page 41 [117].

[89] *See* Scaled Composites Nitrous Oxide Safety Guidelines [15].

[90] *Id.*

[91] Non-stainless steel metal particles were identified in Airgas equipment during post-incident evaluation of equipment. See Section IV.E.1, Contamination Prevention and Gap in Chemistry Knowledge.

[92] *See* Scaled Composites Nitrous Oxide Safety Guidelines [15].

[93] *Id.*

[94] *See* Understanding Explosions at page 204 [107]. A deflagration is a reaction in which the speed of the reaction front propagates through the unreacted mass at a speed less than the speed of sound in the unreacted medium. If the reaction front speed exceeds the speed of sound, it is a detonation.

[95] Although the basis for this temperature limit is not explained, the CSB notes that the 571 °F temperature limit described by Scaled Composites is close to the limit of 575 °F in CGA G-8.3–2016. CGA states that at 575 °F and 51.4 pounds per square inch (psi), nitrous oxide vapor is capable of auto-ignition. See [150], Section 4.3.3.1.

> Put substantial effort into reviewing what will occur if, for any reason, any component of the N_2O [nitrous oxide] oxidizer flow path ever does reach this temperature threshold.[96]

62. The nitrous oxide safety guidelines also addressed the potential for vapor (adiabatic) compression to initiate an explosion due to the presence of contaminants or incompatible materials. The Scaled Composites safety guidelines stated:

> Designs should attempt to minimize adiabatic compression in the system during flow of the N_2O [nitrous oxide] oxidizer.
>
> Adiabatic compression alone has low effectivity in starting a decomposition reaction; however, the presence of contaminants or incompatible materials that can act as fuels may reduce the ignition threshold of N_2O [nitrous oxide] to the point where adiabatic compression in an otherwise adequate system can begin a reaction.[97]

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[96] *See* Scaled Composites Nitrous Oxide Safety Guidelines [15].
[97] *Id.*

6. 2012 Air Liquide Explosion – Moncada, Spain

63. In September 2012, a nitrous oxide storage tank exploded while unloading an Air Liquide nitrous oxide trailer truck at a customer facility in Moncada, Spain killing the driver and injuring five other workers.[98] (Figure 15)

Figure 15. Photo of the damage following the September 2012 nitrous oxide explosion in Moncada, Spain.[99]

64. In January 2013, Air Liquide issued corporate-wide emergency safety guidance to prevent future explosions from nitrous oxide decomposition reactions. In addition, the company also shared safety lessons from its Moncada investigation with industry through an October 2013 presentation to the Compressed Gas Association.[100]

65. The safety information developed by Air Liquide suggests the following accident scenario for the Moncada explosion:

- Prior to the explosion an Air Liquide trailer truck was making a delivery into a customer storage tank using the truck-mounted pump to transfer liquid nitrous oxide;
- The explosion was likely caused by a nitrous oxide decomposition reaction that started from a high pump temperature because either the pump operated

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[98] *See* Spain News Article [123]. Note – use Google Chrome for an English translation.
[99] *See* Additional Spain News Article [141]. Note – use Google Chrome for an English translation.
[100] *See* CGA Safety and Reliability Seminar Presentation Schedule [148].

without enough liquid supply (running dry) or it was not properly cooled down;

- The pump did not have an "adequate or functional"[101] run-dry safety interlock and the nitrous oxide decomposition reaction propagated from the pump into the storage tank, causing the storage tank explosion;
- Contamination introduced within the pump from previous maintenance work on the pump may have contributed to the explosion;
- Flame arrestors were either not present or did not stop the propagation of the nitrous oxide decomposition reaction; and
- The relief valves on the storage tank were not capable of sufficiently reducing the pressure to prevent an explosion.

66. To prevent future nitrous oxide explosions, Air Liquide safety guidance, among other things, recommended:

- Installing a safety interlock to shut down the transfer pump if the pump runs dry or upon high pump outlet temperature;
- Providing a safety interlock to prevent starting the transfer pump until the pump was properly cooled down;[102]
- Including a safety interlock to protect the pump from excessive drive torque, such as from the motor;
- Requiring safety interlocks to "fail safe," such that any associated instrumentation failure would result in a pump shutdown;
- Providing liquid and vapor piping to each bulk tank (storage tanks and trailer trucks) with a flame arrestor. The guidance noted a flame arrestor in the liquid piping to bulk tanks should better protect the tank from a nitrous oxide decomposition reaction that migrates from the pump and into the tank;
- Ensuring pump maintenance shop cleanliness as well as cleaning wetted pump components to industry safety standards for oxygen cleanliness (CGA G-4.1 or EIGA Doc 33/06);[103, 104]

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[101] *See* [161] at page 6.

[102] Air Liquide guidance for the automatic pump shutdown advises that the internal pump temperature should be no more than 9 °F above the liquid equilibrium temperature. For example, if the trailer truck being prepared for loading is operating at 265 psia, the nitrous oxide equilibrium temperature is about -4 °F and the safety interlock should not allow the transfer pump to start until the internal pump temperature is below 5 °F. For nitrous oxide equilibrium conditions, see Thermodynamic Properties of Saturated Nitrous Oxide [113].

[103] In the context of a pump, wetted parts include internal pump components exposed to liquid nitrous oxide during operation.

[104] CGA G-4.1–2009 is the Compressed Gas Association (CGA) standard, *Cleaning Equipment for Oxygen Service*. See CGA G-4.1-2009 [151]. EIGA Doc 33/06 is the European Industrial Gases Association (EIGA) standard, *Cleaning of Equipment for Oxygen Service*. See EIGA Doc 33/06 [109].

- Installing 100 mesh Monel strainers as a flame arrestor on the inlet and outlet of all nitrous oxide transfer pumps;[105, 106, 107]
- Requiring that trailer trucks and storage tanks are electrically bonded; and
- Classifying nitrous oxide transfer pumps as "critical equipment."

7. 2016 Airgas (Air Liquide) Explosion – Cantonment, Florida

67. Against this backdrop of nitrous oxide explosions – including a recent incident in Spain that killed a worker – the nitrous oxide industry incurred yet another tragic incident on August 28, 2016 at the Airgas facility in Cantonment, Florida. A common thread among these incidents may lie in the complexity of reactive chemicals.

68. Process safety expert and university professor Daniel Crowl stated that the chemical industry has a continuing problem with reactive chemicals, but technology and management systems exist to prevent these accidents:

> "The chemical industry has a continuing problem with reactive chemical accidents. This problem is due to the complex nature of chemical reactivity."[108]
>
> "[W]e cannot avoid reactive chemical hazards; however, chemical plant accidents involving reactive hazards are unacceptable. The technology and the management systems do exist to produce these products safely."[109]

69. The Airgas explosion was likely the outcome of a self-reactive nitrous oxide decomposition that can occur if nitrous oxide vapor is heated. The decomposition of nitrous oxide produces primarily nitrogen, oxygen, and heat. Because the reaction produces heat, nitrous oxide decomposition can be self-sustaining and explosive. As will be explained in detail below, Airgas safety management systems were not sufficient to prevent this reactive chemical incident.

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[105] *See* [161] at page 7.
[106] 100 mesh refers to the size of the filter screen hole opening. See Titan Screen and Basket Selection Guide [26].
[107] Monel is an alloy (mixture of metals) consisting of primarily nickel and copper. See Monel [89].
[108] *See* Daniel Crowl's biography on the Michigan Tech website [140].
[109] *See* CSB Safety Video: Reactive Hazards at 19:08 [228].

III. The Incident

1. At approximately 12:10 pm (central daylight time or CDT) on August 28, 2016, an explosion occurred inside the nitrous oxide manufacturing unit at the Airgas facility in Cantonment, Florida.[110] (Figure 16)

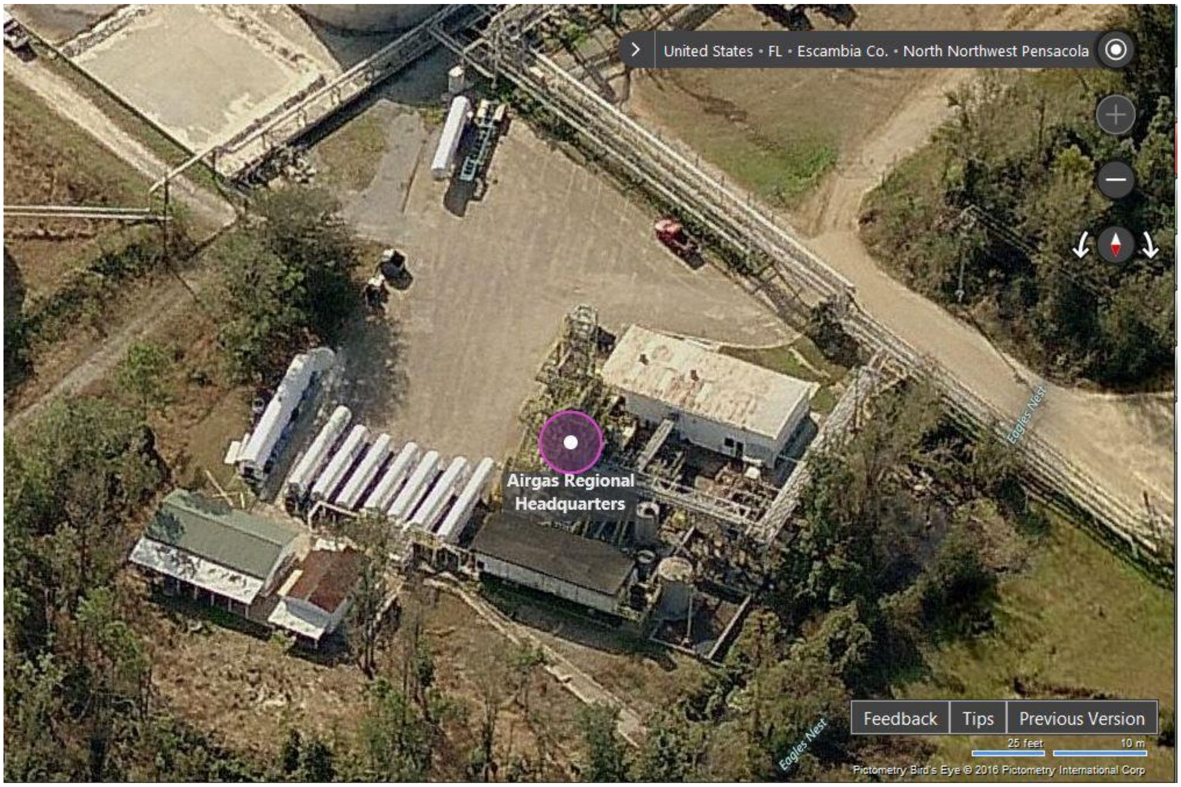

Figure 16. Overhead photo of the Airgas facility in Cantonment, Florida. Photo from Bing Maps.

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[110] As a result of the incident, roughly 250,000 pounds of nitrous oxide was released to the atmosphere.

2. Surveillance video from neighboring facilities captured the explosion (Figure 17) and the intense heat that it released. Based on the video, the duration of this heat release lasted less than two seconds.

Figure 17. Surveillance video of the explosion along the perimeter fence of the Airgas Cantonment, Florida facility.

3. The explosion killed the only employee working at the facility at the time of the incident. The Airgas employee died from "explosion-related fragmentation and blunt force injuries."[111]

4. The magnitude of the explosion was such that large metal fragments of equipment were scattered for hundreds of feet, and the resulting damage rendered the Airgas facility inoperable. (Figure 18) As a result of the explosion, the facility remains shut down as of the date of this report.

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[111] *See* [27].

Figure 18. Photo showing explosion damage at the Airgas facility in Cantonment, Florida.

5. Metal fragments projected into the adjacent chemical manufacturing facility and caused some damage to equipment, including a large cooling tower. The incident did not affect production at the neighboring facility.

6. On the morning of the incident there were six trailers and one shipping container parked in the nitrous oxide loading area. Two of the trailers were involved in the explosion. (Figure 19)

Figure 19. Surveillance video image showing the location of the nitrous oxide trailers on the morning of the incident. The explosion destroyed the two trailers on the left (green oval). Post-incident evaluation identified the left trailer as Trailer 182 and the right trailer as Trailer Y-3.

7. Post-incident evaluation confirmed Trailer 182 and Trailer Y-3 as the two trailers destroyed in the explosion. (Figure 20, Figure 21, Figure 22, and Figure 23)

Figure 20. Pre-incident photos that help identify and locate where Trailer 182 (left) and Trailer Y-3 (right) were in Figure 19. Trailer Y-3 has distinct identifiable physical characteristics in the Figure 19 surveillance video.

Figure 21. Post-incident photo that shows damage from the explosion. Trailer 182 and Trailer Y-3 were originally located in the lower left quadrant of this photo.

Figure 22. Pre-incident (top) and post-incident (bottom) photos of Trailer 182. The bottom photo shows fragments of Trailer 182 during efforts to reconstruct their original location.

Figure 23. Pre-incident (left) and post-incident (right) photos of Trailer Y-3. The right photo shows fragments of Trailer Y-3 during efforts to reconstruct their original location.

8. Surveillance video of the explosion captured two distinct clouds. (Figure 24, Figure 25, and Figure 26) The first cloud is brown and originated with intense heat that is consistent with a decomposition reaction that developed in Trailer 182.[112] The second cloud is white and is consistent with the rapid vaporization from Trailer Y-3 when it released its full 36,000 pounds of liquid nitrous oxide without an accompanying decomposition reaction.

Figure 24. Surveillance video images capturing the intense heat of the explosion and the formation of two distinct clouds.

Figure 25. Surveillance video images capturing the explosion, the formation of two distinct clouds, and the dissipation of the white cloud.

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[112] The brown cloud is likely the result of nitrogen oxides formed as a by-product of the nitrous oxide decomposition. CGA G-8.3 states: "While nitrogen and oxygen are the primary products from nitrous oxide decomposition, the higher nitrogen oxides (NO/NO_2) are also produced." See [150], Section 4.3.2.

Figure 26. Surveillance video images capturing the explosion, the formation of two distinct clouds, and the dissipation of the white cloud.

9. At the time of the incident, Trailer Y-3 contained a full load of liquid nitrous oxide. It appears likely from reviewing surveillance video and in examining recovered physical evidence that a fragment of Trailer 182 struck Trailer Y-3, causing Y-3 to rupture and release its contents without decomposition.

IV. Technical Analysis

A. Trailer 182 was not loaded, but needed to be loaded

1. One Airgas employee, an operator, was working at the facility at the time of the incident. Airgas surveillance video captured many of the activities he performed. Surveillance cameras at the facility are motion activated and only record when they detect motion. The Airgas cameras recorded the operator performing routine activities such as checking equipment, testing samples, recording data, and changing a process filter.

2. Airgas cameras were not located in a position to record activities near the nitrous oxide storage tanks, transfer pumps, or rear of the trailer trucks. As a result, none of the recordings show the operator loading a trailer truck. The recordings also stop approximately 10 minutes before the incident. This is likely due to a combination of camera position and lack of detected motion. Further, the explosion interrupted electrical power and prevented the surveillance system from restarting and recording the incident. As noted above, however, cameras from two other companies captured surveillance footage of the explosion.

3. Evaluation of Airgas records and post-incident observations indicate that all of the trailers and the shipping container shown in Figure 19 were fully loaded before August 28, 2016, except Trailer 182. Airgas completed loading of the last trailer prior to the incident, before midnight (CDT) on August 27, 2016. When this trailer was loaded, only 16 inches of liquid nitrous oxide remained in the bottom of the storage tank and Airgas needed additional inventory to load Trailer 182.

4. The August 28, 2016, shift relief log at 6:00 am (CDT) indicates that Trailer 182 was empty; it had not been loaded with nitrous oxide.[113] In addition, during the 12 hours from the time the last trailer was loaded (August 27, 2016, before midnight CDT) through the last recorded computer data before the incident (August 28, 2016, at approximately 12:10 pm CDT), no recorded computer data indicates a decrease in storage tank level as would be expected if Trailer 182 had been filled.[114] Rather, the level in the storage tank steadily increased. The increase in storage tank inventory is consistent with the Cantonment nitrous oxide production rate, and indicates that Trailer 182 was not loaded at the time of the incident. (Figure 27)

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[113] When nitrous oxide trailer trucks return from customer deliveries they are still full of nitrous oxide vapor and may contain some amount of nitrous oxide liquid.

[114] The force of the explosion breached piping between the nitrous oxide pumps and the trailer loading piping, causing all of the nitrous oxide in the storage tank to drain out.

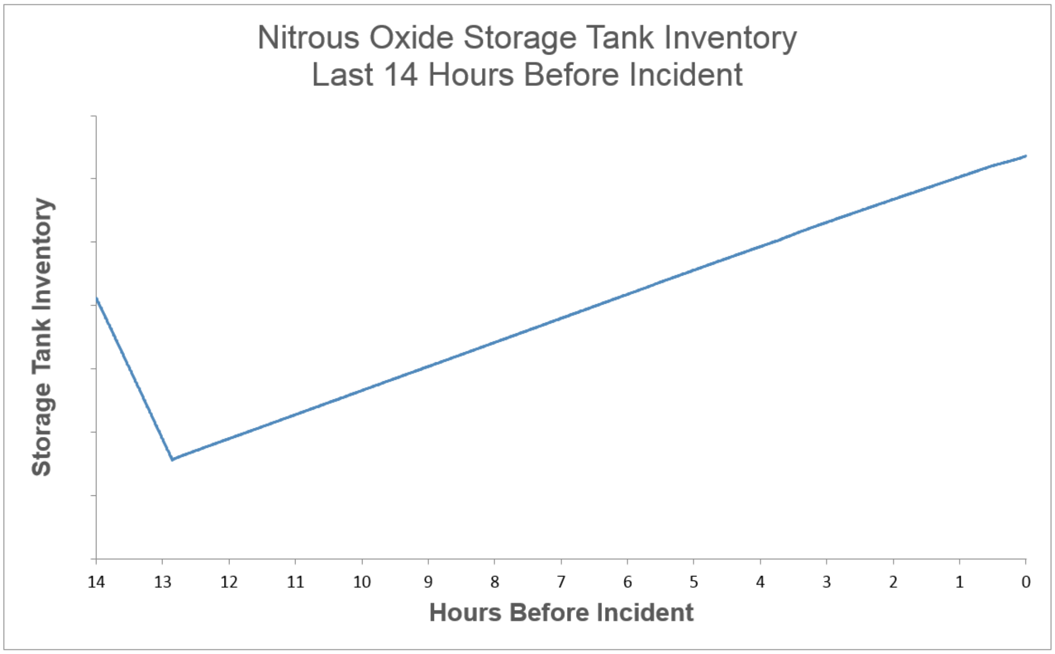

Figure 27. Nitrous oxide storage tank inventory during the last 14 hours before the incident. Tank inventory decreased during loading of a trailer before midnight. The inventory steadily increased after that trailer was loaded, indicating that no truck or shipping container loading occurred during the last twelve hours. In order to protect actual production rate data, this chart does not show inventory values.

5. Unlike the storage tank, Airgas does not record computer process data for its liquid nitrous oxide transfer system. For example, Airgas did not record the pump motor status (on or off), motor power, discharge pressure, discharge flow, nitrous oxide temperature, or other process data. In addition, the Airgas process data computer lacked data-recovery capability to aid accident investigators.[115]

6. Before loading a trailer, a sample of the existing trailer vapor content is taken and analyzed to ensure the trailer was not contaminated since being previously loaded. Data contained in company records shows an Airgas operator recorded sample results from Trailer 182 on August 27, 2016, between 6:00 pm and midnight (CDT), confirming no contamination and indicating that Trailer 182 was ready to be loaded.

7. Shipping records indicate that Airgas personnel scheduled Trailer 182 to be loaded in order to depart at 2:00 pm (CDT) August 29, 2016, for a customer delivery in California. To meet this schedule, Airgas employees stated they would expect Trailer 182 to have been loaded on Sunday, August 28, 2016.

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[115] Airgas retained a computer expert to develop a method to recover data from the storage drive of the process computer. The work to retrieve the data was complicated because the commercial computer data system was not designed for post-accident data retrieval. Despite hiring an external computer expert, Airgas provided this data to CSB investigators 115 days after the explosion. If chemical manufacturing companies, used a real-time data recording system that includes a method to recover data after an accident, timely access to relevant data would aid industry in performing accident investigations. A data-recovery system would also aid the CSB in performing its mission, enabling the agency to provide stakeholders with more timely accident investigations informed by all relevant data.

B. Most Likely Incident Scenario

8. A nitrous oxide explosion is most likely to occur during initial transfer into a large vessel that is empty or near-empty, such as a customer storage tank or a delivery trailer. Industry safety standards advise directing such transfers into the liquid portion of a receiving vessel because this configuration acts as a layer of protection and allows a potential decomposition reaction starting at the pump to be quenched [stopped] in the liquid.[116]

9. Trailer 182 recently returned to Cantonment after delivering product to other customers. Having returned for reloading, the trailer did not contain a protective inventory of liquid nitrous oxide. Since Trailer 182 contained nitrous oxide vapor, but little or no liquid, it was susceptible to an explosion because the nitrous oxide decomposition reaction propagates through vapor.

10. A combination of physical evidence, computer data, and company records suggest that just before the incident, the Airgas operator likely initiated a transfer of liquid nitrous oxide from a storage tank to load Trailer 182 for shipping to a customer in California. Although other causes may be possible (see Section IV.E, Other Possible Causes), the CSB concluded that a nitrous oxide decomposition reaction likely started from the transfer pump and propagated into Trailer 182 during the transfer of product.[117]

11. Based on conditions and design of the pump system (detailed in Section IV.D, Nitrous Oxide Loading Pump System Design), the pump likely lost prime or ran dry during startup, which generated heat and increased the temperature of pump components. Consistent with at least three other historical nitrous oxide industry explosions, this temperature increase during pump startup likely initiated a nitrous oxide decomposition reaction. Because loading operations had likely started, a flow path existed for this reaction to propagate into Trailer 182, resulting in the explosion.[118]

12. At the time of the incident, existing safeguards to prevent a nitrous oxide explosion when loading trailers at the Airgas facility consisted of a run-dry protective interlock on the pump and makeshift flame arrestors created from strainers packed with steel wool. The CSB's investigation revealed that these safeguards were poorly designed and ineffective (Section IV.C). In addition, the system design placed the Airgas operator directly in harm's way.

13. To start the pump, an operator must manually push and hold two buttons in place. One button bypasses the run-dry safety interlock and the second button energizes the pump motor. After

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[116] *See* [150], Section 7.3.3.

[117] Other possible contributing causes include contamination and static electricity.

[118] The post-incident position of at least a dozen valves appears to have been altered by the force of the explosion. As a result, these valve positions are not reliable evidence for evaluating pre-incident piping alignment. See Section IV.F, Post-Incident Valve Positions.

satisfying the low-flow set point for the run-dry safety interlock, the operator can then release the buttons and the pump should continue to run.[119] (Figure 28)

Figure 28. Photo showing the location of the nitrous oxide pump bypass and start buttons (yellow arrow), superimposed, before the incident. The red arrow points to the post-incident location of the actual metal frame where the buttons were mounted. The metal frame was attached to the base of the Smith pump. The nitrous oxide transfer pumps were located to the right of the yellow arrow. Nitrous oxide storage tank two is shown in the background.

14. Post-incident physical evidence, including blast damage observations and the location where emergency responders recovered the body of the deceased Airgas employee, indicate that before the explosion the Airgas operator was located between Trailer 182 and the south end of the nitrous oxide storage tank. (Figure 29) This location is consistent with the operator pressing and holding the interlock bypass button at the time of the explosion, as required by the interlock design.

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[119] The run-dry safety interlock at Airgas was designed to monitor the flow and shut off the pump motor if a low-flow rate was detected. As will be discussed in Section IV.C.2 ("Run-Dry" Safety Interlock), CGA safety standards also required this interlock to protect the pump from operating at high temperature, but the Airgas safety interlock design lacked temperature protection.

Figure 29. Photo showing an approximate location of the Airgas operator (yellow star) just before the incident. Trailer 182 was to the left of the operator and aligned with the two bollards on the right.

C. Ineffective Safeguards

15. Ineffective safeguards in this incident included using a filtration strainer packed with steel wool as an inadequate substitute for an engineered flame arrestor and a pump start-up procedure that required bypassing the run-dry safety interlock when needed most.

16. The failure of these safeguards allowed the nitrous oxide decomposition reaction to propagate to Trailer 182 and explains why the Airgas employee was located near the pump start switch at the time of the explosion. The equipment design required the operator to bypass the safety interlock until the pump achieved an adequate flow rate.

1. Flame Arrestors

a) Background

17. Flame arrestors protect people and equipment from fires and explosions.[120] A flame arrestor is a safety device that “allows gas to pass through it but stops a flame in order to prevent a larger fire or explosion.”[121]

18. The International Organization for Standardization (ISO) defines flame arrestors as “safety devices fitted to openings of enclosures or to pipe work and are intended to allow flow but prevent flame transmission.”[122]

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[120] *See* [2] at page 38.
[121] *See* ENARDO Flame Arrestor Technology [28].
[122] *See* ISO 16852:2016 [29].

19. A variety of different approaches to flame arrestor designs exist, but each is based on the general idea of cooling the vapor to stop the reaction from continuing. One source states:

> The technique often used in flame arrestors is to cool the propagating flame or explosion enough to extinguish the fire. Thermal mass, usually in the form of metal, is used to extract enough energy from the reacting gases that the flame can no longer be supported and is extinguished. Many different arrestor designs are available including gauzes, perforated plates, expanded metal, sintered metal, metal foam, compressed wire wool, loose filling, hydraulic arrestors, stacked plate, and crimped ribbon.[123]

20. In 2002, the Center for Chemical Process Safety (CCPS) published *Deflagration and Detonation Flame Arresters*, which provides safety guidance for flame arrestors.[124] CCPS states: "Proper application of a flame arrester can help avoid catastrophic fire and explosion losses by providing a flame barrier between at risk equipment and anticipated ignition sources."[125]

21. CCPS also notes: "Flame arresters have often failed in practice. There have been significant advances in flame arrester technology over the last decade that explain many 'failures' as due to misapplication. Plant inspections have shown that misapplication of flame arresters continues to be common."[126]

22. Furthermore, CCPS states: "Flame arresters … can only be proven by tests simulating the conditions of use. The user should ensure that a flame arrester has been properly tested to meet the intended purpose, and should be prepared to stipulate the required performance standard or test protocol to be followed."[127]

23. The Institution of Chemical Engineers (IChemE) is a global professional organization.[128] In a published flame arrestor guidance document, IChemE describes the importance of testing flame arrestors in the environment they are being used. IChemE states:

> [I]n testing a flame arrester the environment in which it will be used must be taken into account. It cannot be assumed that because a flame arrester has been tested and passed for use in one environment it will perform equally well in all environments. With our present incomplete understanding of the mechanism of operation it is necessary to simulate as closely as possible in the tests the environment in which it will be used.[129]

24. CGA G-8.3–2016, *Safe Practices for Storage and Handling of Nitrous Oxide*, allows strainers to serve as a flame arrestor. CGA states "Strainers should be installed on the suction and discharge of

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[123] *See* [2], Section 1.6.1.3.
[124] *See* Deflagration and Detonation Flame Arresters [101].
[125] *See* [101], Section 3.1.
[126] *Id*., at Section 3.1.
[127] *Id*., at Section 3.1.
[128] *See* IChemE Website [30].
[129] *See* Performance Requirements of Flame Arresters in Practical Applications at page 56 [79].

liquid pumps to provide a heat sink that assists in quenching a decomposition flame front."[130] The standard provides no basis, however, to conclude that such a device could serve as an effective safeguard. Furthermore, no specifications are provided with respect to engineering standards such as strainer hole size or screen mesh size.

25. An Airgas technical employee participated in the development of an earlier version of CGA G-8.3. He acknowledged that there was no "rigorous study" backing the CGA safety standard to ensure these strainers could effectively halt a nitrous oxide decomposition reaction.

26. As noted, Smith manufactured the original nitrous oxide pump at the Airgas facility, and that company advises against using strainers as flame arrestors. In the company's nitrous oxide pump literature, Smith states, "We highly recommend the installation of specially-designed flame arrestors on both sides of the pump (near the inlet and outlet)." The company further states, "It should be noted here that strainers are not designed to break-up flame fronts. The recommended flame-arresting device is a specialty product."[131]

27. In published "lessons learned" from a report detailing an incident that appears to be the 2001 Eindhoven incident, European officials stated: "Furthermore, flame arrestors should be placed around the [nitrous oxide] pump."[132]

b) Airgas Flame Arrestor

28. Consistent with CGA G-8.3–2016, *Safe Practices for Storage and Handling of Nitrous Oxide*, Airgas installs y-strainers on the pump inlet and outlet to serve as a "flame arrestor."[133]

29. As shown in Figure 30, Airgas also fills the strainer basket with steel wool to create a flame arrestor, with the idea that the steel wool will help quench a potential nitrous oxide decomposition reaction.

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[130] *See* [150], Section 5.7.

[131] *See* Pumps for low-pressure nitrous oxide transfer, AL-45 at page 5, [31]. Also, see Flame Arrestor Animation to see an example of an engineered flame arrestor [225].

[132] Major Accident Reporting System - nitrous oxide trailer truck explosion [32].

[133] CCPS also describes the various types of flame arresting elements that are in use. CCPS lists compressed metal wool as a flame arrestor element that is not commercially available in the United States, but is available in the United Kingdom. See [101], Section 3.2.

Figure 30. Airgas uses strainers filled with steel wool on pump suction and discharge piping to serve as a flame arrestor. Airgas relies on these strainers to prevent a nitrous oxide decomposition reaction from propagating to the trailer being filled, where the reaction could result in an explosion. The left photo shows a y-strainer recovered from the Cantonment site with its cap removed revealing the basket filled with steel wool. The right photo shows a close-up of a different y-strainer basket also recovered from the Cantonment site containing steel wool.

30. When installed in this manner, Airgas technical personnel concluded the y-strainer would act as a "heat sink" and absorb the excess heat to stop a nitrous oxide decomposition reaction, but they also acknowledged, "[t]here is no rigorous study" to support the flame arrestor design.

31. IChemE describes common types of flame arrestors including compressed wire wool, the general type of flame arrestor used by Airgas. Flame arrestor information published by IChemE describes the Airgas flame arrestor design and some of its weaknesses. IChemE states: "As the name [compressed wire wool] implies, these types of matrices are made by compressing a mass of fine wire into an appropriate holder."[134] IChemE then noted that wire wool has a high resistance to flow and is difficult to reliably assemble:

> Their resistance to flow is high, which limits their applications, particularly as their effectiveness as an arrester increases with the degree of compression. Questions have, however, been asked about the reliability of arresters with this type of matrix in view of the difficulty of reproducing them with any degree of certainty.[135]

32. At Airgas, the y-strainer basket on the ACD pump discharge is relatively flexible and did not withstand significant differential pressure, such as a pressure wave generated from a nitrous oxide decomposition reaction. Post-incident evaluation of the ACD pump discharge strainer revealed that at some point the strainer basket dislodged from the y-strainer housing and into the downstream piping. (Figure 31 and Figure 32) Since the steel wool installed inside the strainer basket was no

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[134] *See* Performance Requirements of Flame Arresters in Practical Applications at page 50 [79].

[135] *Id.*, at page 50.

longer present, this allowed an open path, through the center of the open strainer basket, for a decomposition reaction to propagate from the pump to Trailer 182.

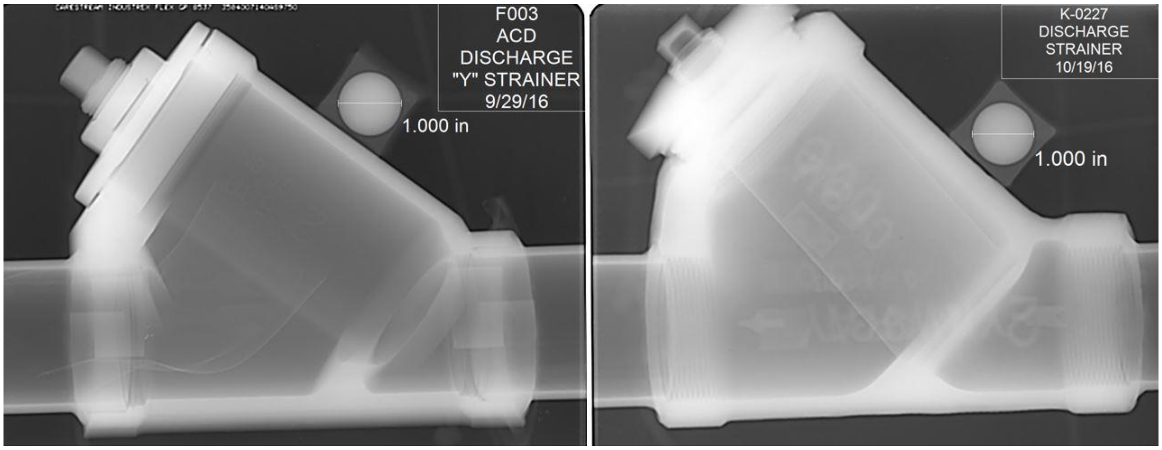

Figure 31. Post-incident x-ray images of y-strainers. An x-ray of the ACD pump discharge strainer (left) shows that the mesh basket dislodged into the downstream piping. The image on the right is the y-strainer from the Trailer 182 Cryostar pump discharge strainer and illustrates what an x-ray looks like when the strainer basket is in the proper location.

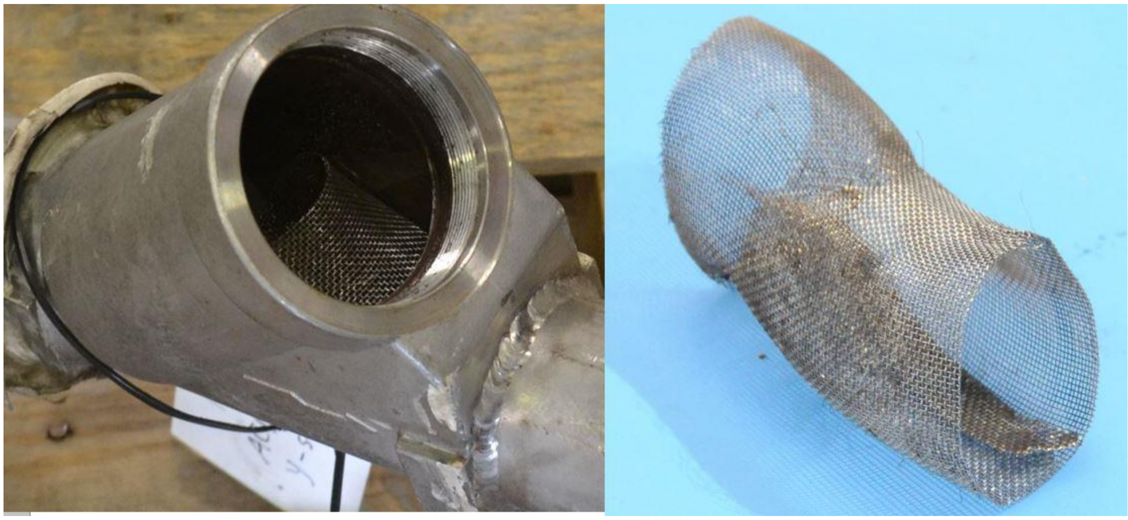

Figure 32. Photos of the ACD pump discharge y-strainer. The left photo shows the strainer basket location as seen with the y-strainer cap removed. The basket dislodged from the housing and was located in the downstream piping creating an open path to Trailer 182. The photo on the right is the strainer basket from the ACD pump discharge y-strainer removed from the y-strainer housing, post-accident.

33. During post-accident investigation activities, CSB investigators and Airgas contractors found a metal fragment located in the ACD pump outlet piping downstream of the flame arrestor. (Figure 33) The fragment showed physical discoloration. The discoloration may be consistent with heating

from a decomposition reaction.[136] The presence and condition of this metal fragment further supports the CSB's overall conclusion that the ACD pump likely initiated a nitrous oxide decomposition reaction that propagated through the open y-strainer basket and into Trailer 182.

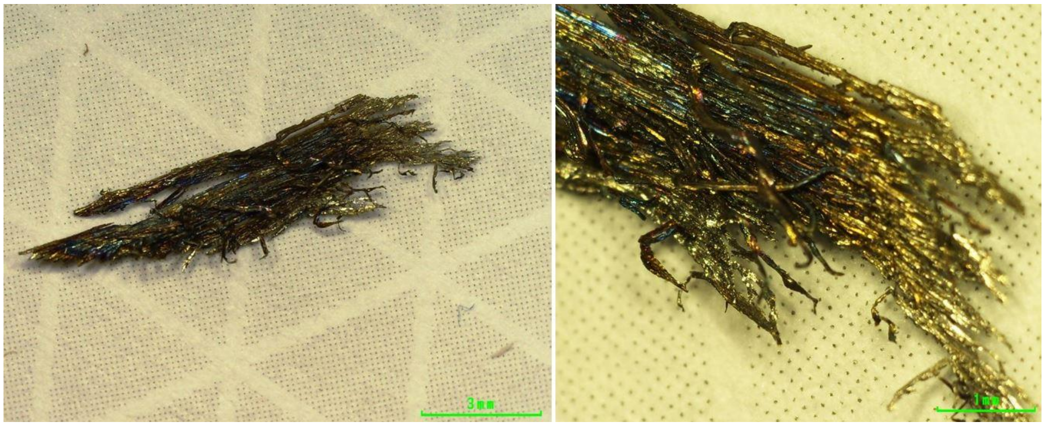

Figure 33. Photo of heated metal fragment. This metal fragment located in the ACD discharge piping downstream of the flame arrestor (y-strainer) shows discoloration that may be consistent with heat from a nitrous oxide decomposition reaction. The scale for the left and right photos is three millimeters and one millimeter, respectively.

34. After filling a y-strainer with steel wool and putting the device in use, Airgas did not inspect the y-strainer to ensure it can function as intended as part of a preventive maintenance program. Post-incident evaluation of the ACD pump suction strainer revealed the strainer basket to be partially empty. (Figure 34) The combination of small particles of material in the pump suction line, missing steel wool, and discolored steel wool in the strainer basket together suggest that the steel wool may have deteriorated.

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[136] Color variations on metal are the effect of various thicknesses of oxide films that form when heated in an oxidizing environment, such as air, nitrous oxide, or oxygen. See [3], page 523.
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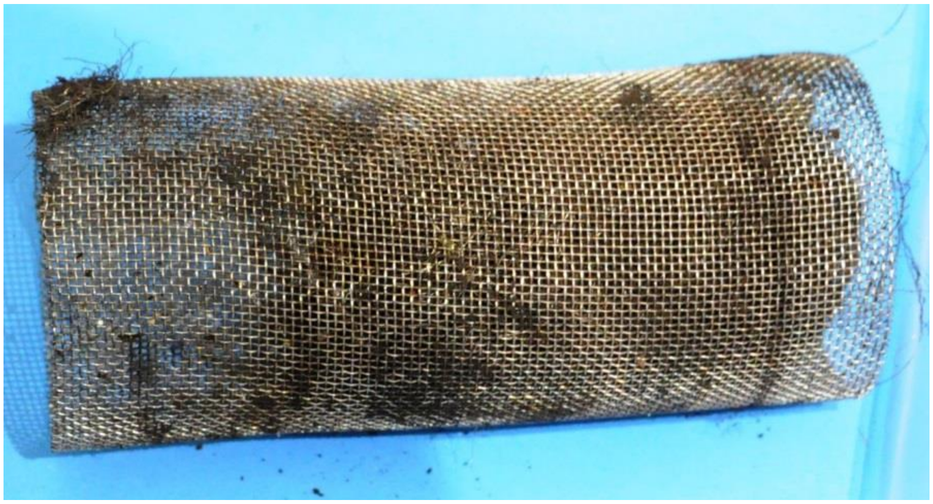

Figure 34. Photo of y-strainer basket from the inlet piping to the ACD pump. The left side of the basket is inserted the furthest into the y-strainer.

Figure 35. Photo showing the top end of the ACD pump suction piping y-strainer basket with missing and discolored steel wool.

35. CGA nitrous oxide safety standards do not require testing to confirm flame arrestors will be effective. Likewise, Airgas did not conduct any testing to confirm that a y-strainer filled with steel wool can actually halt a nitrous oxide decomposition reaction. The company also lacks a standard for the design of the strainer, the screen mesh size, or the grade or quantity of steel wool installed. (Figure 36)

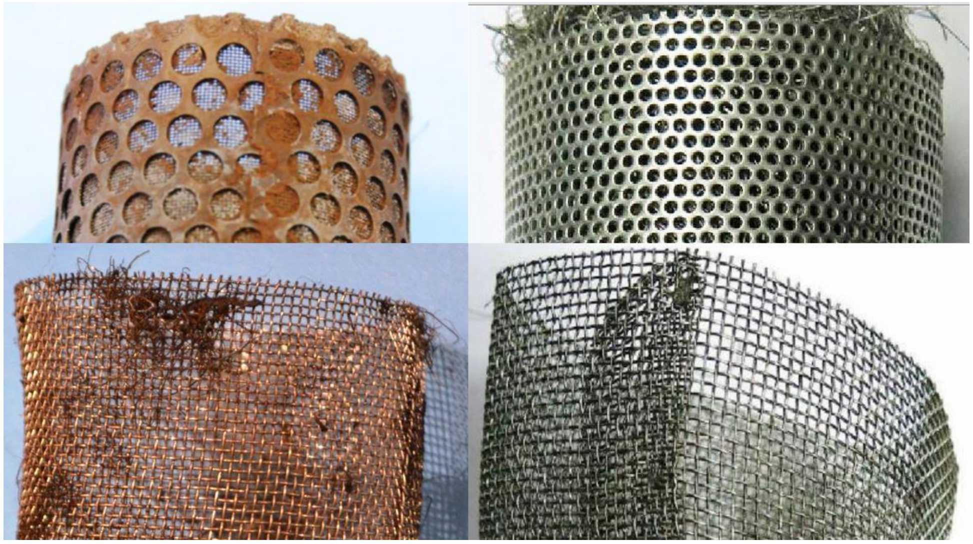

Figure 36. Strainers used by Airgas. Airgas lacked an engineering standard for strainers used as a flame arrestor. The company used a variety of strainer designs at Cantonment. Airgas used these strainers as a flame arrestor to stop a potential nitrous oxide decomposition reaction from propagating past the strainer to prevent a trailer truck or storage tank explosion.

36. The Airgas manufacturing manual includes a section describing the nitrous oxide trailers used to transport nitrous oxide to its customers. This document includes a description of the flame arrestors and states: “Flame arrestors shall be installed at the suction and discharge side of each trailer pump. A standard Y-strainer may act as a flame arrestor. The Y-strainer will be loosely packed with brass or stainless steel wool (do not use steel wool).”

37. Although written for the trailer pumps, Airgas also uses this flame arrestor approach for the transfer pumps. Though the manual says not to use steel wool inside the y-strainers, Airgas personnel stated that they do use steel wool inside the nitrous oxide transfer pump y-strainers. Airgas does not have documentation explaining the warning not to use steel wool, whether in the manual or any other corporate documents provided to the CSB.

38. While the Airgas manufacturing manual says the y-strainer will be loosely packed with brass or stainless steel wool, Airgas personnel told CSB investigators that they “completely pack” the y-strainer with steel wool. The company does not have documentation that explains what “loosely packed” means or how to pack the y-strainer with steel wool. Airgas also lacks specifications for the strainer hole or mesh size and the type or quantity of the steel wool.

39. Airgas personnel did not know the basis for using a y-strainer as a flame arrestor; however, it may date back to explosion tests conducted after the 1980 trailer explosion at the Richmond, California facility. The CSB obtained a copy of the Puritan-Bennet investigation report from Airgas. In this report Puritan-Bennett concluded:

> The use of a steel strainer and one and one-half inch diameter pipe downstream of the strainer effectively stops the propagation of the explosion. This was proven during two tests by samples analyzed via gas

> chromatography. More convincingly, one piece of cotton downstream of the strainer failed to burn when a similar piece placed upstream of the strainer on the side that was heated by the torch, was consumed by the reaction of nitrous oxide.[137]

40. The Puritan-Bennett investigation report noted: "Additional testing will be necessary to determine the effectiveness of the quenching action."[138] There is no evidence showing Puritan-Bennett performed this "additional testing." In addition, the report did not provide any details on the strainer hole or mesh size used in these tests, and Puritan-Bennett did not develop an engineering design standard for internal use. Furthermore, these strainers did not contain steel wool during testing.

41. Based upon the available evidence, the CSB could not determine if the presence of steel wool contributed to the incident; however, Airgas lacks a technical basis to support using steel wool to stop a nitrous oxide decomposition reaction. Assuming some strainers alone can stop the propagation of the reaction, packing steel wool inside the strainer might defeat the purpose of the strainer and instead support the propagation of nitrous oxide decomposition. Steel wool supports combustion in air and burns even hotter in oxygen. (Figure 37) In a nitrous oxide decomposition environment, steel wool would burn hotter than in air, but less vigorously than in oxygen.[139] Thus, heating the steel wool could conceivably initiate a nitrous oxide decomposition reaction on the protected (downstream) side of the flame arrestor.

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[137] *See* [20] at page 158.

[138] *Id*., at page 169.

[139] Nitrous oxide has an oxypotential of 0.6. Oxypotential is a "Dimensionless number that indicates the oxidizing power of a gas compared to pure oxygen. The oxypotential value of 100% oxygen is 1.0 and air is 0.21." See AIGA - Safe Practices for Storage and Handling of Nitrous Oxide, Section 4.3.1 [215].

Figure 37. Video images of steel wool combustion. The photo on the left shows steel wool burning in air[140] and the photo on the right shows steel wool combustion in oxygen.[141]

42. The steel wool used at Airgas is a coarser grade than the steel wool used in these videos (See footnotes 140 and 141). When tested by the CSB, combustion of the Airgas steel wool proved more difficult to sustain than the combustion shown in these videos.

c) Special Flame Arrestor Design and Testing Needed

43. The CSB could not locate any safety standards that apply to using flame arrestors to stop self-decomposing chemicals, such as nitrous oxide. Existing flame arrestor testing standards, such as ISO 16852:2016 *Flame arresters -- Performance requirements, test methods and limits for use*, are based on combustion reactions in air, such as burning propane in air.[142] As such, ISO 16852:2016 does not apply to "flame arresters used for explosive mixtures of vapours and gases, which tend to self-decompose [e.g., acetylene] or which are chemically unstable," such as nitrous oxide.[143, 144]

44. For most combustion-based flame arrestors, "the flame arrester element itself experiences very little warming, because it is subjected to a high temperature for an extremely short period of time — a few microseconds."[145]

45. This short heating duration, however, may not apply to nitrous oxide decomposition where the heat source, such as heat generated by a pump, might continue to heat the flame arrestor element until a safety interlock can detect the heat and stop the pump. If there is a prolonged heat source at the inlet of the flame arrestor, the flame arrestor itself will increase in temperature, and it may reach the

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[140] *See* video of steel wool burning in air [226].
[141] *See* video of steel wool combustion in oxygen [95].
[142] *See* ISO 16852:2016 [29].
[143] *Id*.
[144] Acetylene can also decompose explosively, but commercial flame arrestors are available for acetylene. See Protego: Acetylene Applications [94].
[145] *See* *Protect Your Process with the Proper Flame Arresters* at page 20 [33].

decomposition threshold temperature limit. This could allow a nitrous oxide decomposition reaction to propagate downstream and result in an explosion.

46. In an article published in 1986, IChemE described how continual heating of a flame arrestor could cause the safety device to fail. IChemE states:

> A possibility that up to now has only been briefly mentioned is the failure of an arrester due to continuous burning on the matrix. If there is a continuous flow of flammable gas from the downstream side of an arrester to the upstream side (remember the sides are defined in terms of the direction of flame propagation) then even though the arrester prevents flame propagation initially a flame may stabilise on the upstream side. The arrester could eventually fail by the flame literally burning through the matrix or the matrix becoming hot enough to ignite the gas on the other side.[146]

47. The unique flame arrestor application needed to stop the propagation of a nitrous oxide decomposition reaction may require special design and testing to ensure the device will be effective in the specific application. Air Liquide should complete this testing and design work.

2. “Run-Dry” Safety Interlock

48. Airgas equipped the nitrous oxide transfer system used to load trailer trucks with an automatic shutdown to prevent the pump from running dry – a run-dry safety interlock. The company uses this protection system to prevent an explosive nitrous oxide decomposition reaction. It consists of a flow meter downstream of the pump, which will stop the pump motor if the flow drops below 15 gallons per minute.

49. To start a pump with this type of shutdown design, a delay or override is necessary to allow the pump to achieve 15 gallons per minute of flow before the interlock is functional. Airgas workers stated that this is accomplished by holding down two buttons at the pump’s start switch, which overrides the shutdown as long as the operator is physically present to push those buttons.

50. When the operators visually verify that the pump flow is greater than 15 gallons per minute, they can remove their hand from the start and bypass buttons and the pump will continue to run. If flow drops below 15 gallons per minute, the pump will stop.

51. Airgas employees described the nitrous oxide pump interlock system to the CSB. Their description indicates that the Airgas system does not meet the safety guidance of CGA G-8.3–2016, *Safe Practices for Storage and Handling of Nitrous Oxide*. While Airgas installed the system with low-flow protection, which automatically stops the pump motor if the downstream flow meter detects

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[146] IChemE uses “matrix” as an alternate term for a flame arrestor element. At Airgas, the “matrix” would include both the strainer basket and the steel wool. See *Performance Requirements of Flame Arresters in Practical Applications* at pages 55-56 [79].

low-flow, this safety interlock is not equipped with required pump temperature protection.[147] As a result, the pump could be started – or continue to run – at hot temperatures.

52. In addition, the safety interlock is not robust since it lacks redundancy and is thus susceptible to single points of failure.[148] A single flow meter is used for both the safety interlock and for the operator to monitor trailer loading. Furthermore, the low-flow interlock uses a single set of electrical contacts to stop the pump motor.

53. Although Air Liquide issued emergency safety guidance following the 2012 Moncada explosion that included corporate safety interlock requirements for nitrous oxide pumps, the pumps at Cantonment did not have this safety protection. Additional safety measures included fail-safe instrumentation, a permissive interlock to ensure proper cool-down, and temperature instrumentation to detect overheating and shutdown the pump.

a) Safety Instrumented Systems and ISA-84

54. The International Society of Automation (ISA) develops consensus standards for, among other things, safety instrumentation. ISA84, Electrical/Electronic/Programmable Electronic Systems (E/E/PES) for Use in Process Safety Applications is the ISA committee that developed a three-part series of standards to help companies safely control hazards.[149] In describing its safety instrumentation standards, ISA84 states:

> This three-part series gives requirements for the specification, design, installation, operation, and maintenance of a safety instrumented system so that it can be confidently entrusted to place and/or maintain a process in a safe state. Through its working groups, ISA84 has also developed several key technical reports to provide guidance on the implementation and use of the three-part series of standards.[150]

55. ANSI/ISA-84.00.01-2004 Parts 1-3 (IEC 61511 Mod), *Functional Safety: Safety Instrumented Systems for the Process Industry Sector* ("ISA-84") is the industry standard for safety instrumented

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[147] One Airgas employee informed the CSB that the company's discharge flow meter, approximately 20 to 30 feet downstream of the pump is equipped with a high temperature shutoff at 59.69 °F. The company, however, did not provide documentation indicating this programmable option was in effect or explain how a downstream temperature indicator could ensure effective low temperature protection given that when the pump is cooled down and started, no flow is initially present through this flow meter.

[148] *See Safety controls, alarms, and interlocks as IPLs* [34].

[149] *See* Understanding ISA 84 [35].

[150] *See* ISA84 Committee website [36].

systems (SIS).[151] "Interlock" is a common name for a safety instrumented system. ISA-84 provides a life-cycle approach to ensure interlocks achieve desired risk reduction of the hazard.[152]

56. ISA-84 "applies to a wide variety of industries within the process sector including chemicals, oil refining, oil and gas production, pulp and paper, non-nuclear power generation[.]"[153]

57. OSHA identified ISA-84 as recognized and generally accepted good engineering practice (RAGAGEP) in 2000[154] and reaffirmed its position in 2005.[155]

58. OSHA also addressed the importance and broad application of the ISA-84 safety instrumentation standard – including chemical manufacturing processes that are not covered by the Process Safety Management (PSM) regulation, such as nitrous oxide manufacturing. OSHA stated:

> It is also important to note that there are a large percentage of processes which are not covered by PSM which may include SIS [safety instrumented systems] covered by S84.01. The employer may be in violation of the General Duty Clause, Section 5(a)(1) of the OSH Act, if SIS are utilized which do not conform with S84.01 and hazards exist related to the SIS which could seriously harm employees.[156]

59. Although OSHA stressed the importance of applying ISA-84 to processes not covered by the PSM standard, Airgas did not apply the ISA-84 safety standard to the nitrous oxide pump run-dry safety interlock system. This interlock is critical to prevent a nitrous oxide decomposition reaction from high pump temperature. By applying ISA-84, Airgas could have reduced the risk of the pump starting a decomposition reaction.

60. As part of its life-cycle approach to safety, ISA-84 requires periodic testing of safety interlocks to confirm the system is functional.[157]

61. Airgas performs an annual test of its run-dry safety interlock; however, the company does not have a testing procedure, and the method employees use to confirm that the safety system is functional creates unnecessary danger to workers because it could initiate an explosion.

62. Airgas tests the run-dry interlock with the pump running during the actual loading of a trailer. An Airgas employee will slowly close the inlet block valve to the pump until the flow drops below the

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[151] *See* ISA 84 - The Standard for Safety Instrumented Systems [139]. The precise name of the three standards is: (1) ISA-84.00.01-2004 Part 1 (IEC 61511-1 Mod) Functional Safety: Safety Instrumented Systems for the Process Industry Sector - Part 1: Framework, Definitions, System, Hardware and Software Requirements, (2) ISA-84.00.01-2004 Part 2 (IEC 61511-2 Mod) Functional Safety: Safety Instrumented Systems for the Process Industry Sector - Part 2: Guidelines for the Application of ANSI/ISA-84.00.01-2004 Part 1 (IEC 61511-1 Mod) – Informative, and (3) ISA-84.00.01-2004 Part 3 (IEC 61511-3 Mod) Functional Safety: Safety Instrumented Systems for the Process Industry Sector - Part 3: Guidance for the Determination of the Required Safety Integrity Levels – Informative. See ISA-84 Standards at pages 1 and 2 [220]

[152] *See* ISA 84 - The Standard for Safety Instrumented Systems [139].

[153] *See* ISA-84 2004 Part 1 at pages 16-17 [37].

[154] *See* 2000 OSHA Interpretation Letter - ISA-84 [133].

[155] *See* 2005 OSHA Interpretation Letter - ISA-84 [134].

[156] *See* 2000 OSHA Interpretation Letter - ISA 84 [133].

[157] *See* presentation on ISA-84 life cycle [38].

set point and the pump shuts down. In describing the approach Airgas uses to test the safety interlock, one employee explained:

> We would pump from a storage tank to a trailer to put it under normal operation and I'll start pinching back on the suction to the pump and I'll just sit there and watch the meter and it'll slowly…the gallons per minute will start to slowly decrease and once it gets to 15 gallons a minute, it should shut off.

63. This is a high-risk approach to testing the interlock. To determine if the safety device is functioning, the company's test creates the exact highly hazardous circumstances this interlock should prevent.

64. Closing the inlet block valve during trailer loading can cause vapor formation in the pump inlet, resulting in the pump running dry, and could initiate an explosive nitrous oxide decomposition reaction. As demonstrated by the nature of the physical damage to the Airgas facility at Cantonment, a potential nitrous oxide decomposition reaction unnecessarily puts workers conducting such testing at great risk.

65. Airgas should apply ISA-84 and develop a new procedure for testing safety interlocks that evaluates and controls process safety hazards. Alternative approaches could allow for testing the run-dry interlock without creating the risk of an explosion. For example, some of the flow can bypass around the flow meter such that full system flow to the trailer continues, but then begin gradually reducing flow through the meter to verify that the low-flow set point will function as designed and turn off the pump. Such an approach can verify the instrumentation is functional without initiating the actual low-flow condition that can initiate an explosive nitrous oxide decomposition reaction.

D. Nitrous Oxide Loading Pump System Design

66. Airgas did not have an appropriate focus on process safety. Many engineering issues existed at Cantonment that contributed to an increased likelihood for pumps to run dry, generate heat, and start a nitrous oxide decomposition reaction. These issues include:

    - Reliance on equipment manufacturers to perform pump system engineering;
    - Providing incorrect process data to pump manufacturers;
    - Not following pump manufacturer recommendations;
    - Lack of a preventive maintenance program for nitrous oxide pumps;
    - Not ensuring an adequate minimum storage tank level; and
    - Lack of automatic process control for trailer truck loading.

1. History of Nitrous Oxide Transfer Pumps at Cantonment

67. Since 2014, Airgas used pumps from three different manufacturers – Smith, Cryostar, and ACD to load trailers at the Cantonment facility.

a) Smith Precision Products

68. According to the Puritan-Bennett explosion investigation report, the Smith positive displacement gear pump had "been the industry's choice for many years." The CSB learned that Smith supplied the nitrous oxide industry with gear pumps for about 55 years.

69. Dry running of a Smith nitrous oxide pump contributed to the 1980 nitrous oxide explosion in Richmond, California. Puritan-Bennett was using the Smith gear pump as its standard nitrous oxide pump at all of the company's facilities, and it used a Smith pump when constructing the Cantonment, Florida nitrous oxide facility.

70. Through 2014, all North American nitrous oxide facilities used Smith pumps to move nitrous oxide and load nitrous oxide trailers. In addition, trailers were also equipped with Smith pumps to unload nitrous oxide at customer facilities.

71. In 2014, Smith notified its nitrous oxide pump customers that the company made a business decision to no longer manufacture its pump for nitrous oxide service.[158] As a result, Airgas began a process of finding a suitable pump to replace its fleet of Smith pumps.

b) Cryostar

72. Although using the Smith pump was the basis for nearly all of the company's experience with nitrous oxide transfer operations, Airgas did not perform a hazard review or management of change when the company designed, installed, and began using the Cryostar centrifugal pump.

73. In June 2014, Airgas ordered a Cryostar centrifugal pump to use as a potential replacement to its fleet of Smith pumps.

74. Airgas installed this Cryostar pump in parallel to the existing Smith pump and planned to use it for loading trailers and shipping containers at the Cantonment facility.

75. In January 2015, Airgas loaded its first trailer with the Cryostar pump. Company email communications indicate that the pump performed well and decreased trailer loading time because the Cryostar pump provided a larger flow rate than the Smith pump. But the Cryostar pump soon developed mechanical seal reliability problems and by March 2015, two mechanical seals failed. Based on pump manufacturer literature and pump usage history at Airgas, a mechanical seal for these pumps should last 12 to 18 months.

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[158] Smith stopped producing their pump for economic reasons and not because of nitrous oxide safety concerns.

76. The short (30-day) average life for these mechanical seals at Airgas resulted from operating conditions being significantly different from design conditions reported by Airgas. Cryostar records indicate that Airgas provided incorrect process data during the pump selection process and the mechanical seal was not operating within design parameters. Multiple process conditions were not accurate, including temperature, pressure, and density of the liquid nitrous oxide. When Airgas provided Cryostar with more accurate process conditions, Cryostar provided a different mechanical seal that corrected the mechanical seal reliability problem.

c) ACD

77. Cryostar manufactured its pump in France and obtaining pumps and parts took longer than Airgas desired. During the period of Cryostar reliability problems, Airgas bought a centrifugal pump from a company called ACD, manufactured in California.

78. In the summer of 2015, Airgas replaced the Cryostar pump installed at the Cantonment, Florida facility with the new pump from ACD. Airgas employees informed the CSB that the ACD pump performed well. As a result, the company did not perform maintenance, inspection, or repairs after installing the ACD pump.

79. According to the ACD pump manual, the mechanical seal requires annual replacement, which was due around the time of the August 28, 2016 incident. Because Airgas did not have a preventive maintenance program for the ACD pump, there was no replacement plan for the mechanical seal.

80. Airgas workers all said they use the ACD pump and not the Smith pump to load trailers because the ACD pump outperformed the Smith pump. As a result, the company used the ACD pump to load nearly all nitrous oxide trailers at the Cantonment facility from September 2015 to the incident on August 28, 2016. (Figure 38) There is no indication that the Smith pump operated on the day of the incident.

Figure 38. Post-incident photo showing the ACD pump inlet and outlet piping to the trailer loading piping. The explosion breached the discharge piping system and drained the remaining nitrous oxide in the storage tank to atmosphere. The frost line on the equipment shows this flow exited through the ACD pump. The discharge of the Smith pump (yellow oval) is not frosted and the discharge valve is closed.

81. Airgas did not perform an engineering evaluation of the ACD pump and instead Airgas “let the vendor do that.” In reviewing communication records between Airgas and ACD, however, the CSB identified no communications that suggested ACD performed an engineering evaluation of the Airgas nitrous oxide transfer pump. Rather, all communication supported the traditional vendor role – supply equipment to meet the customer process conditions and needs with no agreement or understanding as to an engineering evaluation role for ACD.

82. In specifying process conditions for the ACD pump, Airgas provided erroneous information to ACD, but some information was different from the information the company provided to Cryostar. Process conditions including fluid density and operating temperature were still not accurate.

83. Airgas specified the fluid density as 10.7 pounds per gallon, which is higher than for the normal nitrous oxide density of about 8.7 pounds per gallon. The specified density matches the density of liquid nitrous oxide at -127 °F and atmospheric pressure.[159] Although these conditions may reflect the initial startup conditions, they are not consistent with the normal pump inlet pressure Airgas provided to ACD of 240 to 300 pounds per square inch gauge (psig).

84. Although the ACD pump looked similar to the Cryostar pump, there were significant differences between them. For example, the ACD pump required more than two additional feet of liquid height to prevent developing vapor within the pump.[160] This additional, required pressure increased the

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[159] *See* Thermodynamic Properties of Saturated Nitrous Oxide [113]. The specified density was 1.281 kilograms per liter, which is equivalent to 79.97 pounds per cubic foot.

[160] Pump manufacturers express the required inlet liquid pressure as feet of net positive suction head (NPSH). The required NPSH for the ACD pump is 3.52 feet, 2.7 times larger than the 1.3 feet of NSPH required for the Cryostar pump. Having a

likelihood for the pump to run dry, generate heat, and start a nitrous oxide decomposition reaction. Although required by CGA G-8.3–2016, Airgas did not evaluate this difference in inlet pressure requirements or make any process modifications to ensure the ACD pump received adequate inlet liquid pressure.[161] As a result, the ACD pump was more likely to run dry, generate heat, and initiate a nitrous oxide decomposition reaction.

2. Pump Recycle Piping

85. Both the ACD and Smith pumps have a relief valve on the pump outlet piping that can circulate flow back to the suction piping. Figure 39 shows the relief valve on the ACD pump outlet piping. Airgas equipped the Smith pump with a similar relief valve. Post-incident testing revealed that the ACD pump relief valve leaked, but did lift at its set pressure, a differential pressure across the relief valve of 40 psig.[162] By design, the normal differential pressure of the ACD pump was 60 psig. Because the normal ACD pump outlet pressure exceeds the set pressure of the relief valve, the relief valve was probably open and a significant circulation of flow from the pump outlet to the pump inlet likely occurred.

Figure 39. Photo of the ACD pump relief valve (blue oval). Post-incident testing showed that this valve likely circulated nitrous oxide back to the pump inlet. Due to the low temperature of the nitrous oxide (about -10 °F), this piping is insulated. This photo shows the piping after removal of the insulation.

86. Airgas configured the relief valve piping on the ACD pump similar to what Smith says not to do.[163] Centrifugal pumps, such as the ACD pump, add heat to the process fluid as the fluid flows through the pump. This heat increases the liquid temperature. Thus, the temperature of the nitrous oxide exiting the ACD pump will be higher than the temperature of the nitrous oxide entering the pump.

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significantly higher NPSH requirement increases the potential for vapor generation in the pump. The Cryostar and Smith pumps had similar NPSH requirements.

[161] *See* [150], Section 8.2.

[162] The Smith pump relief valve was also tested post-incident. Although it had a set pressure of 40 psig, the relief valve leaked, but never lifted, even at 50 psig of inlet pressure.

[163] *See* Smith pump - Do's and Don'ts at pages 15 and 16 [39].

As a result, the nitrous oxide circulation through the relief valve should increase the fluid temperature and could generate vapor in the pump inlet piping. (Figure 40) To avoid vapor in the pump inlet piping, a better design is to direct the relief valve outlet back to the storage tank, away from the pump supply nozzle.

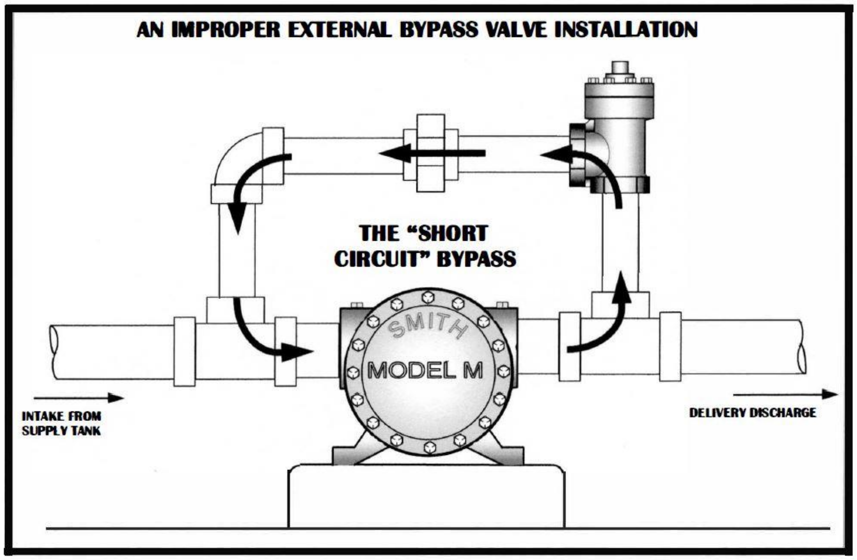

Figure 40. Schematic from Smith pump literature illustrating an improper piping design. Airgas configured the relief valve piping on the ACD pump similar to what Smith says not to do.

87. CGA G-8.3–2016 supports designing nitrous oxide pumps to startup with return piping back to the storage tanks. The standard states:

> Best practice for liquid transfer pumps is to install the pump with a flooded suction line and a liquid return connection to help quench a decomposition reaction.[164]

3. Instrumentation to Monitor Pump Performance

88. While both Cryostar and ACD recommended specific instrumentation to monitor pump performance such as pump inlet pressure and temperature, pump outlet pressure and temperature, and pump differential pressure, Airgas did not follow these recommendations. Furthermore, Airgas lacks documentation showing the company considered these manufacturer recommendations.

4. Mechanical Seal – A Continual Source of Heat

89. Industry standards and historical incidents (Richmond, Eindhoven, and Moncada) show that inadequate liquid supply to an operating pump is a potential cause of a nitrous oxide explosion. An operating pump generates heat and without enough liquid flow the temperature of pump

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[164] *See* [150], Section 5.7.

components increases. At times, nitrous oxide industry pumps have developed enough heat to initiate explosions.

90. In the design of the Cryostar pump piping system, Airgas did not account for the pressure drop across y-strainers stuffed with steel wool that the company used as a flame arrestor. While a clean y-strainer may have low-pressure drop, a y-strainer "completely packed" with steel wool is more restrictive. Industry y-strainer literature for one manufacturer indicates a clogged y-strainer can increase pressure drop by a factor of 10.[165] Airgas did not evaluate the effect these devices could have on pump operation. The presence of these flame arrestors could partially vaporize the liquid nitrous oxide entering the pump and result in dry running and thus elevated temperature conditions, which could start a decomposition reaction.

91. Airgas did not perform an engineering analysis or install instrumentation, such as pressure or differential pressure indication, to ensure that using a y-strainer filled with steel wool on the pump suction piping would not result in dry running conditions. Industry literature describes potential problems with clogged strainers on centrifugal pump performance.[166, 167] One source states, "… any benefit of a suction strainer is far outweighed by the risks, which can lead to pump failures and other system problems."[168]

92. The ACD pump is a close-coupled design that uses the motor bearing to support the pump shaft. (Figure 41) This design eliminates the need for a pump bearing that could potentially overheat and trigger a nitrous oxide decomposition reaction.

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[165] *See* Mueller y-strainer pressure drop chart [40].
[166] *See* Suction Pipeline Design [42].
[167] *See* Oil and Gas Processing discussion of pump suction strainers [43].
[168] *See* Are suction strainers necessary on centrifugal pumps [44].

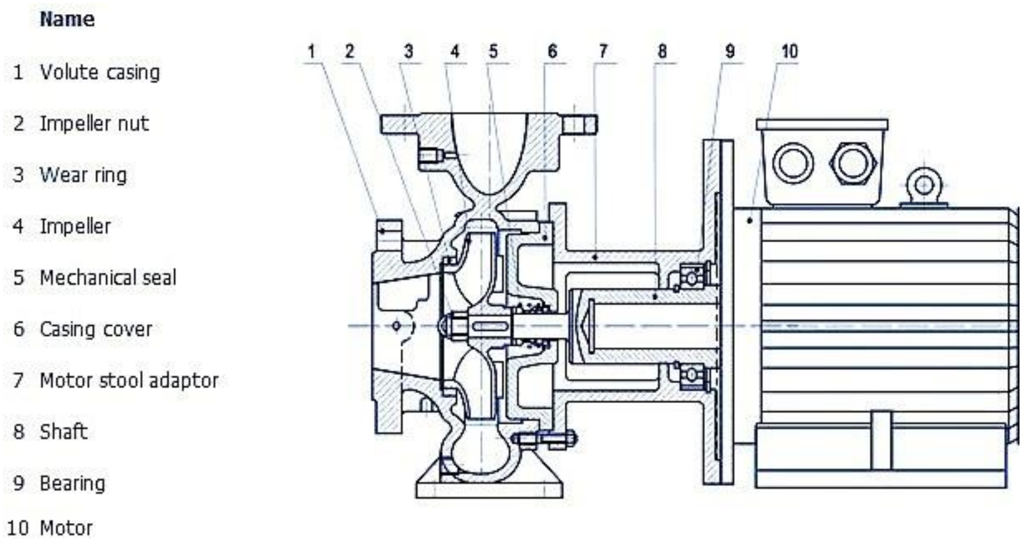

Figure 41. Schematic of a typical close-coupled pump.[169] Although this is not an ACD pump, it is similar and illustrates how the motor shaft can directly turn the pump impeller without an additional pump shaft and bearing.

93. Due to the close-coupled pump design, the only continual source of heat within the ACD pump is the mechanical seal. As a result, the mechanical seal is the most likely heat source to start an explosive nitrous oxide decomposition reaction.

94. The rotating and stationary surfaces of a mechanical seal require cooling and lubrication to prevent heat, wear, and failure. By design, the mechanical seal installed in the ACD pump relies on the liquid nitrous oxide to cool and lubricate the seal faces. During dry running conditions, the lack of liquid nitrous oxide can generate significant heat due to insufficient cooling and lubrication of the mechanical seal faces. "Dry running as result of inadequate lubrication … during operation, leads to massive temperature increases and possible damage to the sliding faces and secondary seals."[170]

95. Although in most equipment applications this heat generation is a concern for reliable seal operation, in nitrous oxide pumps, an unlubricated mechanical seal is a potential source of heat that can trigger an explosive nitrous oxide decomposition reaction. Because the Airgas ACD pump outlet connection is 1.5-inch and the piping is 2-inch, temperatures as low as 50 °F may be enough to sustain a nitrous oxide decomposition reaction. (Figure 42)

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[169] *See* close-coupled pump [227].

[170] *See* Eagle Burgmann Brochure - Mechanical Seal Technology and Selection at page 11 [41].

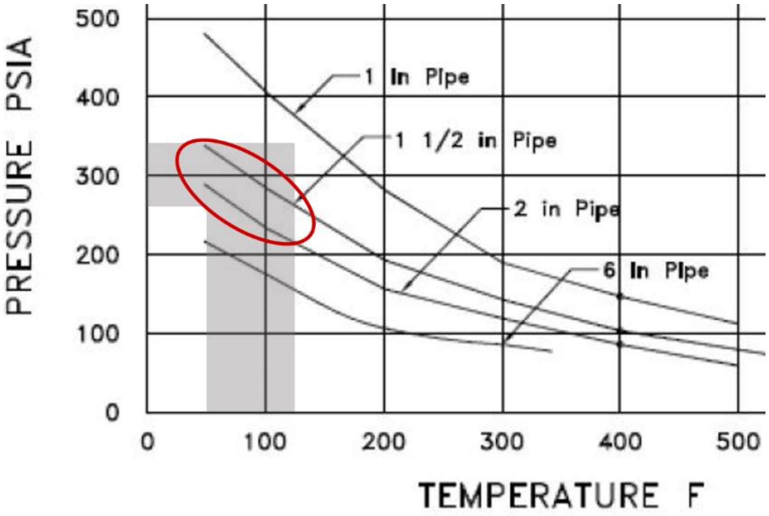

Figure 42. CGA Propagation threshold for nitrous oxide decomposition reaction at the ACD pump conditions.[171] The red oval shows the temperature needed to sustain propagation of a nitrous oxide decomposition in the ACD pump at Airgas. Although not measured, typical operating pressure in the ACD pump is likely in the range of 265 to 330 psia. At this pressure and with the piping used at Airgas, the temperature needed to sustain a nitrous oxide decomposition is in the range of 50 to 125 °F. Figure 9 shows the full CGA nitrous oxide propagation threshold chart.

96. An explosive nitrous oxide decomposition reaction does not require a significant increase in temperature. CGA states, "Temperatures above 300 °F (150 °C) shall be avoided by all practical means to reduce the likelihood of an explosive decomposition of the nitrous oxide."[172]

97. The guidance provided by CGA to avoid temperatures above 300 °F does not align with Figure 42, which shows that once the reaction is initiated, temperatures as low as 50 °F can propagate a nitrous oxide decomposition reaction at the ACD pump conditions. CGA should clarify its temperature guidance in light of the Airgas incident.

98. Following a physical inspection of the ACD pump mechanical seal after the incident, the technical representative from the seal manufacturer stated that the seal showed signs of wear and dry running. (Figure 43 and Figure 44)[173]

99. In addition, the CSB contracted with an engineering consultant to evaluate the mechanical seal from the ACD pump. The engineering contractor confirmed the blue coloring (top right photo in Figure 43) and the surfacing cracking (bottom right photo in Figure 43) are consistent with heat that is likely the result of poor lubrication from dry running conditions.[174]

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[171] *See* [150], Section 4.3.3.3.

[172] *Id*., at Section 5.7.

[173] Figure 43 and Figure 44 come from a report on metallurgical testing results developed by a consultant that functioned as a third party laboratory for all relevant parties. This consultant provided testing results, but not analysis.

[174] The CSB's engineering consultant also noted that the y-strainer filled with steel wool would make dry running more likely and that the uninsulated pump casing and heat from the totally enclosed fan cooled (TEFC) motor would also provide heat to the pump. This animation shows how a TEFC motor cools itself, but could provide additional heat to an attached pump.

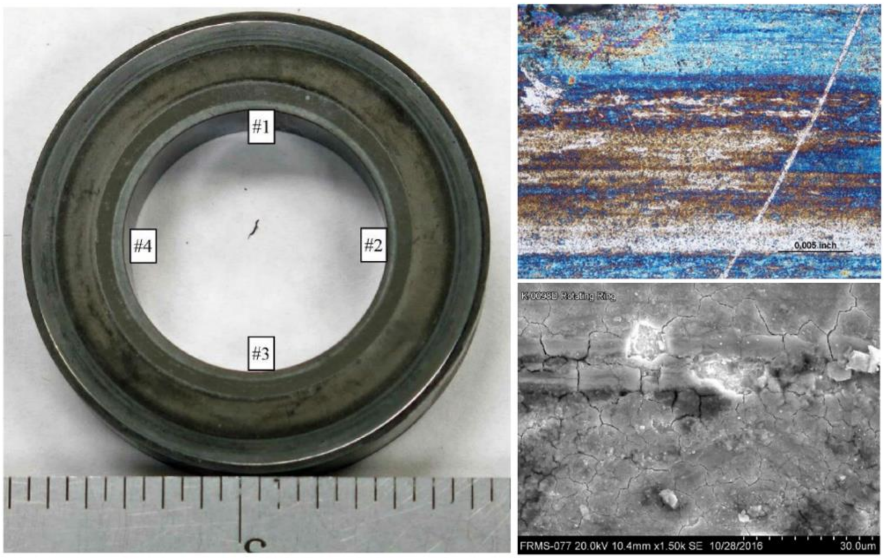

Figure 43. ACD Pump Mechanical Seal Rotating Face. The scale for these images is 1/16-inch (left), 0.005-inch (top right), and 30-micrometers (bottom right).

100. The CSB’s engineering contractor also noted that the chipping of the carbon stationary seal face that is shown in the left photo of Figure 44, at Location #6, is consistent with separation of the mechanical seal faces from excessive vaporization. When the faces forcefully come back together, the softer carbon face can crack or chip.

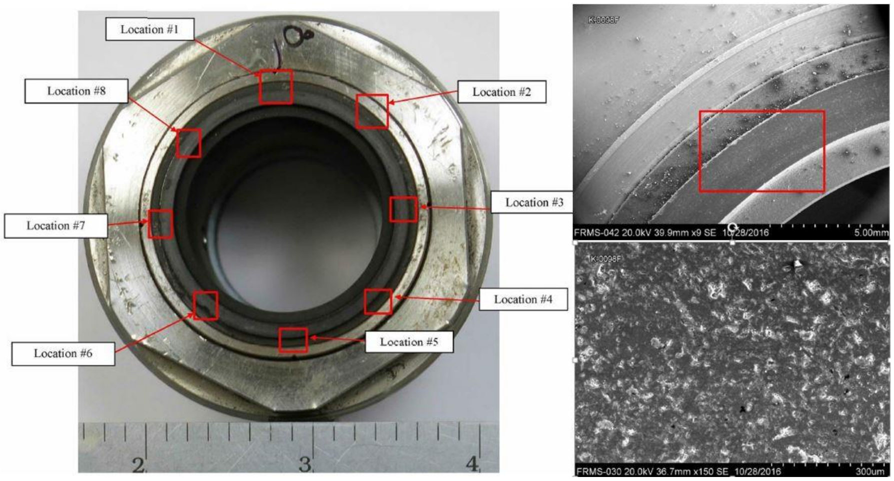

Figure 44. ACD Pump Mechanical Seal Stationary Face. The scale for these images is 1/8-inch (left), 5-millimeters (top right), and 300-micrometers (bottom right).

101. The mechanical seal from the ACD pump shows physical damage consistent with dry running conditions that are likely the result of process conditions not meeting pump manufacturer requirements, such as the pump inlet pressure. In addition, the physical evidence indicates that at times, the mechanical seal operated at high temperature conditions that are likely sufficient to start a nitrous oxide decomposition reaction.

5. Pump Manufacturer Safety Warnings

102. Of the three nitrous oxide pump brands used by Airgas – Smith, Cryostar, and ACD – only Smith provides nitrous oxide decomposition safety warnings in its pump literature.[175] Among its nitrous oxide safety information, Smith pump documentation states, "great care must be taken to avoid an explosion caused by heat."[176]

103. Smith company literature also informs users about the potential problems with contamination. The literature states:

> Actually, liquefied Nitrous Oxide is listed as a highly confirmed oxidizing agent. One of its chief characteristics is that it readily yields free Oxygen through heat gain decomposition. Therefore, contaminants could cause violent combustion within the confines of the tank and piping system.[177]

104. Cryostar pump documentation provides some general nitrous oxide safety information including physical properties, lack of flammability, odor characteristics, methods for leak detection, and anesthetic and narcotic exposure effect. The company does not provide information about nitrous oxide decomposition hazards.

105. ACD provides no specific nitrous oxide safety information in its pump manual.

106. Many equipment manufacturers including ITT, one of the world's largest pump suppliers and manufacturer of the Goulds 3196, a common process pump,[178] establish a product stewardship program to ensure safety is considered in both product development and in customer use.[179]

107. The Product Stewardship Society defines product stewardship as, "Responsibly managing the health, safety, and environmental aspects of raw materials, intermediate, and consumer products throughout their life cycle and across the value chain in order to prevent or minimize negative impacts and maximize value."[180]

108. Through an effective product stewardship program, nitrous oxide pump manufacturers can play an important safety role by referencing and reinforcing critical nitrous oxide safety hazards and appropriate precautions to their customers. To help prevent future incidents, Cryostar and ACD should provide nitrous oxide decomposition hazard warnings and refer users to both CGA G-8.3 and this CSB investigation report for additional information on how to prevent catastrophic nitrous oxide explosions.

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[175] *See* Smith Precision Pumps nitrous oxide literature [31].
[176] *Id.*
[177] *Id.*
[178] As of 2008, the Goulds 3196 was the most popular process pump in the world. See Goulds 3196 the World's Most Popular Process Pump [45].
[179] *See* ITT Product Stewardship [46].
[180] *See* product stewardship definition [96].

6. Pump Cool Down

109. Before starting a transfer of nitrous oxide from storage to a trailer truck or shipping container, the pump and piping are at ambient temperature and cooling is needed to prevent vapor formation within the pump. Forming vapor in the pump can cause the pump to run dry and result in heat generation that may start an explosive nitrous oxide decomposition reaction.

110. Airgas cools the pump and piping by opening the suction valve to the pump and a drain valve on the pump discharge. This action introduces liquid nitrous oxide to the pump, which initiates the cooling process. As the cold liquid contacts the warm piping, some liquid converts to vapor. This vapor exits the piping through the open drain valve and vents to atmosphere. As the piping continues to cool, the amount of vapor decreases and eventually liquid exits the piping through the open drain valve. When the operator sees liquid draining to atmosphere, they close the drain valve.

111. Airgas relies on a visual observation approach that may not effectively cool down the pump. The company instructs operators to look for a frost line to develop on the discharge piping and then ensure that liquid comes out of the outlet piping bleed valve. Airgas operators told CSB investigators the transfer pump would sometimes shut down from low-flow due to lack of adequate cooling when first loading a trailer. When this occurred, operators simply repeated the pump cooling procedure.

112. Both ACD and Cryostar specify a time for the cooling in order to ensure the pump and piping are cooled. Cooling time is 5-10 minutes for the ACD pump and 15-20 minutes for the Cryostar pump.

113. Although Airgas operators described problems with insufficient pump cooling, too much cooling is also possible and can create additional problems. By reducing the pressure to atmospheric pressure, the liquid in the piping system can be as low as -127 °F.[181] Due to this pump cooling approach, the pump and piping can be significantly cooler than the temperature of nitrous oxide in the storage tank, which is approximately 0 to -10 °F.

114. All three pump manufacturers – Smith, Cryostar, and ACD – provided a recommended piping arrangement that included piping from the pump discharge back to the storage tank, but away from the pump liquid supply line to prevent nitrous oxide vapor from recycling back to the pump during startup.

115. Smith pump literature states, "The proper method [to remove vapor] for piping is illustrated, below." (Figure 45) The liquid flows out of the pump, and either through a hand valve and back to the supply tank, or through a bypass valve, set at a predetermined differential pressure which avoids overloading the pump, and back to the tank."[182]

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[181] *See* Thermodynamic Properties of Saturated Nitrous Oxide [113].
[182] *See* Smith pump - Do's and Don'ts at pages 8 and 9 [39].

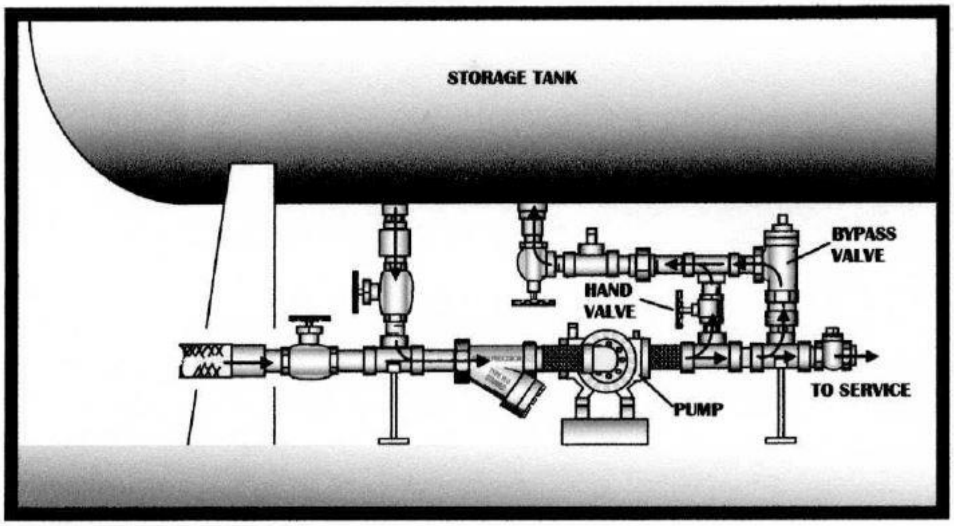

Figure 45. Bypass piping configuration recommended by Smith in its product literature.

116. Cryostar literature also supports the use of a bypass line to facilitate cool down. The Cryostar operation manual states, "For faster cool down and for easier start-up a bypass line should be provided." The Cryostar manual also includes the bypass line as part of the startup procedure and instructs the operator to verify the bypass valve is open before starting the pump. The Cryostar manual also cautions the user not to overcool the pump and further states: "If the pump is overcooled (support arms completely frosted) it should be started only after the shaft has been checked for free rotation."

117. Of the three pump manufacturers, ACD provided the least detailed instructions. ACD cautions users: "Never operate the pump without first cooling down to normal operating temperature." ACD also cautions users against overcooling, stating: "Never operate the pump if the bearing housing has become excessively cold (frosted over)."

a) Worker Exposure to Nitrous Oxide

118. Airgas procedures require routine venting of nitrous oxide to the atmosphere when workers prepare to start nitrous oxide pumps and when disconnecting hoses after completing trailer loading. Airgas periodically monitors worker exposure to nitrous oxide and acknowledges that at times worker exposure exceeded established limits.[183, 184]

119. Although not prohibited by environmental regulations, venting nitrous oxide to atmosphere during pump cool down and before disconnecting trailer hoses can expose workers to nitrous oxide

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[183] The ACGIH exposure limit (threshold limit value) for nitrous oxide is a time weighted average of 50 parts per million. NIOSH established a recommended exposure limit of 25 parts per million. OSHA does not have an established exposure limit for nitrous oxide. See Nitrous Oxide in Workplace Atmospheres [130].

[184] Following the 2007 Scaled Composites explosion, Cal/OSHA cited Scaled Composites for failing to ensure that its "employees were not exposed in excess of the nitrous oxide permissible exposure limit of 50 parts per million." See Cal/OSHA Investigation File - Scaled Composites Explosion at page 15 [117].

vapor.[185] Since nitrous oxide is a common anesthetic in dentistry and medical treatment, workers could potentially be impaired from exposure to nitrous oxide at relatively low exposure concentrations.[186] In addition, the Airgas safety data sheet suggests using engineering controls, such as the pump manufacturer cool down piping arrangement, to control worker exposure to nitrous oxide.[187]

120. To control worker exposure to nitrous oxide, CGA G-8.3–2016 recommends, among other things, "ensuring the filling system is designed so that nitrous oxide is not released into the work environment via venting or leaking."[188]

121. On weekends and during weekday night shifts, only one Airgas employee is present to operate the process and load nitrous oxide trailers. To monitor the status of lone workers, Airgas purchased a "man down" system to alert responders if an Airgas worker was disabled. Although Airgas procedures required workers to wear this monitoring device when working alone, Airgas employees informed CSB investigators that this system did not work so workers did not wear the monitoring device.

122. Airgas employees confirmed that company management knew about the problems with the man down system and were trying to "get it working." Nevertheless, Airgas continued to assign lone operators on some shifts to load nitrous oxide, where procedures required venting to atmosphere adjacent to where the operators stood. In these circumstances, a worker could be overcome by the effects of the product – or coincidentally could suffer any other serious health or safety emergency accompanied by loss of consciousness – with no ability to call for help or obtain support from coworkers.

123. To control worker exposure to nitrous oxide, Airgas should modify equipment design and operating practices to prevent nitrous oxide releases into the work environment from leaking or venting equipment. In addition, as part of its efforts to evaluate overall process safety, the company should evaluate its safety practices when operating the facility with just one employee.

b) Flexible Connections between Piping and Pump

124. Airgas nitrous oxide transfer pumps use stainless steel piping on both the suction and discharge. The company did not perform piping stress analysis to ensure that initial cool down does not produce excessive stress on the pump, which could adversely affect pump performance and cause the mechanical seal to generate excessive heat.[189]

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[185] In its 2015 corporate Sustainability Report, Airgas stated: "Nitrous oxide (N_2O) is a greenhouse gas with nearly 300 times the global warming impact of carbon dioxide. Annually, Airgas produces and packages about 30 million pounds of this gas for sale to whipped cream manufacturers, electronics producers, and medical and dental customers." See Airgas Sustainability Report 2015 [88].

[186] *See* Nitrous Oxide and the Inhalation Anesthetics [98].

[187] *See* Nitrous Oxide Safety Data Sheet (SDS) [58]. "Appropriate Engineering Controls: Use only with adequate ventilation. Use process enclosures, local exhaust ventilation or other engineering controls to keep worker exposure to airborne contaminants below any recommended or statutory limits."

[188] *See* [150], Section 4.4.3.

[189] *See* *How Do Plant Pipe Strain Problems Affect My Pumping Systems?* [114].

125. Although not installed by Airgas, all three of the pump manufacturers (Smith, Cryostar, and ACD) recommend flexible connectors on the suction and discharge of the pump. The Cryostar manual explains that these flexible connections are to "avoid any transmission of vibrations to the pump or excessive stresses on the pump flanges." The ACD manual explains, "[s]hort flexible lines at the pump port connections are highly recommended to isolate the piping from any pump vibrations and to compensate for thermal expansion and contraction."

126. Airgas does not use these flexible connections on the pumps used to load trailers at the Cantonment, Florida facility, but the company does use them on trailer pumps used for unloading nitrous oxide at customer facilities. (Figure 53)

7. Storage Tank Level

127. Despite the importance of not allowing the nitrous oxide transfer pump to run dry, Airgas never established or evaluated a minimum required nitrous oxide storage tank level.

128. The two primary nitrous oxide storage tanks are each equipped with a level transmitter and a weight scale to allow operators to monitor the nitrous oxide inventory using the process control computer. Although only the level transmitters are shown on the Airgas engineering drawings (Piping and Instrument Diagrams), employees informed CSB investigators that the scale is used to monitor the pounds of nitrous oxide in each tank.

129. The storage tank scales are not equipped with a low-level alarm. In addition, although the tank level transmitters include a low-level alarm, the alarm is not useful because the alarm set point is well below the minimum detection capability of the transmitter.

130. Operators described a common practice of loading a truck as soon as a nitrous oxide storage tank contained enough liquid inventory to fill it. Airgas relies on its operators to ensure there is an adequate level of nitrous oxide in the storage tank before starting the pump to load a nitrous oxide trailer truck. The company provides no engineering controls to ensure the pump does not run dry due to operating the pump with a low level in the storage tank.

131. In addition, there are no safeguards to prevent the operator from inadvertently aligning an empty or near-empty storage tank to the transfer pump. With two nitrous oxide storage tanks that typically supply feed to the loading pump, a near empty storage tank can be lined up to the pump, resulting in a dangerous condition. The operator could be attempting to start and thus bypassing the interlock intended to prevent operating the pump at these conditions. With the interlock defeated, the pump can run dry during startup and trigger an explosion. Some method of differentiating between the tanks should be established to help operators avoid inadvertently aligning an empty or near empty tank, which could cause a pump to run dry and threaten a nitrous oxide decomposition reaction.

132. The plant manager, however, stated that operators set an alarm on the storage tank level at the beginning of the trailer truck loading process. To understand how this works, consider a storage tank that contains 40,000 pounds of nitrous oxide. If a tank trailer can hold 36,000 pounds of nitrous oxide, according to the plant manager, an operator could set an alarm on the storage tank to go off when the tank inventory reaches 5,000 pounds, with 1,000 pounds remaining to transfer.

Although not covered by Airgas procedures, this type of alarm could help ensure the operator is physically present when the 36,000-pound transfer of nitrous oxide into the trailer truck is complete. If set, storage tank alarms should sound in the control room and outside in the plant. During interviews with CSB investigators, however, none of the Airgas operators said they use this alarm system.

133. While truck-loading operations take place, it is normal for the nitrous oxide manufacturing process to be operating – producing nitrous oxide product and filling the same storage tank while product flows into a trailer. This simultaneous operation was taking place on the day of the incident. The process was accumulating liquid in Storage Tank 2 – the same tank operators were using to load trailer trucks.

134. This common practice of simultaneously sending nitrous oxide to and removing nitrous oxide from the same storage tank makes it unlikely for operators to use the alarm system to monitor trailer truck loading. The simultaneous operation complicates the calculations and makes the alarm system less useful.

135. Operators stated that the truck loading process is a manual activity with no automatic controls other than the safety interlock associated with the pump. There is also no level indicator on the trailer truck to indicate how much nitrous oxide is loaded.

136. Airgas must improve its safety management practices with respect to storage tank and trailer truck levels in order to control nitrous oxide liquid level and prevent developing heat inside the pump caused by dry running. Such improvements can strengthen the company’s ability to prevent a decomposition reaction and explosion such as the one suffered at Cantonment.

8. Cantonment Design did not Incorporate Lessons from 1980 Richmond, California Incident

137. Puritan-Bennett owned the Richmond nitrous oxide manufacturing plant at the time the company started construction of the Cantonment facility; however, the Cantonment process design did not implement important lessons learned from the 1980 nitrous oxide explosion at the Richmond facility. These lessons, stated below, include potential causes of the August 28, 2016 explosion:[190]

- Provide at least five feet of liquid above the pump to ensure an adequate liquid supply to the pump;
- Use both a strainer and a metallic flame arrestor on each side (inlet and outlet) of the pump;
- Install a safety interlock to shut the pump motor off when there is low motor load (power consumption); and

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[190] *See* [20].

- Construct piping to circulate liquid back to the storage tank during initial starting and cool down of the pump.

138. By helping to prevent vapor formation and heat generation in the pump, preventing propagation of a nitrous oxide decomposition reaction, and shutting down the pump when vapor formed, each of these design features could have helped to prevent the August 28, 2016 explosion.

9. Critical Equipment and Preventive Maintenance

139. Following the September 2012 Moncada explosion, Air Liquide issued emergency safety guidance that required nitrous oxide pumps to be included in the company's critical equipment program. Among other things, this program places special emphasis on associated safety interlocks, maintenance, and operating procedures.

140. Airgas established a critical equipment procedure applicable to the Cantonment facility. Airgas states, "nitrous oxide plants … fundamentally require a preventative maintenance program for their safe operation."

141. The purpose of this Airgas procedure is "to identify critical equipment, their critical parts and specifications, and to develop a preventive maintenance inspection and maintenance schedule."

142. The company defines critical equipment as "[e]quipment necessary to safely operate a process."

143. Airgas defines a critical part as "[a] necessary component of a critical equipment unit that allows safe operation."

144. Although the nitrous oxide loading pump, flame arrestors, and run-dry interlock all meet the Airgas critical equipment or critical part definitions, none of this equipment is on the company's list of critical equipment.

145. Critical equipment is also required to have a preventive maintenance schedule. The policy states:

> A schedule shall be developed for each critical equipment unit. The schedule shall indicate the frequency of each maintenance action necessary, to maintain the unit in a safe and operable condition. All frequencies established, shall meet at a minimum, the manufacturer's recommended schedules and all internal Airgas standards.

146. During the most recent corporate safety audit in May 2016, Critical Equipment received a perfect score. The Airgas audit, however, looks at whether or not a certain program exists. The audit did not assess the accuracy of the critical equipment list.

147. As an example, for the critical equipment list, the auditor is asked to evaluate if:

> "An inventory of all critical equipment and critical parts is developed and maintained."

> "A preventive maintenance schedule is developed for each critical equipment unit and addresses each critical part to assure the unit's safe operation. The schedule shall include general equipment listed in this procedure."
>
> "Equipment is provided preventative maintenance according to the developed schedule. Give credit only with supporting documentation."

148. As part of efforts to strengthen overall process safety management, Airgas (Air Liquide) should improve its auditing practices. Robust audits should identify gaps in critical safety programs and ensure the company strengthens these programs.

E. Other Possible Causes

1. Contamination Prevention and Gap in Chemistry Knowledge

149. Given the history of contamination associated with historical nitrous oxide explosions, the presence of contaminants and potentially incompatible materials in Airgas equipment, and the company's limited knowledge of relevant contamination chemistry, the CSB could not rule out contamination as a contributing factor to this incident.

150. Previous investigations of explosive nitrous oxide decomposition reactions suggest that contamination may have been causal to two-thirds of the historical incidents, including the 1980 Richmond, California; 2001 Eindhoven, the Netherlands; 2007 Mojave, California; and 2012 Moncada, Spain incidents.

151. Post-incident equipment evaluation at Airgas identified a number of potential contaminants in equipment, including many metallic particles. Contaminants such as metal particles can act as a catalyst and may have contributed to the explosion. The CSB found significant degradation of strainers and steel wool. (Figure 45) Many metallic particles collected in downstream equipment, including ball valves. (Figure 46)

Figure 46. Photos of strainer corrosion and metallic particles. Post-incident evaluation of nitrous oxide pump strainers revealed equipment corrosion and metallic particles. These metallic particles may have acted as a contaminant and could have played a role in the explosive nitrous oxide decomposition reaction.

Figure 47. Photos of metal particles in ball valves. Many metallic particles, including steel wool fibers, collected in equipment downstream of the nitrous oxide transfer pumps.

152. Studies conducted after previous explosions, including the 2007 Scaled Composites explosion, provided some warning that the presence of contaminants or catalysts can increase the risk of an explosion during operations, such as nitrous oxide liquid transfer.[191] Nonetheless, Airgas did not evaluate its process for potential contaminants and catalysts.

153. In a CSB safety video on reactive hazards, process safety expert Dennis Hendershot stated:

> The most important thing to managing reactive chemistry hazards is that you have to have a thorough and complete understanding of your chemistry under design conditions and also under all foreseeable abnormal conditions.[192]

154. An exact knowledge and understanding of how these metallic particles may have developed, flowed downstream, and potentially contributed to the incident is lacking. Historically, Airgas never performed testing to understand the effect steel wool, strainer degradation, or the resulting metallic particles may have on promoting nitrous oxide decomposition. As a result, the company's understanding of nitrous oxide decomposition chemistry was not "thorough and complete."[193]

155. The company also installed potentially incompatible materials in its equipment. For example, as shown in Figure 48, an O-ring located inside a Trailer 182 relief valve reportedly contained butadiene, which may not be compatible with nitrous oxide.[194] Post-accident examination indicates that flow through this valve occurred.

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[191] Scaled Composites published nitrous oxide safety guidelines following its investigation into the causes of the explosion. See Scaled Composites Nitrous Oxide Safety Guidelines [15].

[192] *See* CSB Safety Video: Reactive Hazards at 18:52 [228].

[193] *See* CSB Safety Video: Reactive Hazards at 18:52 [228].

[194] Although additional testing is required to confirm, the O-ring may be butadiene rubber. The Parker O-Ring Handbook indicates insufficient data is available to use a butadiene rubber O-ring with nitrous oxide. See Parker O-Ring Handbook at page 199 [120].

Figure 48. O-ring in Trailer 182. This photo shows the O-ring (inner black circle) for the Trailer 182 relief valve that may be incompatible with nitrous oxide. The area near the O-ring shows evidence of heat exposure.

156. Although an incompatible material could burn in nitrous oxide and create enough heat to start an explosion, the CSB did not identify any evidence showing this incident initiated by the opening of a relief device due to high pressure in Trailer 182. The available data, however, is limited to two points in the 18-hour period before the explosion.

157. Airgas operators record trailer pressure every 12 hours. Airgas operators recorded Trailer 182 pressure as 280 psig at 6:00 am (CDT) on the morning of August 28, 2016. This pressure was 30 psi lower than the value of 310 psig recorded at 6:00 pm (CDT) on August 27, 2016.

158. To preserve any physical evidence within the Trailer 182 pressure relief valve that was in service at the time of the incident, this valve was not lift-tested to evaluate set pressure. Trailer 182 was equipped with a spare relief valve as shown in Figure 49. The spare relief valve was tested and lifted at 350 psig. With the two Trailer 182 pressure data points of 280 and 310 psig being less than 90 percent of the likely relief valve set pressure of 350 psig, it is unlikely that lifting the relief valve due to high trailer pressure initiated the incident.

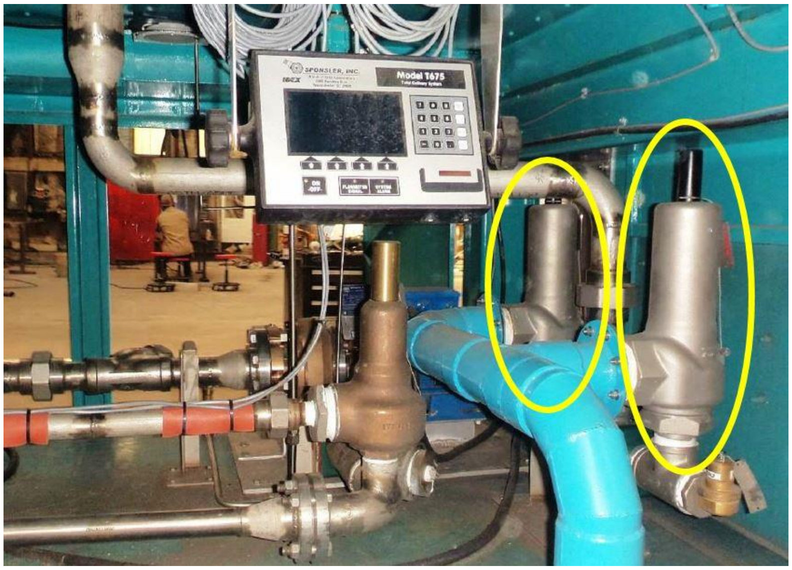

Figure 49. Trailer 182 relief valves. This pre-incident photo taken at a maintenance facility shows the location of the two relief valves (yellow ovals) that protect Trailer 182 from high pressure. Only one valve is in service at a time. A 3-way valve, obscured by the blue piping, can change which valve is in service.

159. CGA G-8.3–2016, *Safe Practices for Storage and Handling of Nitrous Oxide,* describes the potential role that contamination can have on decomposition reactions. The standard notes, "Oil and grease are unacceptable contaminants in a nitrous oxide installation and can create a severe fire hazard."[195] CGA also warns about the danger of combustible materials in nitrous oxide. The standard states:

> Any combustible material, such as hydrocarbon lubricants or flammable mixtures will promote violent decomposition and lower the propagation threshold. A flammable mixture will lower the propagation threshold even if present below the lower explosion limit. All equipment that will be in contact with nitrous oxide shall be cleaned for oxygen service and lubricants shall be oxygen compatible.[196]

160. CGA does not specify any "restriction regarding the use of common commercial metallic materials for nitrous oxide installations" but states "carbon steel, manganese steel, chrome molybdenum steel, stainless steel, brass, copper, copper alloys, and aluminum are considered to be suitable for use with nitrous oxide."[197]

161. CGA requires more stringent metallurgy requirements for strainers; however, the standard states: "Filters or strainers shall be designed considering the oxidizing properties of nitrous oxide. Mesh

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[195] *See* [150], Section 4.3.1.3.
[196] *Id*., at Section 4.3.3.4.
[197] *Id*., at Section 5.2.1.

filters or strainers made from high nickel alloys (such as Monel, Inconel, nickel 200 alloys) or high copper alloys (such as brass) are preferred due to increased resistance to oxidizer fires."[198, 199]

162. Although the CGA standard provides guidance on metallurgy for equipment, it does not specifically address the potential for metal corrosion products to act as a catalyst in promoting nitrous oxide decomposition as noted in the safety guidance Scaled Composites developed following the 2007 explosion in Mojave, California.

163. Post-incident, Airgas started development of a contamination-testing program focused on safety, not only quality control. Company testing with respect to this issue remains ongoing, and the CSB encourages Airgas to complete this testing and to share its results with the CSB and with the nitrous oxide industry through the Compressed Gas Association.

2. Electrical Safety

164. Although the CSB did not identify a static charge accumulation scenario based on all available physical evidence, the agency could not eliminate static discharge as a possible cause of the August 28, 2016 explosion.

165. CGA identifies static discharge as a source known to initiate nitrous oxide vapor decomposition reactions.[200] In addition, CGA states: "Nitrous oxide installations shall be grounded in accordance with local regulatory requirements, for example NFPA 70 [or the] National Electric Code."[201]

166. CGA refers to trailers as transport tanks. To address static electricity concerns with trailers, CGA states: "All parts of the transport tank shall be bonded to ensure electrical continuity."[202]

167. Although Air Liquide corporate guidance issued following the 2012 Moncada explosion required all parts of trailer trucks and storage tanks to be electrically bonded, Airgas did not have a program to ensure effective electrical bonding or grounding when loading or moving nitrous oxide to trailer trucks or shipping containers. Due to the absence of an effective bonding or grounding program when loading nitrous oxide, the CSB could not eliminate the possibility that static electricity caused the Cantonment explosion.

168. To ensure a spark from static electricity does not trigger a nitrous oxide decomposition explosion, Airgas should develop and implement a comprehensive electrical bonding and grounding program.

F. Post-Incident Valve Positions

169. Nearly all of the block valves used for nitrous oxide loading operations are quarter-turn ball valves. (Figure 50) The "ball" in such valves refers to the internal component of the valve, which is a ball with a hole through the middle that rotates 90 degrees to either allow flow or prevent flow. The

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[198] *Id*., at Section 5.4.
[199] *See* high performance alloys including Monel, Inconel, and Nickel 200 [90].
[200] *See* [150], Section 4.3.3.
[201] *Id*., at Section 5.7.
[202] *Id*., at Section 7.3.4.

valve handle position indicates the position of the ball – open when parallel and closed when perpendicular to the valve body. The "quarter-turn" refers to how the valve is operated – requiring a 90-degree turn of the handle to move the ball from closed to open and vice-versa, making quarter-turn ball valves relatively easy to operate. Because they are easy to operate, however, the position of many quarter-turn ball valves at Airgas likely changed from the force of the explosion.

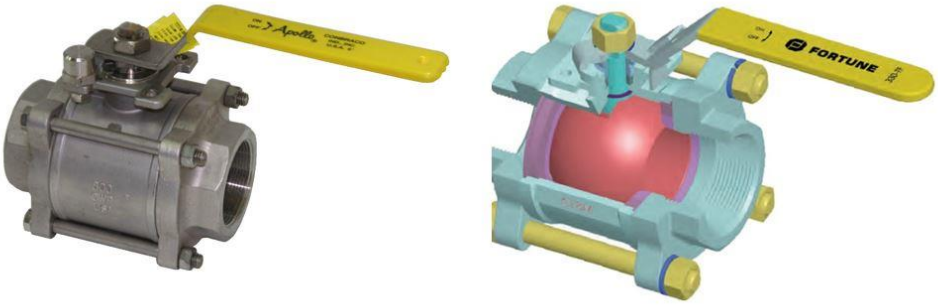

Figure 50. Images of quarter-turn ball valves similar to those installed at the Airgas Cantonment facility.[203, 204]

170. During field evaluation, the CSB found the ACD centrifugal pump inlet piping open to nitrous oxide storage tank two at the time of the incident. On the outlet (discharge) side of the ACD centrifugal pump, the first valve is open, but a downstream valve is almost fully closed. (Figure 51) The CSB concluded that this quarter-turn ball valve was most likely open at the time of the incident, and that the force of the explosion changed the position of the valve.[205]

Figure 51. Post-incident photo of the nitrous oxide transfer pumps. The yellow circle identifies the nearly closed discharge valve – a quarter-turn ball valve.

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[203] *See* Fortune valve [47].
[204] *See* Apollo valve [48].
[205] The post-incident position of at least a dozen valves appears to have been altered by the force of the explosion. As a result, these valve positions are not reliable evidence for evaluating pre-incident piping alignment.

171. As shown in Figure 52, an electrical power cable likely ejected from Trailer 182 (Figure 53) and entangled into the pump piping. This electrical cable may have pulled or pushed the valve handle towards the closed position during the explosion.

Figure 52. Post-incident photo of nitrous oxide transfer pumps. The orange oval shows the discharge valve that may have nearly closed during the explosion by the Trailer 182 power cable. The open position of this valve handle is towards the left and parallel to the piping. This is the same valve circled in yellow in Figure 51

Figure 53. Pre-incident photo of the black electrical cable located inside the equipment box located at the bottom and towards the rear of Trailer 182. This photo also shows an example of the flexible hose connections recommended by pump manufacturers and used by Airgas on trailer pumps.

172. If the quarter-turn ball valve was in the closed position just before the incident and slightly opened by explosion, the ACD nitrous oxide pump could still be the source of heat that triggered the explosive decomposition reaction. It is conceivable that as the operator was starting the pump he had difficulty establishing flow and shut the pump off after the decomposition reaction already initiated. The operator then could have closed the ball valve as part of the normal practice to fill the pump with liquid for re-cooling. During this short period, Trailer 182 could have exploded.

G. Inherently Safer Design and the Hierarchy of Controls

173. Although industry safety standards recognize the pump as the "primary hazard" during nitrous oxide transfer operations, transferring liquid nitrous oxide from a storage tank to a trailer truck does not require a pump. Inherently safer design could eliminate the transfer pump, such as operating the trailer truck at a lower pressure or increasing the elevation of the storage tank.

1. The Center for Chemical Process Safety (CCPS)

174. In 1985, the American Institute of Chemical Engineers (AIChE) established the Center for Chemical Process Safety (CCPS). The stated purpose of CCPS is "to establish a not-for-profit scientific and educational organization to provide expert leadership and focus to engineering practices and research that can prevent or mitigate catastrophic events involving hazardous materials."[206]

175. Air Liquide is a corporate member of CCPS.[207] CCPS states: "Any corporation, company, foundation, or partnership, located anywhere, having an interest in process safety may become a Member of CCPS through payment of annual dues to AIChE and through designation of a Technical Representative and a Financial Representative to CCPS."[208]

176. The CCPS book *Inherently Safer Chemical Processes – A Life Cycle Approach*,[209] defines inherently safer design as the process of identifying and implementing inherent safety in a specific context that is permanent and inseparable.

177. In the book *Guidelines for Engineering Design for Process Safety*,[210] CCPS states, "inherently safer design solutions eliminate or mitigate the hazard by using materials and process conditions that are less hazardous."[211]

178. Inherently safer technologies are relative; inherently safer technology requires comparing one technology with another with regard to a specific hazard or risk.[212] A technology may be inherently safer with respect to one risk but not safer from another risk. For this reason, it is important to carry out a comprehensive, documented hazard analysis to determine the individual and overall risks in a process in order to minimize the total risks of hazards presented.

179. An inherently safer systems review details a list of choices offering various degrees of inherently safer implementation. The review should include risks of personal injury, environmental harm, and lost production, as well as evaluating economic feasibility.

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[206] *See* purpose of CCPS [138].
[207] *See* CCPS corporate members [50].
[208] *See* CCPS membership qualification [138].
[209] *See* *Inherently Safer Chemical Processes – A Life Cycle Approach* [106].
[210] *See* *Guidelines for Engineering Design for Process Safety* [102].
[211] *Id.*, at Section 5.1.1.
[212] *See* [106], Section 2.2.

180. The CSB often refers to the hierarchy of controls as the appropriate approach for hazard mitigation and in making safety recommendations.[213] As shown in Figure 54, the hierarchy of controls is a method to provide effective risk reduction by applying, in order of robustness, inherently safer design, passive safeguards, active safeguards, and procedural safeguards.[214] This strategy promotes a tiered or hierarchical approach to risk management.

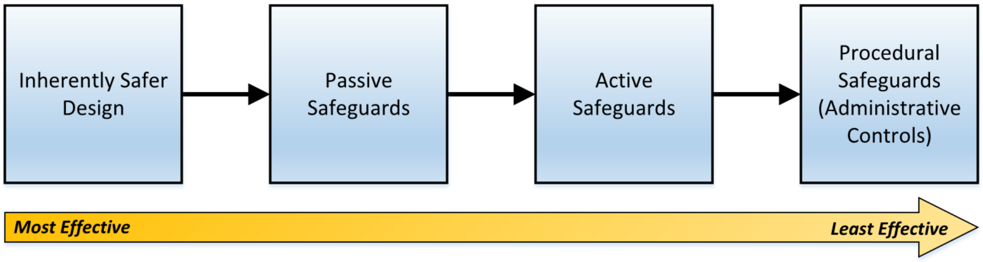

Figure 54. Hierarchy of Controls. The higher in the hierarchy (further to the left), the more effective the risk reduction achieved.

181. As shown in Figure 55, the hierarchy of controls is applicable to the effectiveness ranking of inherent safety principles used to control hazards. Again, the further up (to the left) the hierarchy, the more effective the risk reduction achieved. All concepts in the hierarchy of controls should be included in the process of risk assessment and reduction.

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[213] The CSB describes the concept of the "Hierarchy of Controls" in several previous investigation reports. See recent CSB final investigation reports for Williams - Geismar, Louisiana [236], Tesoro - Martinez, California [235], Tesoro - Anacortes, Washington [231], Chevron - Richmond, California [229], and Key Lessons for Preventing Incidents from Flammable Chemicals in Educational Demonstrations [233].

[214] *See* CCPS Book, *Inherently Safer Chemical Processes – A Life Cycle Approach* [106], Section 2.1.

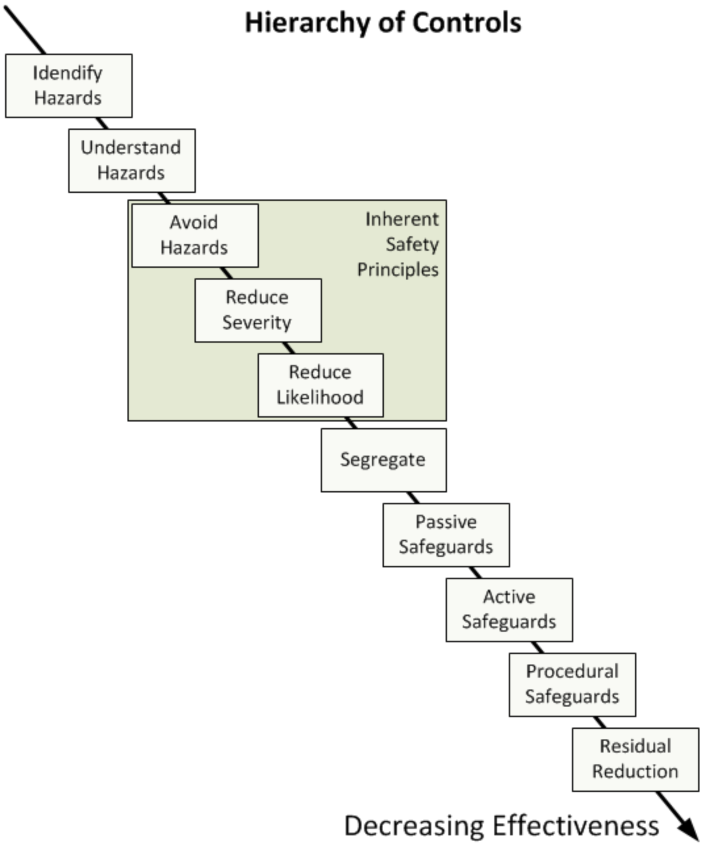

Figure 55. Inherent Safety Principles. The boxes reflect the hierarchy of safer controls from eliminating hazards near the top left through personal protective equipment at the bottom right.[215]

182. In its *Guidelines for Investigating Chemical Process Safety Incidents*, CCPS discusses the importance of evaluating inherently safer design when developing recommendations. CCPS states:

> Recommendations that lead to inherently safer designs are preferred to those limited to adding-on extra mitigation or prevention features. Inherently safer designs limit reliance on human performance, equipment reliability, or properly functioning preventive maintenance programs for successful prevention of an incident. Inherently safer design changes yield greater economic benefits if they are implemented during the early design phases. Nevertheless, the incident investigation team should consider them when developing recommendations.[216]

183. There may be opportunities to prevent future nitrous oxide decomposition explosions by applying inherently safer design and the hierarchy of controls. For example, increasing the elevation between the nitrous oxide storage tank and the truck loading station could eliminate the need for nitrous oxide transfer pumps. Alternatively, the trailer truck can vent to a lower pressure system to

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[215] *See* Process Plants: A Handbook for Inherently Safer Design [51].
[216] *See* Guidelines for Investigating Chemical Process Incidents [104], page 255.

provide the pressure difference needed between the storage tank and the trailer truck to eliminate the pump. These types of options require careful consideration and engineering, and would represent a significant change in nitrous oxide transfer operations, but such efforts could be worthwhile. Meanwhile, some efforts may not be that difficult to implement. For example, Airgas records indicate that international shipping containers already vent to a lower pressure system during loading because the shipping containers have different design conditions (temperature or pressure) than the storage tanks.[217]

2. Materials of Construction

184. Airgas filter and strainer metallurgy falls short of CGA requirements to use high nickel or high copper alloys.[218] Because degradation of equipment, including strainers, strainer baskets, and steel wool may have contributed to the incident, upgrading equipment material of construction could reduce the risk of future nitrous oxide explosions.

185. Airgas should evaluate and upgrade equipment metallurgy to minimize the presence of future contaminants and catalysts and reduce the risk of starting a nitrous oxide decomposition reaction.

3. Explosion Prevention Systems

186. The National Fire Protection Association (NFPA) publishes NFPA 69, *Standard on Explosion Prevention Systems*, to “provide effective deflagration prevention and control for enclosures where there is the potential for a deflagration.”[219]

187. NFPA 69 defines deflagration pressure containment as:

> The technique of specifying the design pressure of a vessel and its appurtenances so they are capable of withstanding the maximum pressures resulting from an internal deflagration.

188. By increasing the design pressure of the equipment involved in transferring and shipping nitrous oxide, in may be possible to contain a decomposition reaction.

189. Airgas should evaluate passive explosion prevention systems such as the protective methods established in NFPA 69, *Standard on Explosion Prevention Systems.*

4. Deflagration Venting

190. Although previous nitrous oxide explosions have killed and injured workers, Airgas did not evaluate safeguards such as a deflagration vent system to protect equipment like storage tanks and trailer trucks from catastrophic rupture.

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[217] Rather than venting back to the storage tank, shipping containers are vented to the inlet of a process compressor or to the atmosphere.

[218] High nickel and high copper materials are more resistant to corrosion and CGA states they are, “preferred due to increased resistance to oxidizer fires.” [150], Section 5.4.

[219] *See* free access to the 2014 edition of NFPA 69 at section 4.1 [52].

191. Figure 56 shows the general idea of using deflagration venting or explosion venting to prevent an uncontrolled explosion. The basic idea is that a vessel design can include a section that will preferentially fail to release the force of an explosion in lieu of an uncontrolled explosion. Alternatively, the vessel can be equipped with a safety device such as a panel that will burst open to relieve the pressure.

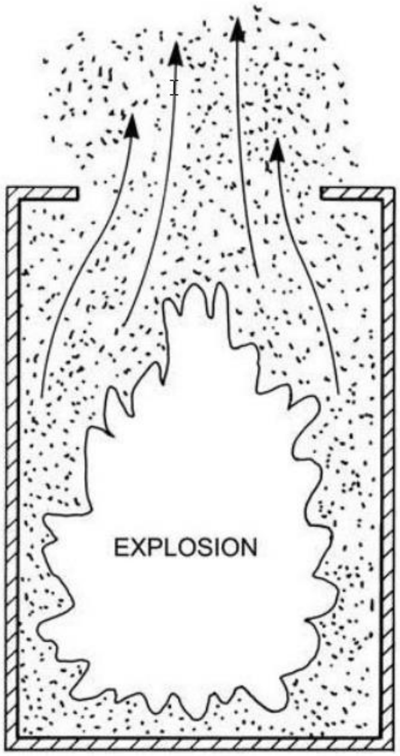

Figure 56. Explosion venting (deflagration venting) illustration.[220]

192. Safety guidance published by Scaled Composites in 2009 recognized the "very high" energy released from a nitrous oxide decomposition explosion in large vessels, such as a trailer truck.[221] The company's safety guidance recommended designing equipment to control and safely reduce this energy in a manner that avoided "catastrophic failure," such as deflagration venting.[222]

193. The National Fire Protection Association (NFPA) publishes NFPA 68, *Standard on Explosion Protection by Deflagration Venting*, to "provide effective deflagration venting for enclosures where there is the potential for a deflagration."[223]

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[220] *See Explosion Hazards in the Process Industries* [108], page 141.
[221] *See* Scaled Composites Nitrous Oxide Safety Guidelines [15].
[222] *Id*.
[223] *See* free access to the 2013 edition of NFPA 68 [53]).

194. NFPA 68 requires that “deflagration venting shall be arranged to avoid injury to personnel by the vent discharge.”[224]

195. Airgas should evaluate safeguards such as the protective methods established in NFPA 68, *Standard on Explosion Protection by Deflagration Venting*.

5. Protective Physical Barrier

196. Although the goal should be to prevent future nitrous oxide explosions, the history of nitrous oxide explosions indicates the nitrous oxide manufacturing industry has not attained this level of safety performance.

197. Blast walls are used in the offshore industry to ensure “escape and evacuation of personnel off the platform.”[225] Although the use of blast walls has been critiqued as a less robust safety approach than inherently safer design options,[226] it remains a viable secondary option that can protect workers from injury or death caused by explosions.

198. Similar to nitrous oxide, liquid oxygen pumps have been involved in significant process safety incidents such as “fire, explosion, dispersion of molten metal or metal fragments.”[227] Unlike nitrous oxide, however, industry safety standards for liquid oxygen pumps advise using “barriers or shields to protect personnel and equipment in the event of an incident,” such as an explosion.[228]

199. To protect workers, industry safety standards provide design requirements for barriers including:

> A barrier may be reinforced concrete or equivalent, low-carbon steel plate, or other suitable material. It shall be structurally designed to withstand the impact of projected parts or debris, jet of liquid, and possible flame impingement. The barrier should be dimensioned to protect personnel involved in the pump operation, in maintenance on adjacent equipment, or individuals working in or passing through what would be the pump hazard area.[229]

200. As part of its post-incident corrective actions and process hazard analysis, Airgas should evaluate potential use of physical barriers to protect workers from nitrous oxide explosions during transfer and loading operations.[230]

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[224] *Id.*, at Section 4.2.1.3.
[225] *See* Why Do We Still Have Blast Walls on Offshore Platforms? [54].
[226] *Id.*
[227] *See* AIGA 55/14: *Installation Guide For Stationary Electric-Motor Driven Centrifugal Liquid Oxygen Pumps* [215], Section 3.5.
[228] *Id.*, at Section 6.1.1.2.
[229] *Id.*, at Section 6.3.3.
[230] *See* Explosion and Blast Safety Systems [56].

V. Nitrous Oxide Industry Regulatory Analysis

A. CSB Reactive Hazards Study

1. In September 2002, the CSB unanimously approved Improving Reactive Hazard Management, a report covering a "two-year special CSB investigation into hazards at U.S. sites that manufacture, store, or use potentially reactive chemicals."[231]

2. The CSB's reactive hazards study noted that, "Uncontrolled reactions have led to serious explosions, fires, and toxic emissions. The impacts may be severe in terms of death and injury to people, damage to physical property, and effects on the environment."[232]

3. Former CSB Chair Carolyn Merritt said, "There have been many positive changes in chemical industry process safety since 1984, when the Bhopal nightmare occurred. But the CSB has found that accidents involving reactive chemicals still occur all too frequently and often with tragic results."[233, 234, 235]

4. In March 2003, former CSB Board Member Dr. Gerald Poje testified:

> Reactive hazards are the dangers associated with uncontrolled chemical reactions in industrial processes. These uncontrolled reactions - such as thermal runaways and chemical decompositions - have been responsible for numerous fires, explosions, and toxic gas releases. From 1980 … [to] 2001, 167 serious reactive accidents caused 108 fatalities in the U.S., according to the CSB's reactive hazards investigation.[236]

5. The CSB found that similar to nitrous oxide, "More than half of the accidents involved chemicals that are exempt from OSHA and EPA process safety rules."[237]

6. In September 2002, the Board recommended that OSHA amend its Process Safety Management (PSM) standard to protect workers more fully from reactive chemical hazards. The CSB directed a similar recommendation to the EPA, whose Risk Management Program (RMP) rule is designed to protect the public and the environment from chemical accidents.

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[231] *See* CSB news release [57].

[232] *See* CSB Hazard Study - Improving Reactive Hazard Management at page 1 [230].

[233] *See* CSB Safety Video: Reactive Hazards at 1:18 [228].

[234] "The 1984 toxic release in Bhopal, India, which caused several thousand known fatalities, resulted not only in the creation of the CSB but also in the first Federal regulations specifically designed to prevent major chemical accidents that threaten workers, the public, and the environment. One of these regulations is the OSHA PSM standard, which was adopted in 1992." See CSB Investigation Report: Tesoro Anacortes Refinery at page 85 [231].

[235] *Id*., at 0:12. Bhopal was a chemical reactives incident. The toxic release at Bhopal was the result of an exothermic chemical reaction between methyl isocyanate and water.

[236] *See* CSB news release [137].

[237] *Id*. Although OSHA or EPA rules may not have covered the specific chemical involved in these accidents, other chemicals in the process may have resulted in the process being covered by these Federal regulations.

7. The study also noted that:

> In 1992, OSHA promulgated its Process Safety Management (PSM) Standard (29 CFR 1910.119). The standard covers processes containing individually listed chemicals that present a range of hazards, including reactivity, as well as a class of flammable chemicals. Reactive chemicals were selected from an existing list of chemicals identified and rated by the National Fire Protection Association (NFPA) because of their instability rating of "3" or "4" (on a scale of 0 to 4).[238]

8. OSHA used NFPA 49–1975, Hazardous Chemicals Data to identify reactive chemicals.[239] NFPA 49–1975, Hazardous Chemicals Data does not list nitrous oxide as a hazardous or reactive chemical.[240]

9. The NFPA diamond identifies the reactivity of nitrous oxide as zero (0). (Figure 57)

Figure 57. NFPA Diamond for nitrous oxide.[241]

9. The CSB study concluded that, "Reactive incidents are a significant chemical safety problem,"[242] and that, "The OSHA PSM Standard has significant gaps in coverage of reactive hazards because it is based on a limited list of individual chemicals with inherently reactive properties."[243]

10. The CSB also concluded that, "NFPA instability ratings are insufficient as the sole basis for determining coverage of reactive hazards in the OSHA PSM Standard."[244]

11. As a result of the study, CSB recommended that OSHA, "Amend the Process Safety Management (PSM) Standard, 29 CFR 1910.119, to achieve more comprehensive control of reactive hazards that could have catastrophic consequences."[245] The CSB recommendation included language to

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[238] An NFPA instability rating of "4" means that materials in themselves are readily capable of detonation or explosive decomposition or explosive reaction at normal temperatures and pressures. A rating of "3" means that materials in themselves are capable of detonation or explosive decomposition or explosive reaction, but require a strong initiating source or must be heated under confinement before initiation. See CSB Hazard Study - Improving Reactive Hazard Management at page 2 [230].

[239] *Id.*, at page 49.

[240] *See* [59].

[241] *See* Airgas nitrous oxide Safety Data Sheet (SDS) at page 11 [58].

[242] *See* CSB Hazard Study - Improving Reactive Hazard Management at page 23 [230].

[243] *Id.*, at page 23.

[244] *Id.*, at page 23.

[245] *Id.*, at page 25.

"broaden coverage of hazards from self-reactive chemicals" to include chemicals such as nitrous oxide.[246] The status of this recommendation is Open – Unacceptable Response / No Response Received.[247, 248]

12. The CSB also recommended that OSHA, "Implement a program to define and record information on reactive incidents that OSHA investigates or requires to be investigated under OSHA regulations."[249] The status of this recommendation is Open – Unacceptable Response / No Response Received.[250]

13. The CSB hereby reiterates CSB Recommendation 2001-01-H-1 and CSB Recommendation 2001-01-H-2.[251] The CSB urges OSHA to reconsider its decision not to implement these recommendations.

B. EPA and OSHA

14. The CSB found that the major safety hazards associated with nitrous oxide manufacturing are not regulated by EPA RMP or OSHA PSM,[252] although there have been process safety incidents, "such as violent decomposition of nitrous oxide and the rupture of nitrous oxide tanks [that] have occurred at production, storage, and distribution facilities."[253]

15. The EPA RMP rule does not include nitrous oxide in its list of regulated substances.[254] In addition, the OSHA PSM standard does not cover nitrous oxide because the chemical is not included in OSHA's list of highly hazardous chemicals.[255]

16. In 1974, OSHA incorporated by reference the Compressed Gas Association (CGA) Pamphlet G-8.1-1964, *Standard for the Installation of Nitrous Oxide Systems at Customer Sites*.[256] Under 29 C.F.R. § 1910.105, OSHA regulates the piped systems for the in-plant transfer and distribution of nitrous oxide. OSHA requires companies to design, install, maintain, and operate these systems to

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[246] *See* CSB Hazard Study - Improving Reactive Hazard Management at page 23 [230].

[247] *See* CSB Recommendation 2001-01-H-1 Status [234]

[248] *See* CSB Status Designation Explanation [136]. Open - Unacceptable Response/No Response Received (O - UR) means that a response to the recommendation has not been received within 270 days of issuance or the recipient responds by expressing disagreement with the need outlined in the recommendation. The Board believes, however, that further dialogue or advocacy may persuade the recipient to act.

[249] *See* CSB Hazard Study - Improving Reactive Hazard Management at page 26 [230].

[250] *See* CSB Recommendation 2001-01-H-2 Status [234].

[251] *See* CSB Recommendation 2001-01-H-1 and 2001-01-H-2 Status [234].

[252] Airgas stated that their nitrous oxide process is not covered by RMP or PSM. OSHA communicated to the CSB investigation team that they conducted a review of the PSM regulation and agree that the air gas nitrous oxide process is not covered by the PSM regulation.

[253] *See* [150], Section 1.

[254] *See* EPA List of Regulated Substances under the RMP [129].

[255] *See* OSHA List of Highly Hazardous Chemicals [125].

[256] 29 C.F.R. § 1910.105. See OSHA 1910.105 [124].

the 1964 version of CGA G-8.1.[257] This standard, however, "does not apply to nitrous oxide manufacturing plants."[258]

17. OSHA did not adopt CGA G-8.3 because the standard did not exist when Congress authorized the Secretary of Labor to adopt national consensus standards without going through the normal rulemaking process.[259]

18. Although OSHA maintains records for previous U.S. nitrous oxide incidents,[260] records for the 1980 Richmond incident are not available in its database.[261] That State of California also, maintains investigation records, but Cal/OSHA informed the CSB that it only maintains records for seven years, and thus the records for the two nitrous oxide explosions in California are no longer available.[262]

C. FDA

19. As nitrous oxide has use as a drug, the U.S. Food & Drug Administration (FDA) regulates its manufacture. Nitrous oxide medical applications include use as a sedative or a method of controlling pain, primarily in dental procedures. FDA regulations, however, focus on product quality, and touch upon safety of patients who are administered nitrous oxide. As a result, Airgas management systems focused on product quality, as well as patient safety, but Airgas focused little attention on process safety.

20. Airgas Process Validation policy explains, "Nitrous Oxide is commonly used as an anesthetic gas for medical procedures. As such, its production and use is regulated by the U.S. FDA."[263]

21. The company policy further clarifies its adherence to FDA guidance that, "Process validation is a requirement of the Current Good Manufacturing Practices Regulations for Finished Pharmaceuticals, 21 CFR Parts 210 and 211, and of the Good Manufacturing Practice [GMP] Regulations for Medical Devices, 21 CFR Part 820, and therefore, is applicable to the manufacture of pharmaceuticals and medical devices."[264]

22. As part of process validation, companies need to evaluate worst-case conditions. According to guidance published by FDA, the worst-case conditions are, "A set of conditions encompassing upper and lower processing limits and circumstances, including those within standard operating

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[257] *Id.*
[258] *See* [146], Section 2.
[259] *See* Updating OSHA Standards Based on National Consensus Standards [135].
[260] *See* OSHA Nitrous Oxide Incidents [126] and Scaled Composites citations [221].
[261] OSHA fatality and catastrophe investigation summaries are not available for incidents that occurred before 1984. See Fatality and Catastrophe Investigation Summaries [222].
[262] Although Cal/OSHA was not able to provide the CSB with investigation records because the agency only retains them for seven years, the website knightsarrow.com provides a link to its copy of the Cal/OSHA Scaled Composites investigation file: Cal/OSHA Investigation File - Scaled Composites Explosion, [117]. The CSB did not identify public records for the 1980 Richmond, California incident, but obtained a copy of the Puritan-Bennett investigation report from Airgas.
[263] 21 C.F.R. Parts 210 and 211.
[264] Airgas used the 1987 FDA guidance Guideline on General Principles of Process Validation (1987) at Section III [127]. The FDA issued a 2011 update to this guidance. See Guideline on General Principles of Process Validation (2011) [223].

procedures, which pose the greatest chance of process or product failure when compared to ideal conditions. Such conditions do not necessarily induce product or process failure."[265]

23. The Process Validation policy also describes the process Airgas used to establish worst-case conditions. The policy states:

> The Worst Case Conditions were identified and assessed through Failure Mode and Effects Analysis (FMEA). We chose the FMEA format provided by the Compressed Gas Association (CGA) in publication P-B.2 2003; Guideline for Validation of Air Separation Unit and Cargo Tank Filling for Oxygen USP and Nitrogen NF; Third Edition.[266]

24. Airgas performs a failure mode and effects analysis (FMEA) as part of its process validation program, but this analysis did not identify or assess the potential for nitrous oxide decomposition reactions, nor did it evaluate the effectiveness of safeguards to prevent nitrous oxide decomposition hazards, such as the loading pump run-dry safety interlock.

25. Although companies could use a FMEA analysis to identify, evaluate, and control process safety hazards, the FMEA conducted by Airgas focused on product quality and consumer safety. In describing how the company conducted the FMEA, an Airgas manager explained to CSB investigators that the FMEA analysis was "conducted with an eye towards medical quality as opposed to safety."

VI. Air Liquide and Airgas Organizational Analysis

1. Because Airgas management systems did not adequately focus on process safety, each of the following contributed to the Cantonment explosion:

- Airgas never performed a hazard analysis to identify and control process safety hazards;
- Airgas made changes to the nitrous oxide transfer process by selecting a new pump that made an explosion more likely;
- Safeguards implemented by Airgas intended to prevent an explosion, including flame arrestors and safety interlocks were not effective; and
- Airgas management did not observe established industry safety standards and good practices, nor did Airgas embrace its own lessons learned from past incidents – whether at its own sites or at sites that eventually came under the same corporate umbrella following a history of mergers and acquisitions that

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[265] *Id.*, at Definitions.

[266] The U.S. Pharmacopeial Convention (USP) "sets standards for the identity, strength, quality, and purity of medicines, food ingredients, and dietary supplements manufactured, distributed and consumed worldwide." See USP [60]. "The FDA defines process validation as follows: Process validation is establishing documented evidence which provides a high degree of assurance that a specific process will consistently produce a product meeting its pre-determined specifications and quality characteristics." See Guideline on General Principles of Process Validation (1987) at Section IV [127].

most recently concluded with the Air Liquide acquisition of Airgas in 2016. A more effective program aimed at capturing and acting on relevant lessons learned could have provided protection from an explosive nitrous oxide decomposition reaction.

A. Air Liquide (Airgas) Knowledge of Nitrous Oxide Decomposition Hazards

2. At the time of the August 28, 2016 incident, as the owner of all nitrous oxide manufacturing operations in the United States and Canada, Air Liquide had technical knowledge of the explosive hazards with nitrous oxide decomposition.

3. An Air Liquide technical expert developed and presented best practices to prevent nitrous oxide pump incidents at a CGA conference in 2013. This presentation reviewed the decomposition chemistry, identified the past incidents and their causes, described best approaches to run-dry pump interlock strategies, and suggested further industry changes demonstrating a high degree of knowledge with respect to nitrous oxide and related technologies.[267]

4. The company investigated the 2012 explosion in Moncada, Spain, stemming from its operations in that country, and appears to have developed important findings and corrective actions.

5. Air Liquide operated the Richmond, California facility since 2001 and company personnel were knowledgeable about the 1980 incident and lessons learned.

6. Air Liquide was also knowledgeable about the 2001 explosion in Eindhoven, the Netherlands. An Air Liquide nitrous oxide technical expert included the Eindhoven incident in his presentation at a CGA conference in 2013.

7. In addition, Airgas technical staff helped write the CGA G-8.3 industry safety standard, *Safe Practices for Storage and Handling of Nitrous Oxide*.

8. Although Air Liquide knew how to prevent a nitrous oxide explosion, there were gaps in safety knowledge and an overall lack of focus on safety management systems to control these process safety hazards remained at Cantonment, even after Air Liquide acquired Airgas.

B. Gaps in Air Liquide (Airgas) Nitrous Oxide Safety Knowledge

9. Airgas maintained files on previous incidents and nitrous oxide decomposition studies. While these files contained information on most of the previous nitrous oxide explosion incidents, the Airgas files lacked important safety information on the 2007 Scaled Composites explosion.

10. The Airgas files showed that company personnel tried to learn about the details of the Scaled Composites incident in July 2008. Although Airgas supplied nitrous oxide to the Scaled

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[267] *See* [161].

Composites space program,[268] neither the government nor Scaled Composites provided copies of their investigation reports to Airgas.

11. Notably missing from the Airgas files on previous incidents, however, are the nitrous oxide safety guidelines that Scaled Composites publicly issued in July 2009.[269]

12. Furthermore, no records provided by Airgas to the CSB indicate the company ever considered or developed a program to follow important recommendations in the Scaled Composites safety guidelines, such as:

    - Test for ignition sources, including friction, static discharge, or impact;
    - Ensure no component could exceed a temperature of 571 °F;
    - Evaluate compatibility of elastomers, plastics, metals, and lubricants;
    - Remove all incompatible materials from a nitrous oxide flow path;
    - Eliminate all corrosion prone metals from nitrous oxide flow path or storage; and
    - Design pressure vessels, such as storage tanks or trailers, to provide a controlled vent during an overpressure event, to prevent a catastrophic vessel failure.[270]

13. In 2003, CCPS published, *Essential Practices for Managing Chemical Reactivity Hazards*, an industry consensus guidance document specifically aimed at protecting workers and the public from uncontrolled chemical reactions, such as the decomposition of nitrous oxide.[271] CCPS states that managing chemical reactivity hazards is not a "one-time" activity.[272] Rather, effective management of reactivity hazards requires a continual management commitment to protect against the potential consequence of chemical reactivity incidents.[273] Such a commitment includes an on-going effort to learn and incorporate key lessons from other major accidents. In addition, CCPS provided specific guidance to address reactivity hazards within a company's safety management system.[274]

C. Process Safety Management

14. Reactive hazards, such as nitrous oxide decomposition, require an effective safety management system to prevent major accidents. Because neither the EPA nor OSHA regulate nitrous oxide manufacturing, process safety management systems are not legally required for nitrous oxide manufacturing. If the chemical were subject to heightened regulatory standards, then

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[268] *See* Airgas Helps Fuel SpaceShipOne [142].
[269] *See* Scaled Composites Nitrous Oxide Safety Guidelines [15].
[270] *Id.*
[271] *See* Essential Practices for Managing Chemical Reactivity Hazards at page viii [100].
[272] *Id.*, at page 17.
[273] *Id.*, at page 17.
[274] *Id.*, at page 65.

manufacturers would be responsible for implementing a number of process safety tools that would improve the process safety performance of the industry.

15. As a result of its investigation, and in the absence of enhanced regulatory coverage, the CSB is recommending that the U.S. nitrous oxide manufacturing companies, Airgas and Matheson,[275] work together with the CGA to develop and implement a safety management system to manage process safety hazards, including nitrous oxide decomposition hazards of nitrous oxide manufacturing in the United States. Some of these tools are discussed below.

16. In OSHA 3132, *Process Safety Management*, OSHA defined "The Problem" of major accidents in the U.S. chemical manufacturing industry, which that agency attempted to address through its Process Safety Management (PSM) regulation. OSHA stated:

> Unexpected releases of toxic, reactive, or flammable liquids and gases in processes involving highly hazardous chemicals have been reported for many years. Incidents continue to occur in various industries that use highly hazardous chemicals which may be toxic, reactive, flammable, or explosive, or may exhibit a combination of these properties. Regardless of the industry that uses these highly hazardous chemicals, there is a potential for an accidental release any time they are not properly controlled. This, in turn, creates the possibility of disaster.[276]

17. In addition, OSHA publication 3133, *Process Safety Management Guidelines for Compliance*, described process safety management as "the proactive identification, evaluation and mitigation or prevention of chemical releases that could occur as a result of failures in process, procedures or equipment."[277]

18. More recently, in its 2016 publication *Guidelines for Implementing Process Safety Management*, CCPS described the current state of PSM and the global adoption of management systems to control process safety hazards. CCPS stated:

> Companies have been implementing process safety management (PSM) systems for over 25 years. A variety of PSM structures have been used - some based upon regulatory requirements and many more based upon evolving industry good practices. These PSM systems are designed to manage the hazards and risks associated with processes using hazardous chemicals or energy. Management of these aspects requires a PSM system to focus on nurturing the performance of equipment and people throughout the life cycle of their deployment in a facility. The adoption of PSM

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[275] Matheson is the current owner of the nitrous oxide manufacturing facilities in Richmond, California and Donora, Pennsylvania.

[276] *See* OSHA Publication 3132, *Process Safety Management* (2000) [132].

[277] *See* OSHA Publication 3133, *Process Safety Management Guidelines for Compliance (1994)* [131].

> systems has gone global, offering many new opportunities to improve upon implementation practices of the past.[278]

19. Despite the global adoption of process safety management systems recognized by industry safety leaders, however, the CSB investigation of the August 28, 2016 Airgas incident revealed that, although not required, the company's lack of a process safety management system to identify, evaluate, and control hazards led to the explosion. The contributing causes of the explosion that killed the Airgas employee all stemmed from the company's lack of an effective overall process safety management system.

1. Airgas Process Safety Policy

20. Airgas developed a "Process Safety" policy for the Cantonment facility. The policy does address some key aspects of process safety including requirements for inspection of safety devices. The policy states, "All process safety items such as relief valves, pressure and temperature switches, etc. must be periodically inspected and tested to ensure their proper functioning." The policy also addresses potential changes to safety devices, stating, "No change shall be made to the plant which in any way will eliminate, circumvent or compromise a process safety device."

21. Although Airgas does not use management of change terminology in the Process Safety policy, the policy does address changes to alarm and shutdown set points. The policy states, "… alarm and shutdown set points shall not be changed prior to consulting the plant manager." The policy also prohibits equipment changes without approval, stating, "Maintenance and repair must be limited to the replacement with like components unless cleared through the plant manager."

22. The remainder of the Airgas process safety policy focuses on major process hazards and contains significant coverage of nitrous oxide decomposition. The policy states, "Pure nitrous oxide is a stable compound when at the temperatures and pressures normally encountered in the field. However, given the right combination of temperature and pressure, nitrous oxide can be made to decompose; possibly explosively."

23. As shown in Figure 58, the Airgas process safety policy explains nitrous oxide explosion limits. According to Airgas, at the pressure used to transfer liquid nitrous oxide from the storage tanks to a trailer, boiling water (212 °F) is hot enough to start an explosion.

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[278] *See* *Guidelines for Implementing Process Safety Management* [103], Introduction.

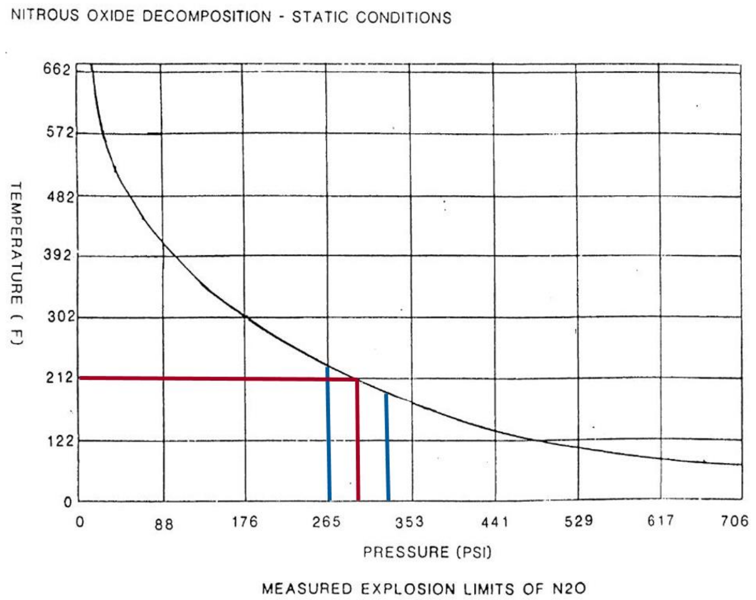

Figure 58. Airgas nitrous oxide explosion limits. This chart is from the Airgas process safety policy and shows the pressure and temperature conditions necessary for an explosive nitrous oxide decomposition reaction. According to this chart, at the normal pressure of the nitrous oxide transfer pumps, boiling water is hot enough to start an explosion. Recall that the ACD pump pressure ranges from 265 to 330 psia (blue lines). The average pressure is roughly 300 psia and corresponds to a decomposition temperature of 212 °F (red lines).

24. The policy states:

> "Two events must take place for a nitrous oxide decomposition to occur at our plants:
>
> a. The temperature/pressure combination must be suitable to support decomposition.
> b. An ignition source must be provided to initiate, or start the decomposition.
>
> Each of the following has been reported to initiate a nitrous oxide decomposition:
>
> Open Flames
> Hot Surfaces
> Electric Arcs
> Rapid Gas Compression
> Mechanically or Statically-Produced Sparks
> Presence of Combustible Materials
> Exothermic Chemical Reactions"[279]

25. The Airgas process safety policy emphasizes the importance of avoiding sources of heat; stating:

> "… Never weld on a line containing nitrous oxide. Blow the line out with air prior to welding. Repair defective mechanical components such as compressor valves and pump seals promptly. When not operating properly, these devices can generate a great deal of heat. Pressurize

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[279] An exothermic chemical reaction produces heat.

> nitrous oxide pressure vessels slowly. Rapid pressurization will generate a great deal of heat." (Emphasis in the original.)

26. The policy also discusses contaminants that can "enhance the potential for decomposition" stating:

> Examples of these impurities include combustible materials such as hydrogen and hydrocarbons. In addition, nitrous oxide decomposition may occur more readily upon exposure to combustible solids such as activated carbon. Given these facts, it is important that combustibles be kept out of the process stream when possible. For example, do not use excessive pipe sealant or install new piping sections without removing any oil left from machining, etc. In those cases when it is not possible to eliminate the combustible material from the gas stream, special care must be taken in pressurizing vessels, performing maintenance, etc.

27. The Airgas process safety policy then discusses each section of the process where the process temperature and pressure are capable of starting a decomposition of nitrous oxide. Despite the long history of industry explosions during liquid nitrous oxide transfer operations, however, Airgas did not identify the trailer truck loading operation as an area where an explosive nitrous oxide decomposition reaction could occur.

2. Trailer Loading Procedure

28. Although Airgas did not identify the potential for nitrous oxide decomposition during trailer loading in its process safety policy, the company did identify the hazard in its trailer loading procedure. In the company's procedure, designed "to transfer nitrous oxide from plant storage tanks to bulk trailers for shipping," Airgas detailed the steps to prepare for trailer loading. These steps included checks to ensure the trailer is ready to be loaded, hooking up the liquid and vapor hoses, purging the connections to remove air, and equalizing the storage tank vapor space with the trailer vapor space to ensure the two tanks are at approximately the same pressure.

29. Next, the loading procedure instructed the operator to "Open the proper pump suction valve." To fill the pump with liquid (prime the pump), the procedures states: "Open pump bleed valve. When liquid has flooded the pump suction, the pump is cold and the discharge line is frosted. Liquid will come out of the pump bleed valve."

30. Before the step instructing the operator to start the pump, the procedure cautions the operator that if the pump runs dry an explosion could occur.

> **CAUTION: ENSURE PUMP IS PRIMED PRIOR TO STARTING THE PUMP. IF THE PUMP IS RUN DRY AND HEATS TO A TEMPERATURE THAT PROVIDES SUFFICIENT ENERGY TO DECOMPOSE NITROUS OXIDE AN EXPLOSION COULD OCCUR.** (Bold and all caps in original.)

31. Although the company recognized the potential for an explosive nitrous oxide decomposition, Airgas provided no effective safeguards and simply instructed the operators to stop the pump if there was a "marked change in sound level."[280] After starting the pump, the procedure instructs the operator to monitor the change in pump sound level. The procedure states:

> **IMPORTANT: IF THERE IS A MARKED CHANGE IN THE SOUND LEVEL OF THE PUMP, STOP THE PUMP IMMEDIATELY. DRY OPERATION OR CAVITATION IN THE PUMP COULD CAUSE THIS. THIS MAY OCCUR IF THE STORAGE TANK RUNS EMPTY OR THE INLET PIPING BECOMES BLOCKED OR OBSTRUCTED.** (Bold and all caps in original.)

32. Rather than applying the hierarchy of controls and inherently safer design that could eliminate the pump, Airgas required the operator to be physically present and listen to the pump in order to prevent a nitrous oxide explosion.

3. Airgas and Air Liquide Process Hazard Analysis

33. Recommending that Air Liquide perform a hazard analysis for its operations at Cantonment, before resuming production of nitrous oxide, is not enough to ensure safe facility operation. Although not subject to Federal process safety management regulations, Air Liquide did conduct hazard reviews of the Richmond and Donora nitrous oxide manufacturing processes. The CSB evaluated these hazard reviews and found similar problems in those PHAs that were found in – and contributed to – the Cantonment explosion. These problems include:

- Similar to the ineffective run-dry interlock at Cantonment, at Richmond and Donora, critical safety interlocks did not conform with industry safety standards, such as ISA-84;
- At Richmond and Donora, Air Liquide used a strainer as a flame arrestor, which failed at Cantonment; and
- For Richmond and Donora, Air Liquide understated the consequences of a nitrous oxide explosion during trailer loading, and those facilities likely need additional safeguards.

a) Hazard Analysis Guidance

34. OSHA safety guidance is important to protect workers even for chemical manufacturing processes that OSHA does not regulate with its Process Safety Management (PSM) rule, such as nitrous oxide. In OSHA's Publication 3132, introduced above, the agency highlighted the importance of a process hazard analysis and explained the basic concept. OSHA stated:

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[280] Cavitation in a pump refers to the formation of vapor bubbles when the liquid pressure falls below its vapor pressure. See water pump cavitation video [237].

> The key provision of PSM is process hazard analysis (PHA)—a careful review of what could go wrong and what safeguards must be implemented to prevent releases of hazardous chemicals.[281]

35. In its *Guidelines for Risk Based Process Safety*, CCPS describes the fundamental concept of hazard analysis. The CCPS guidance states:

> Hazard Identification and Risk Analysis (HIRA) is a collective term that encompasses all activities involved in identifying hazards and evaluating risk at facilities, throughout their life cycle, to make certain that risks to employees, the public, or the environment are consistently controlled within the organization's risk tolerance. These studies typically address three main risk questions to a level of detail commensurate with analysis objectives, life cycle stage, available information, and resources. The three main risk questions are:
>
> - Hazard - What can go wrong?
> - Consequences - How bad could it be?
> - Likelihood - How often might it happen?[282]

b) Lack of Hazard Analysis of Cantonment Process

36. Although nitrous oxide manufacturing at Cantonment began in 1982, none of the companies who owned and operated the plant ever performed a hazard analysis of the process. Neither applicable good practice industry standards nor government regulations required performing a formal process hazard analysis at the Airgas facility in Cantonment. Nevertheless, good process safety practice includes performing a rigorous hazard analysis in the circumstances presented.

37. Puritan-Bennett owned the Richmond nitrous oxide manufacturing plant at the time the company started construction of the Cantonment facility; however, the Cantonment process design did not implement important lessons learned from the 1980 nitrous oxide explosion at the Richmond facility. These lessons include:

- Provide at least five feet of liquid above the pump to ensure an adequate liquid supply to the pump;
- Use both a strainer and a metallic flame arrestor on each side (inlet and outlet) of the pump;
- Install a safety interlock to shut the pump motor off when there is low motor load (power consumption); and

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[281] *See* OSHA Publication 3132, *Process Safety Management* (2000) [132].
[282] *See* *Guidelines for Risk Based Process Safety* at Section 9 [105].

- Construct piping to circulate liquid back to the storage tank during initial starting and cool down of the pump.

38. Air Liquide owned and operated the Cantonment facility for three months before the August 28, 2016 incident. Although likely required by applicable Air Liquide policies, which Air Liquide did not share with the CSB, the company did not complete or develop a plan to perform a process hazard analysis on the nitrous oxide manufacturing operations at the Cantonment, Florida facility.

c) Air Liquide Process Hazard Reviews at Richmond and Donora

39. Air Liquide performed an analysis of process safety hazards for the Richmond, California and Donora, Pennsylvania nitrous oxide manufacturing facilities, which the company owned since 2001. Even if Air Liquide conducted a similar hazard analysis for the nitrous oxide transfer and trailer truck loading operations at Cantonment, the company may not have prevented the August 28, 2016 incident. Reasons supporting this conclusion include:

- Air Liquide hazard analyses for its Richmond, California and Donora, Pennsylvania facilities show similar risks for a nitrous oxide explosion during trailer loading as the Cantonment facility;
- Although Richmond and Donora did have run-dry safety interlocks that may meet CGA standards, neither site employed ISA-84;
- At Richmond and Donora, Air Liquide used a strainer as a flame arrestor, which failed at Cantonment;
- Despite the 1980 explosion at Richmond, the Air Liquide hazard reviews for both Richmond and Donora understated the consequences of a nitrous oxide explosion during trailer loading, and each facility likely needs additional safeguards.

40. As part of the CSB's investigation into the Cantonment incident and before Air Liquide divested the Richmond and Donora facilities to Matheson, the agency requested Air Liquide safety information for all of its nitrous oxide manufacturing facilities. Although the company allowed CSB investigators to review recent process hazard analyses for the Richmond and Donora facilities, Air Liquide declined to cooperate and failed to allow the CSB to retain this important safety information for additional analysis. This information could have aided the CSB's mission by providing a better understanding of nitrous oxide safety hazards in order to make more effective safety recommendations to protect both workers and the public.[283]

41. CSB's review of these safety records focused primarily on hazards associated with loading operations – specifically, transferring liquid nitrous oxide from a storage tank to a trailer truck.

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[283] Air Liquide uses the name Accident Risk Assessment (ARA) for its hazard review.

42. Air Liquide process hazard analysis records listed safeguards to protect against an explosive nitrous oxide decomposition reaction. These safeguards include:

- Use pumps certified for liquid nitrous oxide;
- Low speed pumps are preferred;
- The pump mounting and piping must be free of stress;
- The [pump] motor must be protected against overloads; and
- Install an automatic shutoff that allows the pump to operate only after it has been properly cooled down and filled with liquid to prevent cavitation.[284]

43. Similar to the Cantonment facility, the Richmond and Donora hazard review documents revealed that these sites also considered the automatic pump shutoff as a safety device. Like at Cantonment, Air Liquide does not consider these critical safety devices to be safety instrumented functions and the facilities did not appear to apply the industry standard – ISA-84 – to the design of these critical safety systems. As a result, by applying important industry safety standards like ISA-84 to the Richmond and Donora sites, these facilities can likely reduce the risk of a nitrous oxide explosion.

44. At Richmond and Donora, Air Liquide also used strainers as flame arrestors. Air Liquide filled these strainers with stainless steel mesh. Because the hazard analysis indicates no risk reduction credit for these devices – they were not considered safeguards – it is unlikely that the company conducted testing of these strainers to ensure they can stop a nitrous oxide decomposition reaction.

45. For Richmond and Donora, Air Liquide used a risk matrix to evaluate process hazards to ensure that available safeguards drive risk down to appropriate company risk targets. Evaluation of these risk assessments revealed that both facilities considered the potential consequence of an explosion resulting from overheating the nitrous oxide pump to be a severity-level 3 event – serious damage to the facility with the potential for injury. As such, Air Liquide concluded having an automatic pump shutoff device adequately controlled the risk of this hazard, despite the pump shutoff not meeting the ISA-84 industry safety standard.

46. Air Liquide considers a severity-level 4 consequence event as a "major accident" with the potential for multiple fatalities and massive facility destruction. This higher severity category more appropriately aligns with past nitrous oxide decomposition incidents that caused major damage and could have killed multiple workers. In its 1980 investigation report for the Richmond incident, the explosion damage was so extensive that Puritan-Bennett described the lack of physical harm to the operator as a miracle.[285]

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[284] Information provided by Air Liquide did not include the type of nitrous oxide pump used. The CSB does not know how the Richmond and Donora sites modified their process to address phasing out the Smith gear pumps. At Cantonment, Airgas used centrifugal pumps that operated at roughly twice the speed as the Smith pump with 20 percent more flow.

[285] *See* [20] at page 18.

47. Before the Cantonment incident, Air Liquide's nitrous oxide explosion in Moncada, Spain was the most recent similar tragedy. Consistent with a severity-level 4 consequence, the Moncada explosion killed one worker and injured five others.[286] In light of the facts of the current incident, including the death of the only Airgas employee on-site and the total loss of the Airgas Cantonment facility, a severity-level 4 is likely a more accurate categorization, rather than a severity-level 3.

48. By applying a severity-level 4 consequence to potential explosive nitrous oxide decomposition hazards in company hazard analyses, Air Liquide likely needed additional safeguards to achieve company risk targets. These additional layers-of-protection, which Air Liquide lacked, could have driven risk lower and reduced the potential for a major nitrous oxide explosion.

49. In its *Guidelines for Risk Based Process Safety*, CCPS describes the importance of performing a hazard analysis. The CCPS guidance states:

> To manage risk, hazards must first be identified, and then the risks should be evaluated and determined to be tolerable or not. The earlier in the life cycle that effective risk analysis is performed, the more cost effective the future safe operation of the process or activity is likely to be. The risk understanding developed from these studies forms the basis for establishing most of the other process safety management activities undertaken by the facility. An incorrect perception of risk at any point could lead to either inefficient use of limited resources or unknowing acceptance of risks exceeding the true tolerance of the company or the community.

50. Airgas should develop and implement a program to ensure the company conducts a hazard analysis of its nitrous oxide manufacturing business using good practice guidance, such as the CCPS *Guidelines for Risk Based Process Safety*. This program should ensure an appropriate evaluation of potential consequences and require inherently safer design where feasible. In addition, the hierarchy of controls should guide safeguard selection when establishing recommendations to lower the risk of process safety hazards.

4. Management of Change

51. In its *Guidelines for Risk Based Process Safety*, CCPS discusses the importance of performing a safety review of proposed process modifications. The CCPS guidance states:

> If a proposed modification is made to a hazardous process without appropriate review, the risk of a process safety accident could increase significantly.[287]

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[286] *See* Spain News Article [123]. Note – use Google Chrome for an English translation.

[287] *See* *Guidelines for Risk Based Process Safety* at Section 15.1.2 [105].

52. In its process safety management standard, OSHA stated: "[C]ontemplated changes to a process must be thoroughly evaluated to fully assess their impact on employee safety and health and to determine needed changes to operating procedures."[288]

53. To comply with Federal FDA rules for Good Manufacturing Practices, Airgas developed a management of change (MOC) program. This program, however, only focuses on changes that could affect product quality and *does not* attempt to evaluate or control process safety hazards, such as nitrous oxide decomposition.

54. CGA G-8.3–2016 addresses the need to perform a management of change and a risk assessment for equipment modifications. The standard states:

> Modifications to a nitrous oxide installation or nonroutine maintenance work shall not be made without a risk assessment, which could result in a management of change and requirement for a work permit [...].[289] (Emphasis removed from original.)

55. When the company needed to find a replacement nitrous oxide transfer pump, it did not perform a management of change review to identify and control process safety hazards. Despite the Airgas MOC program requirements that include performing a review when "addition or removal of equipment" changes are proposed, the company did not perform such a review when the Cryostar or ACD pumps were purchased, installed, or operated.

56. When compared to the Smith pump that was in service for more than 30 years, the Cryostar and ACD pumps introduced changes that could increase the risk of an explosion from a nitrous oxide decomposition reaction. These changes included:

- A twenty percent increase in the flow rate, which increases the risk of dry run conditions;
- Doubling of the pump speed, which can increase the heating rate of pump components in dry run conditions;
- Increase in liquid pressure required (NPSH)[290] to the pump, which can affect pump reliability and increase the risk of dry run conditions; and
- Introducing a new y-strainer design using a less robust strainer basket and in addition, creating an unknown pressure drop[291] which could also increase the risk of dry run conditions.

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[288] *See* OSHA Publication 3132, *Process Safety Management* (2000) [132].

[289] *See* [150], Section 5.10.

[290] Pump manufacturers express the required inlet liquid pressure as feet of net positive suction head (NPSH).

[291] While strainer manufacturers provide pressure drop information for an empty strainer, no manufacturer provides this information for a strainer "completely packed" with steel wool. Neither the amount or grade of steel wool used nor the packing method is controlled and Airgas never measured the pressure drop. As a result, the pressure drop across the steel wool-packed y-strainer remains unknown, but is likely substantial.

57. To prevent nitrous oxide explosions, Airgas should develop and implement a program to ensure that the company conducts a robust management of change and risk assessment for its nitrous oxide manufacturing business using good practice guidance, such as the CCPS *Guidelines for Risk Based Process Safety*.

5. Industry Standards

58. Airgas management did not implement important aspects of industry safety standards, despite the fact that chemical industry good practice guidance clearly states the need to maintain knowledge and conformance with such standards to maintain a safe facility.

59. Although Airgas participated in the development of the CGA G-8.3 safety standard, the company is not following important aspects of the standard, including:

- Designing equipment so that nitrous oxide is not released into the work environment from venting (CGA G-8.3–2016, Section 4.4.3);
- Using strainers constructed from high nickel or copper alloys (CGA G-8.3–2016, Section 5.4);
- Preventing metallic particles from being present in nitrous oxide equipment (CGA G-8.3–2016, Section 5.5);
- Verifying that equipment is bonded and electrically grounded to prevent static electricity from initiating a nitrous oxide decomposition reaction (CGA G-8.3–2016, Section 5.7, 6.1.3, 7.3.4, and 8.2);
- Preventing heating of equipment above 300 °F by all practical means (CGA G-8.3–2016, Section 5.7);
- Providing automatic controls to protect equipment from operating at excessive temperatures (CGA G-8.3–2016, Section 5.7);
- Performing management of change and risk assessments on process modifications (CGA G-8.3–2016, Section 5.10);
- Providing an interlock to ensure proper liquid filling and pump cooling before the pump can start (CGA G-8.3–2016, Section 7.4.3);
- Preventing pumps from operating if they lose prime (CGA G-8.3–2016, Section 5.7);
- Using a pump suction filter with as “little pressure drop as possible” (CGA G-8.3–2016, Section 7.4.1);
- Verifying that pump inlet pressure (NPSH)[292] meets manufacturer requirements (CGA G-8.3–2016, Section 8.2); and

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[292] Pump manufacturers express the required inlet liquid pressure as feet of net positive suction head (NPSH).

- Monitoring pump outlet pressure to ensure the pump operates within specified conditions (CGA G-8.3–2016, Section 8.2).

60. In its *Guidelines for Risk Based Process Safety*, CCPS discusses the importance of having a program to stay current with industry standards. The CCPS guidance states:

> Knowledge of and conformance to standards helps a company (1) operate and maintain a safe facility, (2) consistently implement process safety practices, and (3) minimize legal liability. Changes in standards may occur at irregular intervals or on a fixed schedule, and the standards system must keep up with such changes so the company can adjust its compliance activities. The standards system also forms the basis for the standards of care used in an audit program to determine management system conformance.[293]

61. As previously described, OSHA identifies ISA-84 as recognized and generally accepted good engineering practice. Airgas management acknowledged to CSB investigators that the company does not follow ISA-84. As a result, the company's run-dry safety interlock intended to protect workers and the public from nitrous oxide decomposition hazards proved ineffective.

62. Airgas should develop and implement a program to ensure the company identifies and applies relevant industry safety standards to its nitrous oxide manufacturing business using good practice guidance, such as the CCPS *Guidelines for Risk Based Process Safety*.

6. Process Safety Information

63. CCPS defines Process Safety Information (PSI) as:

> Physical, chemical, and toxicological information related to the chemicals, process, and equipment. It is used to document the configuration of a process, its characteristics, its limitations, and as data for process hazard analyses.[294, 295]

64. OSHA explains the importance of Process Safety Information in its PSM guidance publication. OSHA states:

> Complete and accurate written information concerning process chemicals, process technology, and process equipment is essential to an effective process safety management program and to a process hazard analysis.[296]

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[293] *See* *Guidelines for Risk Based Process Safety* at Section 4 [105].
[294] *See* *CCPS Guidelines for Implementing Process Safety Management* [103].
[295] *Id.*, at Glossary.
[296] *See* *OSHA Publication 3133, Process Safety Management Guidelines for Compliance (1994)* [131].

65. For example, for covered processes, OSHA requires companies to have Process Safety Information on the equipment in the process. Among other things, this information must include:

- Materials of construction;
- Piping and instrument diagrams (P&IDs);
- Relief system design and design basis; and
- Safety systems, such as interlocks.[297]

66. At Airgas, although not a federally regulated process, the CSB found this critical safety information was either lacking or not maintained, despite the clear dangers presented by nitrous oxide and the importance of maintaining, updating, and relying on this critical safety-related information.

67. The company's safety information for critical components, such as y-strainers and steel wool intended to stop nitrous oxide decomposition, does not identify the materials of construction.

68. Although the company developed piping and instrument diagrams for the process, Airgas does not maintain the accuracy of these engineering documents. For example, Airgas never added the second nitrous oxide pump information when the company installed the Cryostar pump, nor when the ACD pump replaced the Cryostar pump.

69. In addition, Airgas piping and instrument diagrams do not identify important safety instruments, such as the scale indication used by operators to determine when the storage tanks contained enough nitrous oxide inventory to begin loading a trailer truck.

70. No Airgas engineering documents detail the run-dry safety interlock configuration, nor do they illustrate or explain how the company modified this interlock when Airgas installed the Cryostar or ACD pumps.

71. Furthermore, Airgas lacks documentation for the relief valve design and design basis for the relief valves on the discharge of the Smith and ACD pumps.

72. Effective management of chemical reactivity hazards, such as nitrous oxide decomposition, requires extensive process knowledge – complete and accurate process safety information.[298] Airgas should evaluate which of its nitrous oxide engineering and safety documents contain essential process safety information and develop a comprehensive information management system to ensure this documentation is available, accurate, and maintained.

7. Need for Additional Technical Personnel

73. Airgas did not have any technical personnel located at the Cantonment facility. The CSB's investigation of the August 28, 2016, explosion at Cantonment revealed many problems that stem from a lack of technical personnel. More technical, engineering-focused staff at the facility, on a

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[297] *See* OSHA Publication 3132, *Process Safety Management* (2000) [132].

[298] *See* *Guidelines for Risk Based Process Safety* at Section 8.1.2 [105].

more consistent basis, providing support and other resources for the site while developing greater familiarity with all facility processes, equipment, and operations for the technical personnel, could have addressed or at least alleviated numerous problems, including:

- Many examples of not following the industry safety standard CGA G-8.3 (see Industry Standards, paragraph 59);
- Not applying ISA-84 to safety instrumented functions (interlocks);
- Not evaluating or applying the publicly available safety recommendations issued by Scaled Composites in 2009 (see Gaps in Air Liquide (Airgas) Nitrous Oxide Safety Knowledge, paragraph 11);
- Reliance on equipment manufacturers to perform pump system engineering;
- Providing incorrect process data to pump manufacturers;
- Not following pump manufacturer recommendations;
- Lack of a preventive maintenance program for nitrous oxide pumps;
- Not ensuring an adequate minimum storage tank level;
- Having no automatic process control for trailer truck loading;
- Lack of an electrical bonding and grounding program to ensure trailer truck loading safety;
- Not identifying the nitrous oxide loading pumps, flame arrestors, and run-dry interlock as critical equipment;
- Lack of an inspection program for nitrous oxide flame arrestors;
- Putting workers at risk when testing the run-dry safety interlock;
- Using a potentially incompatible O-ring in a nitrous oxide relief valve;
- Not having a design basis for safety relief valves; and
- Allowing block valves to isolate relief devices in situations that do not adhere to industry safety standard requirements.

74. To ensure the effective management of chemical reactivity hazards, CCPS industry consensus guidance advises companies to ensure that technical resources are readily available to identify chemical reactivity hazards, acquire needed data, assess risk, and develop safeguards.[299]

a) Relief Device Isolation Not Allowed by Industry Safety Standard

75. The American Petroleum Institute (API) is an industry trade association that develops standards and recommended practices for the oil and natural gas industry.[300] These publications apply to chemical

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[299] *See Essential Practices for Managing Chemical Reactivity Hazards* at Chapter 4 [100].
[300] See API Web Site [167].

facilities, including the Airgas facility in Cantonment, Florida. At the time of the, the sixth edition (2014) of the API Standard 521, *Pressure-Relieving and Depressuring Systems* (“API 521-2014”) was the recognized and generally accepted good engineering practice (RAGAGEP) for pressure relieving and disposal systems.

76. The Smith nitrous oxide transfer pump is a positive displacement pump that can generate high pressure. API 521-2014 states:

> The inadvertent closure of a valve on the outlet of pressure equipment while the equipment is on stream can expose the equipment to a pressure that exceeds the MAWP [maximum allowable working pressure]. Every valve (i.e. manual, control, or remotely operated) should be considered as being subject to inadvertent operation. If closure of an outlet valve can result in pressure in excess of that allowed by the design code, a PRD [pressure relief device] is required.[301]

77. As shown in Figure 59, Airgas installed an isolation block valve on the discharge of the Smith pump. The inadvertent closure of this valve can expose this equipment to pressure that exceeds the maximum allowable pressure. The relief valve on the Smith pump discharge piping, however, is located downstream of the isolation block valve and thus may not be available to protect the equipment as required by API 521-2014.

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[301] *See* [218], Section 4.4.2.1.

Figure 59. Photo of the Smith nitrous oxide pump discharge piping. From the outlet of this positive displacement pump, there is an isolation block valve upstream of the relief valve. As a result, the equipment may not be adequately protected from a scenario where this isolation valve was inadvertently closed while operating the pump.

b) Use of Teflon Gaskets

78. The ACD pump manual specifies the appropriate gaskets as "either bonded fiber type or spiral wound metallic type." ACD specifically prohibits the use of polytetrafluoroethylene (Teflon) sheet gaskets in its pump manual. The ACD pump manual states "Do not use sheet TFE [tetrafluoroethylene] or PTFE [polytetrafluoroethylene] as gasket material since they exhibit high creep [deformation] rates."[302] Nevertheless, Airgas used Teflon gaskets in ACD pump flanges, despite ACD's prohibition on use. Moreover, Airgas did not perform an engineering analysis to evaluate the use of Teflon sheet gaskets in its nitrous oxide loading equipment.

79. As seen in Figure 60, the Teflon gasket appears to exhibits telltale signs of creep, with the left-center portion stretched and thinned, because of the material being under pressure, and then deforming the gasket, developing a tear.

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[302] *See* Chemours information about Teflon [61]. Creep is a time dependent deformation process.

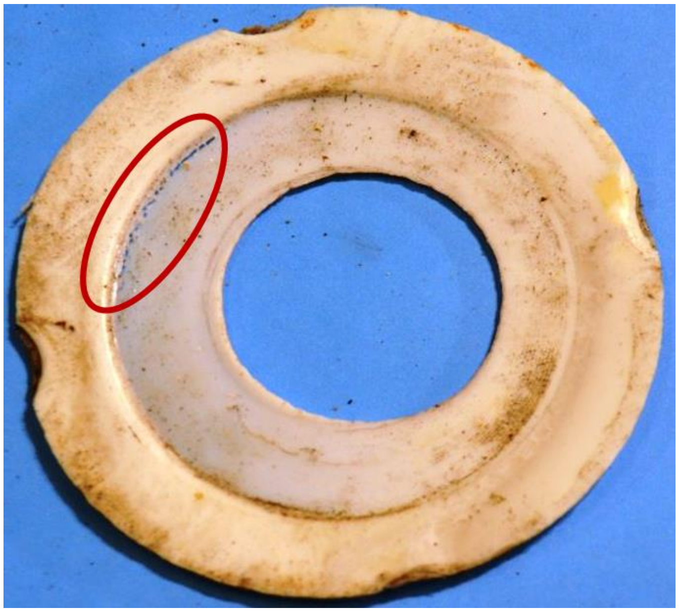

Figure 60. A Teflon gasket used by Airgas to seal nitrous oxide loading equipment connections. This gasket was installed on the discharge of the ACD pump. Creep (deformation) likely developed a tear in the gasket seen here where the blue background is visible between the 9 and 11 o'clock positions.

c) Management Oversight

80. Airgas management could have prevented or remedied such problems by supplementing its workforce, with additional technical staff and by expanding the responsibilities of technically oriented corporate safety staff with additional time spent on the ground auditing, inspecting, and evaluating nitrous oxide facilities and operations, including Cantonment.[303]

81. Even the plant manager at Cantonment likely would have benefited from additional technical resources. He started with Airgas as an operator, a position he held for a year, until transitioning to maintenance for a number of years, when Airgas promoted him to plant manager. In his role, the plant manager appeared to have no specialized technical training relating to nitrous oxide, other than what he learned by working at the Cantonment facility. If Airgas had provided adequate training on how to conduct certain operations safely at the facility, the plant manager and other staff at Cantonment would have learned how to do things in accordance with Airgas policy and procedure, but may not have necessarily understood *why* things should be done in a certain way.[304]

82. Furthermore, in this position, the plant manager reported to the general manager of the company, a chemical engineer by trade and training, who works in the Kansas City area. The plant manager

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[303] These type of issues are reminiscent of the Esso gas plant explosion in Longford, Australia, where technical, engineering focused resources at the plant were lacking, and causal to this highly publicized industrial incident. Six years before to the incident, Esso chose to relocate its engineering workforce from onsite at Longford to Melbourne, where engineers provided support to the operators from a distance, but only when operators felt the need to contact them by telephone for help. In *Lessons from Longford*, Professor Andrew Hopkins describes the effect of this absence of technical support on the ground saying: "Perhaps predictably, these arrangements did not work effectively, and … the absence of engineering expertise had certain long-term consequences which contributed to the accident." [62], page 34.

[304] *See* *Lessons from Esso's Gas Plant Explosion at Longford* [149].

consulted with his manager at least weekly, and often daily, but usually by telephone. The general manager also only visited the site one to three times per year, including a mandatory annual safety meeting.

83. In this context, some responsibility for providing additional technical support could fall to the Airgas corporate safety function. The annual safety audit, however, conducted by a corporate Airgas safety official, lacked a process safety focus. This annual safety audit did not require her to delve into deeper aspects of the site's safety systems; rather, through a question and answer model, corporate practices required her to evaluate compliance with existing company policies. The Airgas audit program did not challenge the status quo with respect to existing, and in some cases long-standing, process safety issues.

84. Airgas should strengthen technical staffing to ensure nitrous oxide processing hazards are appropriately identified, evaluated, managed, and controlled. Furthermore, the company should enhance its auditing practices as part of a long-term process safety management system.

8. Industry Process Safety Management Guidance

85. CCPS defines process safety as:

> A disciplined framework for managing the integrity of operating systems and processes handling hazardous substances by applying good design principles, engineering, and operating practices. It deals with the prevention and control of incidents that have the potential to release hazardous materials or energy. Such incidents can cause toxic effects, fire, or explosion and could ultimately result in serious injuries, property damage, lost production, and environmental impact.[305]

86. The CCPS approach to Process Safety Management (PSM) is based on four pillars:

1. Commit to process safety
2. Understand hazards and risk
3. Manage risk
4. Learn from experience[306]

87. CCPS states that these four pillars "… reflect 15 years of PSM implementation experience and well-established best practices from a variety of industries."[307]

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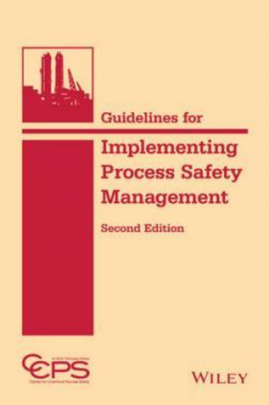
[305] *See* *CCPS Guidelines for Implementing Process Safety Management* [103], Glossary.
[306] *See* Four Pillars of Process Safety Management [122].
[307] *See* *Guidelines for Implementing Process Safety Management* [103], Preface.

88. Although these four PSM pillars are well established, the CSB investigation of this incident revealed that they are lacking at Airgas. Airgas has significant safety gaps in the operational areas represented by these four pillars, which must be addressed to improve safety.

a) Guidelines to Implementing Process Safety Management

89. In June 2016, CCPS released a new edition of its Guidelines to Implementing Process Safety Management.[308]



90. The *goal* of these guidelines is "Ensuring that people can return home healthy and uninjured at the end of each workday, ensuring that our neighbors are unharmed, and having a safe work environment have driven many companies to pursue PSM implementation with the objective of having zero incidents."[309] CCPS states: "It is that goal for which this guideline was developed - to help companies pursue and achieve the 'perfect process safety' vision of zero harm."[310]

91. The *primary purpose* of these guidelines is to:

> [P]rovide an update to the original Guidelines for Implementing Process Safety Management Systems, recognizing that most companies now have some form of PSM system, but that a number of companies, especially smaller companies or those in developing countries, may need a road map of how to efficiently and effectively upgrade their systems.[311]

92. By effectively applying the CCPS *Guidelines to Implementing Process Safety Management*, Airgas can develop a program to manage nitrous oxide decomposition hazards and prevent future nitrous oxide explosions.

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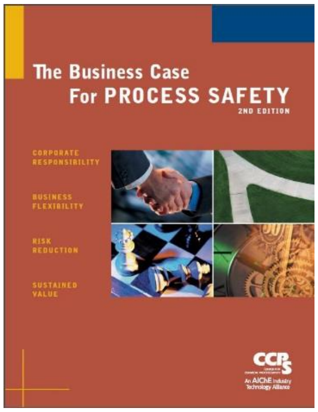
[308] *Id.*
[309] *Id.*, at Section 1.
[310] *Id.*, at Section 1.
[311] *Id.*, at Section 1.

b) The Business Case for Process Safety

93. In 2006, CCPS published a seminal work outlining the results of a study called *The Business Case for Process Safety*.[312] In that study, CCPS asserts that a hallmark of its member companies is that each "have adopted a rigorous philosophy regarding process safety."[313]



94. CCPS argues that the lessons of this study will help any business in four key measures of business performance: corporate responsibility, risk reduction, business flexibility and sustained value, and that good process safety practices amounts to good business. In particular, with respect to risk reduction, CCPS notes:

> Process safety provides unparalleled capacity for enhanced risk reduction. Your company's risk exposure is reduced in the following areas when well-founded process safety systems are in place.
>
> ■**Lives are saved and injuries are reduced** — Both the personal impact of human loss and cost of deaths or injuries are painful. A solid process safety program can help prevent these costs.
>
> ■**Property damage costs are reduced** — In the U.S., major industrial incidents cost an average of $80 million each.
>
> ■**Business interruptions are reduced** — These losses can amount to four times the cost of the property damage from an incident.
>
> ■**Loss of market share is reduced** — After an incident, this loss continues until the company's reputation is restored. Adverse publicity and negative public image can have insurmountable effects.
>
> ■**Litigation costs are reduced** — These are unavoidable after an incident and can total five times the cost of the regulatory fines.

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[312] *See* The Business Case for Process Safety [63].
[313] *Id*., at page 3.

■**Incident investigation costs are reduced —** Investigating an incident and implementing corrective actions can cost millions of dollars.

■**Regulatory penalties are reduced —** For many incidents, a fine after litigation can total 1 million dollars or more.

■**Regulatory attention is reduced —** A major incident usually results in increased regulatory audits and inspections.[314]

95. As a corporate member of CCPS, Air Liquide should implement a robust process safety program following the CCPS *Guidelines for Implementing Process Safety Management* for its nitrous oxide business to manage nitrous oxide decomposition hazards and prevent future nitrous oxide explosions.

VII. Industry Safety Management System Standard

1. As noted above, the CSB reiterates the importance of its two previous recommendations issued to OSHA with respect to reactive chemical hazards. The Airgas incident, however, revealed another reactive chemical safety gap that exists within the nitrous oxide industry. In this instance, however, the CSB concludes that this existing gap may be better addressed outside of a regulatory change. Specifically, the CSB recommends that the nitrous oxide industry, through the Compressed Gas Association and that organization’s member companies, develop its own process safety management system standard to manage and control nitrous oxide decomposition hazards and prevent explosions. This recommendation is similar to the approach taken by the National Transportation Safety Board’s efforts to encourage relevant industry stakeholders, led by the American Petroleum Institute, to develop a process safety management standard for the pipeline industry in that agency’s investigation of the Enbridge Pipeline rupture, which followed at least one other significant pipeline accident in San Bruno, California.[315, 316]

2. The CSB is recommending that the nitrous oxide industry should develop its own process safety management system standard to manage and control nitrous oxide decomposition hazards and prevent explosions.

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[314] *Id*., at page 8.

[315] *See* NTSB Investigation of Enbridge Pipeline Rupture at page 117 [110]. On July 25, 2010, a segment of a 30-inch-diameter pipeline, owned and operated by Enbridge Incorporated (Enbridge) ruptured in a wetland in Marshall, Michigan. The rupture released nearly 850,000 gallons of crude oil. The oil saturated the surrounding wetlands and flowed into the Talmadge Creek and the Kalamazoo River. Local residents self-evacuated from their houses, and the spill negatively affected the environment. Cleanup efforts exceeded $767 million. About 320 people reported symptoms consistent with crude oil exposure, though the spill cased no fatalities.

[316] *See* NTSB Investigation of San Bruno Pipeline Rupture and Fire [64]. On September 9, 2010, a 30-inch-diameter segment of an intrastate natural gas transmission pipeline known as Line 132, owned and operated by the Pacific Gas and Electric Company, ruptured in a residential area in San Bruno, California. The rupture released an estimated 47.6 million standard cubic feet of natural gas. The released natural gas ignited, resulting in a fire that destroyed 38 homes and damaged 70. Eight people were killed, many were injured, and many more were evacuated from the area.

A. NTSB Investigation of Enbridge Pipeline Rupture

3. In July 2012, the National Transportation Safety Board (NTSB) completed its investigation of the July 25, 2010, Enbridge Inc. pipeline rupture in Marshall, Michigan.

4. In its report, the NTSB concluded, "that pipeline safety would be enhanced if pipeline companies implemented SMSs [safety management systems]."[317]

5. The NTSB stated:

> The evidence from [the Enbridge] accident and from the San Bruno accident indicates that company oversight of pipeline control center management and operator performance was deficient. In both cases, pipeline ruptures were inadequately identified and delays in identifying and responding to the leaks exacerbated the consequences of the initial pipeline ruptures.[318, 319]

6. The NTSB found that Enbridge management systems did not focus on pipeline operations. For example, the company considered control center errors to be caused by employees rather than as system deficiencies, contrary to safety management system guidelines. The NTSB concluded:

> Had the company implemented and maintained a comprehensive SMS, it would have focused not only on field operations safety, but also would have incorporated control center operations, pipeline integrity management, and [post-accident] response plans and a comprehensive continuous examination of the safety of pipeline operations.[320]

7. The NTSB identified API as the appropriate group to drive positive safety change through the development of a safety management system standard for the pipeline industry, rather than recommending Federal rulemaking by a regulator. The NTSB stated:

> Because of the improvements to safety that accrue from the use of a comprehensive SMS, the NTSB recommends that the API facilitate the development of an SMS standard specific to the pipeline industry that is similar in scope to the API's RP 750, Management of Process Hazards. The development should follow established American National Standards Institute requirements for standard development.[321]

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[317] *See* NTSB Investigation of Enbridge Pipeline Rupture at page 117 [110].

[318] *Id*., at page 117.

[319] *See* NTSB Investigation of San Bruno Pipeline Rupture and Fire [64].

[320] *See* NTSB Investigation of Enbridge Pipeline Rupture at page 115 [110].

[321] *Id*., at page 117.

8. As the result of an NTSB safety recommendation, the American Petroleum Institute (API) developed API Recommended Practice 1173, *Pipeline Safety Management Systems* (API RP 1173), which could serve as a model for the nitrous oxide industry.[322]

9. Among the stated goals of API RP 1173 is to:

> [P]rovide pipeline operators with a framework to review an existing PSMS [pipeline safety management system] or develop and implement a new PSMS. Newly developing or improving a PSMS will enhance effectiveness of risk management and enable continual improvement of pipeline safety performance. The framework builds upon an operator's existing pipeline safety management programs by drawing upon industry experiences, lessons learned, and existing standards. The intent of the framework is to comprehensively define managerial elements that can identify, manage and reduce risk throughout the entirety of a pipeline's lifecycle and, at the earliest stage, help prevent or mitigate the consequences of an unintended release or abnormal operations.
>
> Particular emphasis is placed on increased proactivity, thinking of what can go wrong in a systemic manner, clarifying safety responsibilities throughout the pipeline operator's organization (including contractor support), the important role of senior management and leadership at all levels, encouraging the non-punitive reporting of and response to safety concerns, and providing safety assurance by regularly evaluating operations to identify and address risks. These factors work together to make safety programs and processes more effective, comprehensive, and integrated.[323]

10. In a press release announcing the development of API RP 1173, the NTSB lauded:

> API formed a multi-stakeholder group including oil and gas pipeline operator personnel and trade association staff, other federal and state agency personnel, and safety experts representing the public. The group met monthly, surveyed the public and created an important framework for the pipeline industry's goal of continuous safety improvement.[324]

11. In doing so, API exceeded the NTSB's recommendation in a positive fashion, going beyond merely facilitating the development of a safety management system standard specific to the pipeline industry, but also addressed safety culture and other safety-related issues in the new recommended practice.[325]

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[322] API issued the first edition of API 1173 in July 2015 to address the 2012 NTSB safety recommendation. See API RP 1173 [219].

[323] *See* API RP 1173 at page x [219].

[324] *See* NTSB Press Release on API 1173 [65].

[325] *Id.*

12. In an address to the American Gas Association, NTSB Chairman Christopher Hart further explained the NTSB's view about the success and strength of API RP 1173:

> We generally endeavor in our recommendations to set the bar pretty high and encourage "stretch" thinking, so very rarely do recommendation recipients exceed what we recommend. Thus, I am pleased to report that when API issued RP 1173, we closed our recommendation as 'exceeds recommended action.'[326]

13. All told, the NTSB achieved a great success with respect to the development and publication of this particular API standard. The CSB would like to model the NTSB's success in this matter with the broad-based development and publication of a new CGA standard, similarly focused, though rooted in CCPS guidance (which the CSB finds more rigorous) than in API 750.[327]

B. Need for Process Safety Management System Standard

14. With respect to reactive chemical hazards, such as explosive nitrous oxide decomposition, former CSB Chair Carolyn Merritt stated, "Much progress has been made in chemical process safety since the Bhopal accident in 1984, but deaths and injuries continue to occur from uncontrolled chemical reactions and significant gaps remain in Federal regulations and industry programs to control reactive hazards. It's time to redouble our efforts to prevent these tragedies."[328]

15. A history of devastating and preventable accidents that caused several fatalities and injuries, as well as significant property damage, demonstrates that nitrous oxide reactive hazards are a real and recurring issue, both in the United States and around the world.

16. The evidence from the history of nitrous oxide explosions indicates that company oversight of nitrous oxide reactivity hazards has been and remains deficient. Nitrous oxide manufacturing should benefit from an industry-specific standard or recommended practice focused on the creation of robust safety management systems in the same fashion that API RP 1173 served the needs of the pipeline industry in the aftermath of the Enbridge pipeline disaster.[329]

17. Therefore, the CSB concludes that implementing a robust safety management system for nitrous oxide manufacturing would enhance safety.

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[326] *See* NTSB Chairman Christopher Hart Keynote Speech [66].

[327] Although API exceeded the NTSB's recommendation in developing API 1173, API modeled this standard using API 750, which the CSB previously analyzed as not being as rigorous as the approach recommended by CCPS. In its Macondo investigation report, the CSB identified that the API approach contains fewer management elements than the CCPS approach. Although the management systems used by API are important, the CSB stated, "[T]hey fall short of the more rigorous approach taken by the Center for Chemical Process Safety (CCPS), which details additional elements that include process safety culture, management review and continual improvement, workforce involvement, and measurement and metrics." See CSB's Macondo Investigation Report - Volume 4 at page 20 [232].

[328] *See* CSB Safety Video: Reactive Hazards at 19:25 [228].

[329] *See* PHMSA Presentation on API RP 1173 Implementation [67].

18. In its 2007 *Guidelines for Risk Based Process Safety*, CCPS noted using a "management system approach to process safety management" was widespread.[330] CCPS also stated:

> Using the same high-intensity practices to manage every hazard is an inefficient use of scarce resources. A risk-based approach reduces the potential for assigning an undue amount of resources to managing lower-risk activities, thereby freeing up resources for tasks that address higher-risk activities.[331]

19. By following a risk-based approach to managing process safety, CCPS concluded that companies will be encouraged to:

- Evolve their approach to accident prevention from a compliance-based to a risk-based strategy.
- Continuously improve management system effectiveness.
- Employ process safety management for non-regulatory processes using risk-based design principles.
- Integrate the process safety business case into an organization's business processes.
- Focus their resources on higher risk activities.[332]

20. In its *Essential Practices for Managing Chemical Reactivity Hazards*, CCPS provides guidance for developing management systems that focus on the "less-obvious nature of chemical reactivity hazards" needed to prevent reactive incidents, such as nitrous oxide explosions.[333]

21. The CGA facilitates the development and maintenance of consensus standards for the nitrous oxide manufacturing industry in the U.S. and Canada. To prevent future nitrous oxide explosions in the U.S., the CSB recommends that the CGA facilitate the development of a robust safety management system standard applicable to nitrous oxide manufacturing with the goal of preventing future nitrous oxide explosions. The development should build upon the CCPS management system model and follow established American National Standards Institute requirements for standard development.

VIII. Air Liquide Post-Incident Actions

1. In the months following the August 28, 2016 incident, Airgas began a safety review of its nitrous oxide production facilities, trucking fleet, and cylinder-filling operations. The company has provided the CSB with periodic updates on the status of its safety initiative and has agreed to

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[330] *See* Guidelines for Risk Based Process Safety at Section 8.1.2 [105], Section 1.
[331] *Id*., at Section 1.
[332] *Id*., at Section 1.
[333] *See* *Essential Practices for Managing Chemical Reactivity Hazards* at Chapter 2 [100].

complete the initiative and address the findings described in this report for its facilities in the United States and Canada. The scope of the initiative is shown in Table 1.

Table 1. Air Liquide Post-Incident Actions

Topic	Current Status
Safety Management System	• Committed to applying a process safety management system for the nitrous oxide business; • Applying additional resources to existing facilities and rebuild of Cantonment; and • Will apply the hierarchy of controls throughout including hazard reviews, management of change, and corrective actions.
Inherently Safer Design	• Gathering requirements and resources to conduct design review; • Developing plan to train key personnel; • Receiving proposals from inherently safer design safety experts; • Plan includes development of an ongoing inherently safety design component to be used in future hazard reviews; and • Commitment to implement inherently safer design where feasible (practicable).
Hazard Analysis	• Complete for Yazoo City and Maitland; • Increasing the basis for a nitrous oxide decomposition explosion consequence to a severity-level in the criticality matrix 4; • Will apply the hierarchy of controls; • Developing safeguard design and availability philosophy; and • Planning to transition to HAZOP and LOPA.[334]

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[334] *See* HAZOP, Hazard and Operability Study and LOPA, Layer of Protection Analysis, [159].

Topic	Current Status
Apply Lessons from Previous Incidents	• Developing plan to use a corporate communication process; and • Will finalize after company investigation of Cantonment incident is complete.
Apply Industry Safety Standards	• Completed gap analysis of CGA G-8.3–2016; • Implementing plan to close gaps at Yazoo City and Maitland; • Developing plan to evaluate ISA-84; • Will incorporate ISA-84 approach in new HAZOP reviews; • Plan developed to train key personnel on safety instrumented systems; and • Adding industry safety standards to an existing program that monitors regulatory updates and changes.
Management of Change	• Implemented an MOC program to nitrous oxide plants (complete).
Contamination	• Developing engineering standard to address material of construction; • Currently testing contamination effect on nitrous oxide decomposition; • Testing program includes lubricants, refrigerants, metals, and metal oxides; • Plan to incorporate testing results into process safety information; and • Commitment to share summary of results with the Compressed Gas Association.
Process Safety Information (PSI)	• Plan developed to apply PSM/RMP program for process safety information to nitrous oxide business.

Topic	Current Status
Technical Staffing	• Assigned an interim subject matter expert to provide additional technical support; • Developing plans and assignments for additional technical subject matter experts; • Obtained approval for additional technical staff resource to focus on process safety; and • Developing an audit tool to ensure long-term commitment to sufficient technical staffing.
Hourly Staffing	• Short term increases in current staffing levels to two operators per shift and will conduct safety review to determine long-term staffing levels and scheduling of tasks in order to improve safe operations; and • Updating training program for operators and drivers.
Audit Program	• Applying Air Liquide audit program; and • Developing a plan to review audit design.
Safety Interlock Testing	• Developing a plan to conduct a safety review of interlock testing all interlock testing procedures; and • Developing a plan to require a safety review of interlock testing procedures for new or modified safety interlocks.
Run-Dry Safety Interlock	• Completed review of run-dry protection systems; • Conducting full engineering assessment to document technical specifications and finalize engineering solution; • Installing redundant systems with independent instrumentation on all nitrous oxide pumps; and • Improvements at other sites for the ground pumps that at similar to pumps at Cantonment (complete).

Topic	Current Status
Transfer Pumps	• Conducting engineering review; • Developing a plan to ensure pump systems meet NPSH guidelines; • Maintaining additional level in some tanks as an interim safety measure; • Developing a plan to have a standard pump and pump design; • Evaluating additional instrumentation through hazard analysis and ISA-84 process; and • Developing a plan for comprehensive electrical grounding and bonding systems.
Flame Arrestors	• Conducted literature review; • Developed preliminary prototype designs; • Developing plan for a comprehensive testing program; • Planning to develop engineering standard, specifications, and written preventive maintenance plan; • Planning to add to critical equipment list; • Planning to develop specific audit tool for periodic evaluation; and • Commitment to share summary of testing results and engineering specification with the Compressed Gas Association.
Operations	• Reviewing pressure relief valve discharge locations; • Reviewing relief valve design; • Reviewing preventive and predictive maintenance; • Developing a plan for engineering modifications to reduce employee exposure to nitrous oxide.
Electrical Grounding	• Developing a program to ensure electrical continuity for tanks and trailers.

IX. Recommendations

Reiterated Recommendations

In September 2002, the CSB unanimously approved Improving Reactive Hazard Management, a report covering a special CSB investigation into hazards at U.S. sites that manufacture, store, or use potentially reactive chemicals, such as nitrous oxide.

As a result of the study, CSB recommended that OSHA, amend its Process Safety Management (PSM) Standard, 29 CFR 1910.119, to achieve more comprehensive control of reactive hazards that could have catastrophic consequences. The CSB recommendation included language to broaden coverage of hazards from self-reactive chemicals to include chemicals such as nitrous oxide. The CSB also recommended that OSHA, implement a program to define and record information on reactive incidents that OSHA investigates or requires to be investigated under OSHA regulations.

The CSB hereby reiterates these important safety recommendations and urges OSHA to reconsider its decision not to implement these recommendations.

New Recommendations

According to its statutory authority under 42 U.S.C. § 7412(r)(6)(C)(i) and (ii), and in the interest of promoting safer manufacturing operations at U.S. facilities handling chemicals, and to protect workers and communities from nitrous oxide explosion hazards, the CSB makes the following safety recommendations:

A. Air Liquide

2016-04-I-FL-R1

1. Complete Post-Incident Actions and Process Safety Initiatives for Nitrous Oxide Operations

The goal of 2016-04-I-FL-R1 is to prevent all nitrous oxide explosions at its facilities, while preventing harm to workers and the public.

Following the August 28, 2016, incident, the company began a comprehensive initiative to review its nitrous oxide production facilities, trucking fleet, and cylinder-filling operations. The scope of the ongoing Air Liquide initiative is shown in Table 1.

Complete the development and implementation of the company's nitrous oxide business process safety initiative as shown in Table 1, consistent with the findings, conclusions, and recommendations contained in this report.

B. The Compressed Gas Association (CGA)

2016-04-I-FL-R2

1. Safety Management System for Nitrous Oxide Manufacturing

Develop and implement a safety management system standard for nitrous oxide manufacturing, to manage known process safety hazards, including nitrous oxide decomposition, which includes appropriate elements based on chemical industry good practice guidance, such as CCPS *Guidelines for Risk Based Process Safety*, *Essential Practices for Managing Chemical Reactivity Hazards*, and *Guidelines for Implementing Process Safety Management*.

2016-04-I-FL-R3

2. Ensure Effective Flame Arrestor Design

Modify Compressed Gas Association (CGA) standard CGA G-8.3, *Safe Practices for Storage and Handling of Nitrous Oxide* to require testing of safety devices, such as strainers used as flame arrestors, for applications where a safety device is used to quench a nitrous oxide decomposition reaction. To ensure that these safety devices meet the intended purpose, the user should test the safety device by simulating conditions of use. In addition, require users to document the required performance standard or test protocol followed.

2016-04-I-FL-R4

3. Require Pump Run-Dry Safety Interlocks Apply ISA-84

Modify Compressed Gas Association (CGA) standard CGA G-8.3, *Safe Practices for Storage and Handling of Nitrous Oxide* to reference and require applying International Society of Automation (ISA) standard ISA-84, *Functional Safety: Safety Instrumented Systems for the Process Industry Sector* to safety interlocks such as the nitrous oxide pump “run-dry” shutdown.

C. Pump Manufacturer – ACD LLC

2016-04-I-FL-R5

1. Provide effective warning about nitrous oxide decomposition hazards

Modify nitrous oxide pump product literature to include warnings about nitrous oxide decomposition hazards, illustrated by examples from historical incidents, and refer users to this CSB investigation report for additional information.

D. Pump Manufacturer – Cryostar USA LLC

2016-04-I-FL-R6

1. Provide effective warning about nitrous oxide decomposition hazards

Modify nitrous oxide pump product literature to include warnings about nitrous oxide decomposition hazards, illustrated by examples from historical incidents, and refer users to this CSB investigation report for additional information.

Members of the U.S. Chemical Safety and Hazard Investigation Board:

Vanessa Allen Sutherland, J.D./M.B.A.
Chairperson

Manuel Ehrlich
Member

Richard Engler
Member

Kristen Kulinowski, Ph.D.
Member

X. Causal Analysis

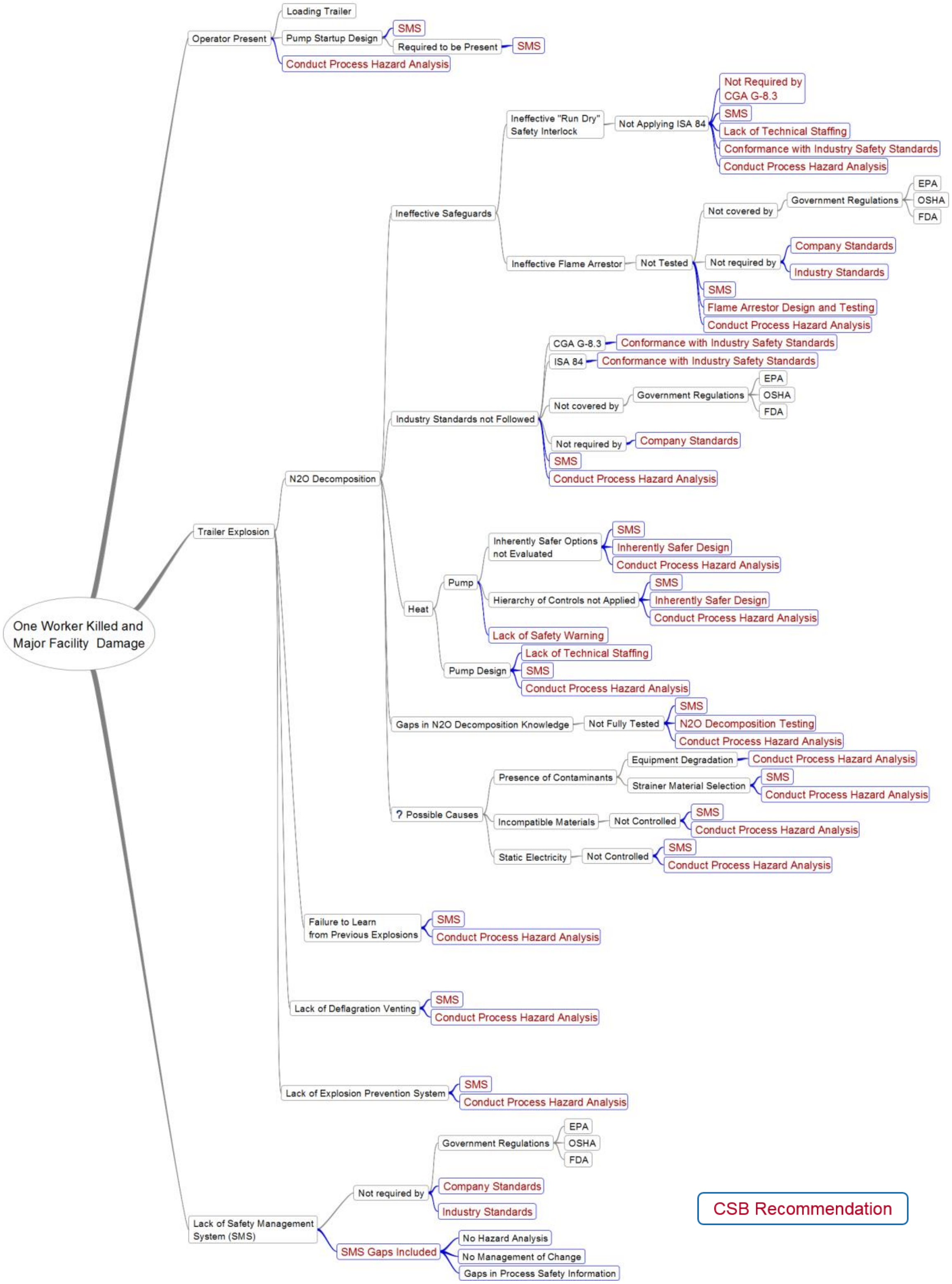

Figure 61. Simplified causal analysis of the August 28, 2016 Airgas incident.

XI. References

[1] K. Munke, "Nitrous Oxide Trailer Rupture," 2 July 2001. [Online]. Available: http://hobbyspace.com/AAdmin/archive/SpecialTopics/Misc/eindhoven.pdf. [Accessed 21 January 2017].

[2] C. E. Baukal, Jr., Ed., The John Zink Hamworthy Combustion Handbook: Design and Operations, vol. 2, Boca Raton, Florida: CRC Press, 2013.

[3] American Welding Society, Jefferson's Welding Encyclopedia, Eighteenth ed., R. L. O'Brien, Ed., Miami, Florida, 1997.

[4] FTC, "ANALYSIS OF PROPOSED AGREEMENT CONTAINING CONSENT ORDERS TO AID PUBLIC COMMENT: In tthe Matter of American Air Liquide Holdings, Inc., File No. 161 0045," [Online]. Available: https://www.ftc.gov/system/files/documents/cases/160513americanairanalysis.pdf. [Accessed 21 January 2017].

[5] Matheson, "Matheson Tri-Gas Completes Acquisition of U.S. Assets Divested by Air Liquide," 8 September 2016. [Online]. Available: http://www2.mathesongas.com/NewsEvents/releases/article.aspx?articleID=214. [Accessed 21 January 2017].

[6] Matheson, "Matheson Corporate Website," [Online]. Available: http://www.mathesongas.com/. [Accessed 21 January 2017].

[7] FTC, "FTC Settlement Would Restore Competition in U.S. Market for Nitrous Oxide," 26 October 2001. [Online]. Available: https://www.ftc.gov/news-events/press-releases/2001/10/ftc-settlement-would-restore-competition-us-market-nitrous-oxide. [Accessed 21 January 2017].

[8] Weldship Corporation, "Texas Trailers Nitrous Oxide Tank Trailers," [Online]. Available: http://www.weldship.com/products/tank-trailers.html. [Accessed 21 January 2017].

[9] "y-Strainer Graphic," [Online]. Available: https://media.licdn.com/mpr/mpr/p/3/005/085/379/030cf46.jpg. [Accessed 21 January 2017].

[10] Liquid Controls Sponsler, Inc., "Precision Turbine Flowmeters," 2009. [Online]. Available: http://www.sponsler.com/pdfs/LT-5007.pdf. [Accessed 21 January 2017].

[11] Sponsler, "Installation & Operation Manual: Model T675 Delivery System Totalizer," September 2009. [Online]. Available: http://www.sponsler.com/manuals/mn-t675.pdf. [Accessed 21 January 2017].

[12] Smith Precision Pumps, "Smith Pumps," [Online]. Available: http://www.smithpumps.com/. [Accessed 21 January 2017].

[13] Cryostar, "Cryostar," [Online]. Available: http://www.cryostar.com/. [Accessed 21 January 2017].

[14] MSDS Online, "MSDS Glossary of Terms: Self-Reactive Substance," [Online]. Available: https://www.msdsonline.com/resources/msds-resources/glossary-of-terms/self-reactive-substance.aspx. [Accessed 21 January 2017].

[15] Scaled Composites, LLC, "Scaled Composites Safety Guidelines for N2O," 17 June 2009. [Online]. Available: http://www.scaled.com/images/uploads/news/N2OSafetyGuidelines.pdf. [Accessed 21 January 2017].

[16] Merriam-Webster, "Definition of: adiabatic," [Online]. Available: https://www.merriam-webster.com/dictionary/adiabatic. [Accessed 21 January 2017].

[17] C. Merrill, "Nitrous Oxide Explosive Hazards," May 2008. [Online]. [Accessed 21 January 2017].

[18] G. D. Lewis, "Explosion and Fire in N2O Tank," West Palm Beach, 1973.

[19] M. L. Tupman, "Storage and Use of Nitrous Oxide: The Nitrous Oxide Decomposition Reaction," 1994.

[20] J. F. Mattrey, "Report of Nitrous Oxide Trailer Explosion at Puritan-Bennett's Manufacturing Plant," Richmond, 1981.

[21] Associated Press, "One Dead in Explosion at Industrial Gases Plant," 11 May 1987. [Online]. Available: http://www.apnewsarchive.com/1987/One-Dead-In-Explosion-At-Industrial-Gases-Plant/id-80e1f13cab0f04bef2af89151e07d95e.

[22] Observer - Reporter, "Explosion in Reading Industrial Gases Plant Kills one Person and Injures Three Others," 11 May 1987. [Online]. Available: https://news.google.com/newspapers?nid=2519&dat=19870511&id=329eAAAAIBAJ&sjid=nWENAAAAIBAJ&pg=5805,1819683.

[23] The Morning Call, "Air Products Sued Over Blast That Killed Man in Reading," 10 August 1988. [Online]. Available: http://articles.mcall.com/1988-08-10/news/2652364_1_nitrous-oxide-air-products-ugi.

[24] R. van Wees, "Investigation of an Explosion of a Nitrous Oxide Tank Truck at Hoek Loos Medical in Eindhoven on 2 July 2001. Summary," TNO Defence, Security and Safety, Rijswijk, 2005.

[25] T. Malik, "Report Cites Rocketship Builder in Explosion Inquiry," 18 January 2008. [Online]. Available: http://www.space.com/4863-report-cites-rocketship-builder-explosion-inquiry.html.

[26] Titan, "Screen and Basket Selection Guide: Choosing the Right Straining Element," [Online]. Available: http://www.titanfci.com/docs/technical-data/sst.pdf. [Accessed 21 January 2017].

[27] A. N. Minyard, M.D., "Records Request Response: MLA16-671," Florida, 2016.

[28] Enardo, "Flame Arrestor Technology," 22 January 2017. [Online]. Available: http://www.enardo.com/pdfs/tech_paper_fat.pdf.

[29] International Organization for Standardization, "Flame arresters — Performance requirements, test methods and limits for use," 22 January 2017. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:16852:ed-2:v1:en.

[30] Institution of Chemical Engineers (IChemE), "About IChemE," [Online]. Available: http://www.icheme.org/about_us.aspx. [Accessed 20 January 2017].

[31] Smith Precision Pumps, "Smith Pumps Utilized in Low-Pressure Liquid Nitrous Oxide Bulk Transfer Service," [Online]. Available: http://www.smithpumps.com/literature/downloads/?file=AL-45.pdf. [Accessed 22 January 2017].

[32] Major Accident Reporting System (eMARS), "Accident Profile," 2 July 2001. [Online]. Available: https://emars.jrc.ec.europa.eu/fileadmin/eMARS_Site/PhpPages/ViewAccident/ViewAccidentPublic.php?accident_code=629.

[33] M. Davies and T. Heidermann, "Protect Your Process with the Proper Flame Arresters," *Chemical Engineering Progress (CEP),* pp. 16-22, December 2013.

[34] A. E. Summers, "sis-tech.com," [Online]. Available: http://sis-tech.com/wp-content/uploads/2013/09/PSP-published-SCAI.pdf. [Accessed 22 January 2017].

[35] W. Johnson, R. R. Dunn and V. J. Maggioli, "Understanding ISA-84: Important Functional Safety Standard for Automation in the Computer Age," May/June 2012. [Online]. Available: https://www.isa.org/standards-and-publications/isa-publications/intech-magazine/2012/june/cover-story-understanding-isa-84/. [Accessed 22 January 2017].

[36] International Society of Automation, "ISA84, Electrical/Electronic/Programmable Electronic Systems (E/E/PES) for Use in Process Safety Applications," [Online]. Available: https://www.isa.org/isa84/. [Accessed 22 January 2017].

[37] International Society of Automation (ISA), "Functional Safety: Safety Instrumented Systems for the Process Industry Sector - Part 1: Framework, Definitions, System, Hardware and Software Requirements," ISA, 2004.

[38] J. L. Bergstrom, "An Overview of ISA 84 Standard for Safety Instrumented Systems (SIS) and the Safety Life Cycle," July 2015. [Online]. Available: http://www.processengr.com/ppt_presentations/safety_lifecycle_training_2015.pdf. [Accessed 22 January 2017].

[39] Smith Precision Pumps, "Do's and Don'ts: Read This Bulletin Before Installing and Operating a Smith Pump," [Online]. Available: http://www.smithpumps.com/literature/downloads/?file=AL-17A.pdf. [Accessed 22 January 2017].

[40] Mueller Steam Specialty, "Theoretical Pressure Drop Curve for Screen Clogging," 2010. [Online]. Available: http://media.wattswater.com/S-MS-PressureDropClog.pdf. [Accessed 22 January 2017].

[41] EagleBurgmann, "Mechanical Seal Technology and Selection," [Online]. Available: https://www.eagleburgmann.com/media/literature-competences-products-solutions/division-mechanical-seals/competences/brochure-mechanical-seal-technology-and-selection. [Accessed 22 January 2017].

[42] Michael Smith Engineers LTD, "Suction Pipeline Design," [Online]. Available: http://www.michael-smith-engineers.co.uk/resources/useful-info/suction-pipeline-design. [Accessed 22 January 2017].

[43] Oil and Gas Processing, "NPSHa Calculations," [Online]. Available: http://www.oilgasprocessing.com/npsh1.htm. [Accessed 22 January 2017].

[44] Shipco Pumps, "Are Suction Strainers Necessary on Centrifugal Pumps?," [Online]. Available: http://www.shipcopumps.com/articles/index.php?category=technical-articles&id=are-suction-strainers-necessary-on-centrifugal-pumps. [Accessed 22 January 2017].

[45] Goulds Pumps, "Goulds Model 3196: Spirit of Continuous Improvement, Excellence Mark the History of the World's Most Popular Process Pump," 6 February 2008. [Online]. Available: Goulds Model 3196: Spirit of Continuous Improvement, Excellence Mark the History of the World's Most Popular Process Pump. [Accessed 22 January 2017].

[46] ITT, "Product Stewardship and Supply Chain," [Online]. Available: http://www.itt.com/Citizenship/products/. [Accessed 22 January 2017].

[47] Fortune Valve, "Stainless Steel Ball Valve No: Series 336," [Online]. Available: http://fortunefusionvalve.en.ec21.com/. [Accessed 22 January 2017].

[48] Conbraco, "Apollo Ball Valve," [Online]. Available: http://cdn.conbraco.com/apollovalves/products/86r-100_2in/HRP_86R-108-01.JPG. [Accessed 22 January 2017].

[49] American Institute of Chemical Engineers (AIChE), "CCPS By-Laws-Amended November 5, 2007," [Online]. Available: http://www.aiche.org/ccps/about/by-laws#Article%20I%20section%202. [Accessed 22 January 2017].

[50] Center for Chemical Process Safety (CCPS), "Member Companies," [Online]. Available: http://www.aiche.org/ccps/community/members. [Accessed 22 January 2017].

[51] T. Kletz and P. Amyotte, Process Plants: A Handbook for Inherently Safer Design, Second ed., Boca Raton, Florida: CRC Press, 2010.

[52] National Fire Protection Association, NFPA 69: Standard on Explosion Prevention Systems, 2014 ed., Quincy, Massachusetts, 2014.

[53] National Fire Protection Association, NFPA 68: Standard on Explosion Protection by Deflagration Venting, 2013 ed., Quincy, Massachusetts, 2013.

[54] M. Stahl, B. Poblete, B. Tulsyan and A. Staszak, "Why Do We Still Have Blast Walls on Offshore Platforms?," in *11th Global Congress on Process Safety*, 2015.

[55] Asia Industrial Gases Association, "Installation Guide for Stationary Electric-Motor Driven Centrifugal Liquid Oxygen Pumps," Singapore, 2014.

[56] Techno Kontrol, "TK-AXBSS Anti-Explosion / Blast Safety Systems," [Online]. Available: http://www.technokontrol.com/en/products/blast.php. [Accessed 22 January 2017].

[57] USCSB, "U.S. Chemical Safety Board Votes 5-0 to Recommend New OSHA, EPA, and Industry Standards to Control Chemical Reaction Hazards," 20 September 2002. [Online]. Available: http://www.csb.gov/u-s-chemical-safety-board-votes-5-0-to-recommend-new-osha-epa-and-industry-standards-to-control-chemical-reaction-hazards/. [Accessed 22 January 2017].

[58] Airgas, "Safety Data Sheet: Nitrous Oxide," 11 February 2016. [Online]. Available: https://www.airgas.com/msds/001042.pdf. [Accessed 22 January 2017].

[59] National Fire Protection Association, Hazardous Chemicals Data 1975, Boston, 1975, p. 314.

[60] U.S. Pharmacopeial Convention, "About USP," [Online]. Available: http://www.usp.org/about-usp. [Accessed 22 January 2017].

[61] Chemours, "Teflon: Safety of Teflon: Nonstick Coating Systems," [Online]. Available: https://www.chemours.com/Teflon/en_US/products/safety/what_is_it.html. [Accessed 22 January 2017].

[62] A. Hopkins, Lessons from Longford: The Esso Gas Plant Explosion, Sydney, NSW: CCH Australia, 2000.

[63] Center for Chemical Process Safety, "The Business Case for Process Safety: 2nd Edition," 2006. [Online]. Available: http://www.aiche.org/sites/default/files/docs/pages/ccpsbuscase2nded-120604133414-phpapp02.pdf. [Accessed 22 January 2017].

[64] USNTSB, "Pacific Gas and Electric Company: Natural Gas Transmission Pipeline Rupture and Fire: San Bruno, California: September 9, 2010," United States National Transportation Safety Board, 2011.

[65] USNTSB, "NTSB: American Petroleum Institute's New Recommended Practice for Pipeline Safety Management Systems Exceeds NTSB Recommendation," 30 October 2015. [Online]. Available: https://www.ntsb.gov/news/press-releases/Pages/PR20151030a.aspx. [Accessed 22 January 2017].

[66] USNTSB, "Keynote speech at the American Gas Association's (AGA) Executive Leadership Summit," 16 November 2015. [Online]. Available: https://www.ntsb.gov/news/speeches/CHart/Pages/hart20151116.aspx. [Accessed 22 January 2017].

[67] B. Kichler, "API RP 1173: Pipeline Safety Management Systems," [Online]. Available: http://www.occeweb.com/TR/PLSLatestSeminar/2016/Safety%20Management%20System%20RP-1173.pdf. [Accessed 22 January 2017].

[68] ACD, "ACD," 2017. [Online]. Available: http://www.acdllc.com/. [Accessed 21 January 2017].

[69] Air Products, "Safety Gram #20: Nitrous Oxide N2O," [Online]. Available: http://www.apsusa.biz/grams/safetygram20.pdf.

[70] Linde, "Safety Data Sheet: Nitrous Oxide," [Online]. Available: http://www.linde-gas.com/internet.global.lindegas.global/en/images/Compressed%20nitrous%20oxide17_24366.pdf?v=1.0.

[71] B. Berger, "Is Nitrous Oxide Safe?," 5 October 2007. [Online]. Available: http://www.spl.ch/publication/SPL_Papers/N2O_safety_e.pdf.

[72] Z. W. Rogowski, "Flame Arresters in Industry," [Online]. Available: https://www.icheme.org/communities/subject_groups/safety%20and%20loss%20prevention/resources/hazards%20archive/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/VII/VII-Paper-05.pdf.

[73] American Petroleum Institute (API), "Flame Arresters in Piping Systems: API Recommended Practice 2028: Third Edition: February 2010," 2010.

[74] European Industrial Gases Association (EIGA), "Safe Practices for Storage and Handling of Nitrous Oxide," Brussels, 2016.

[75] European Industrial Gases Association (EIGA), "Major Hazards," Brussels, 2008.

[76] European Industrial Gases Association (EIGA), "Code of Practice Nitrous Oxide," Brussels, 2004.

[77] Air Liquide, "Air Liquide announces divestiture of U.S. assets to Matheson Tri-Gas in connection with Airgas acquisition," 24 June 2016. [Online]. Available: https://www.airliquide.com/media/air-liquide-announces-divestiture-us-assets-matheson-tri-gas-connection-airgas-acquisition.

[78] J. K. Cawthra and M. Eisentadt, "Summary of Nitrous Oxide Investigations: Final Report," Kirtland Air Force Base, July 1976.

[79] H. Phillips and D. K. Pritchard, "I. CHEM. E. Symposium Series No. 97: Performance Requirements of Flame Arresters in Practical Applications," 1986. [Online]. Available: https://www.icheme.org/~/media/Documents/Subject%20Groups/Safety_Loss_Prevention/Hazards%20Archive/IX/IX-Paper-05.pdf. [Accessed 20 January 2017].

[80] Lawrence Pumps Inc USA (Reprinted with permission by Kelair Pumps), "Pump Clinic ... Issue 31: Inducers for Centrifugal Pumps," [Online]. Available: http://www.wycopump.com/pdfs/pumpclinic31.pdf.

[81] T. Sahoo, "Use of Inducers in Liquefied Petroleum Gas and Condensate Service for Better Performance," in *PROCEEDINGS OF THE TWENTY-SECOND INTERNATIONAL PUMP USERS SYMPOSIUM • 2005*, West Bengal, India, 2005.

[82] "Inducer," [Online]. Available: http://www.mcnallyinstitute.com/CDweb/i-html/i011.htm.

[83] A. Karabeyoglu, "JPC 2012 Presentation: N2O [Nitrous Oxide] Safety," 31 July 2012. [Online]. Available: http://spase.stanford.edu/Hybrid_Rocket_Student_Meeting_files/Arif%20Karabeyoglu%20Presentation.pdf. [Accessed 25 September 2016].

[84] S. Beitler, "Delaware City, DE Industrial Plant Explosion, Aug 1977: Industrial Blast Kills 4 Workers," [Online]. Available: http://www.gendisasters.com/delaware/18038/delaware-city-de-industrial-plant-explosion-aug-1977. [Accessed 23 January 2017].

[85] New Jersey Department of Health and Senior Services, "Hazardous Substance Fact Sheet: Nitrous Oxide," 2004. [Online]. Available: http://nj.gov/health/eoh/rtkweb/documents/fs/1399.pdf. [Accessed 23 January 2017].

[86] T. Argo and E. Sandstrom, "Separation Distances in NFPA Codes and Standards: Final Report," 2014. [Online]. Available: http://www.nfpa.org/Assets/files/AboutTheCodes/59A/RFSeparationDistancesNFPACodesAndStandards.pdf. [Accessed 23 January 2017].

[87] A. Chang, "Spaceship Builder Faulted in Explosion," 7 February 2008. [Online]. Available: http://usatoday30.usatoday.com/tech/products/2008-02-07-2205394662_x.htm. [Accessed 23 January 2017].

[88] Airgas, "Airgas Sustainability Report 2015: Responsibility: Emission and Waste Reduction," 2015. [Online]. Available: https://www.airgas.com/sustainability/emission_and_waste_reduction.html. [Accessed 1 September 2016].

[89] Special Metals, "Monel alloy 400," 5 February 2005. [Online]. Available: http://www.specialmetals.com/assets/documents/alloys/monel/monel-alloy-400.pdf. [Accessed 23 January 2017].

[90] Special Metals, "High Performance Alloys," 2015. [Online]. Available: http://www.specialmetals.com/alloys. [Accessed 23 January 2017].

[91] "Nitrous Oxide Map," 24 January 2017. [Online]. Available: https://www.mapcustomizer.com/map/Nitrous%20Oxide%20Map.

[92] Linde, "Safety Advice. Disolved Acetylene.," 2016. [Online]. Available: http://www.lindeus.com/internet.lg.lg.usa/en/images/2987_0416_07_acetylene_v1138_276011.pdf?v=1.0. [Accessed 24 January 2017].

[93] Air Products, "Acetylene," 2014. [Online]. Available: http://www.airproducts.com/~/media/files/pdf/company/safetygram-13.pdf. [Accessed 24 January 2017].

[94] Protego, "Special Solutions," [Online]. Available: http://www.protego.com/products/special-solutions.html. [Accessed 24 January 2017].

[95] The University of Washington: Department of Chemistry, *Combustion of Steel Wool: Steel wool burns slowly in atmospheric conditions. When placed into a oxygen rich environment it burns much faster.*, UWChemistry, 2012.

[96] Product Stewardship Society, "Core Competencies for the Product Stewardship Professional," [Online]. Available: http://www.productstewards.org/Resources/Documents/PS-Core-Competencies.pdf. [Accessed 22 January 2017].

[97] J. O. Krisjansons, L. E. Bollinger and R. Edse, "Explosion Limit Studies of Nitrous Oxide and Nitrous Oxide - Nitrogen - Air Mixtures to 200 Atm. and 1800R," September 1962. [Online]. Available: http://www.dtic.mil/dtic/tr/fulltext/u2/291701.pdf.

[98] D. E. Becker and M. Rosenberg, "Nitrous Oxide and the Inhalation Anesthetics," *Anesthesia Progress: A Journal for Pain and Anxiety Control in Dentistry,* pp. 124-131, Winter 2008.

[99] Dictionary of Engineering, "Propagation Speed," [Online]. Available: http://www.dictionaryofengineering.com/definition/propagation-speed.html. [Accessed 25 January 2017].

[100] R. W. Johnson, S. W. Rudy and S. D. Unwin, Essential Practices for Managing Chemical Reactivity Hazards, New York, New York: Center for Chemical Proces Safety of the American Institute of Chemical Engineers, 2003.

[101] S. S. Grossel, Deflagration and Detonation Flame Arresters, New York, New York: Center for Chemical Process Safety, 2002.

[102] Center for Chemical Process Safety, Guidelines for Engineering Design for Process Safety,, Second ed., New York, New York: American Institute of Chemical Engineers, 2012.

[103] Center for Chemical Process Safety, Guidelines for Implementing Process Safety Management, Second ed., Hoboken, New Jersey: American Institute of Chemical Engineers, 2016.

[104] Center for Chemical Process Safety, Guidelines for Investigating Chemical Process Incidents, Second ed., New York, New York: American Institute of Chemical Engineers, 2003.

[105] Center for Chemical Process Safety, Guidelines for Risk Based Process Safety, Hoboken, New Jersey: John Wiley & Sons, Inc., 2007.

[106] Center for Chemical Process Safety, Inherently Safer Chemical Processes: A Life Cycle Approach, Second ed., New York, New York: John Wiley & Sons, Inc., 2009.

[107] D. A. Crowl, Understanding Explosions, New York, New York: Center for Chemical Process Safety of the American Institute of Chemical Engineers, 2003.

[108] R. K. Eckhoff, Explosion Hazards in the Process Industries, Second ed., Cambridge, Massachusetts: Elsevier, 2016.

[109] European Industrial Gases Association (EIGA), "Cleaning of Equipment for Oxygen Service: Guideline: IGC Doc 33/06/E," 2006. [Online]. Available: https://www.google.com/search?site=&source=hp&q=cleaning+equipment+for+oxygen+service&oq=cleaning+equipment+for+&gs_l=hp.1.0.0l10.1062.6146.0.8420.26.22.1.0.0.0.329.3226.1j9j7j1.18.0....0...1.1.64.hp..7.18.3071.0..35i39k1j0i131k1j0i20k1j0i67k1.h916SRkps4o. [Accessed 26 January 2017].

[110] USNTSB, "Enbridge Incorporated: Hazardous Liquid Pipeline Rupture and Release: Marshall, Michigan: July 25, 2010," United States National Transportation Safety Board, 2012.

[111] Air Liquide, "Air Liquide in brief," 2017. [Online]. Available: https://www.airliquide.com/media/air-liquide-brief. [Accessed 27 January 2017].

[112] Airgas, "Airgas an Air Liquide Company: Nitrous Oxide," [Online]. Available: http://airgasspecialtyproducts.com/nitrousoxide/. [Accessed 27 January 2017].

[113] Airgas, "Thermodynamic Properties of Saturated Nitrous Oxide," 2016. [Online]. Available: http://airgasspecialtyproducts.com/wp-content/uploads/2016/02/Properties-Nitrous-Oxide.pdf. [Accessed 22 January 2017].

[114] Fluid Sealing Association, "How do Plant Pipe Strain Problems Affecty my Pumping Systems?," March 2009. [Online]. Available: http://www.pumpsandsystems.com/topics/seals/how-do-plant-pipe-strain-problems-affect-my-pumping-systems. [Accessed 28 January 2017].

[115] Space Propulsion Group, Inc., "Nitrous Oxide Safety," 2012. [Online]. Available: http://www.spg-corp.com/nitrous-oxide-safety.html. [Accessed 28 January 2017].

[116] G. W. Rhodes, "Investigation of Decomposition Characteristics of Gaseous and Liquid Nitrous Oxide," Air Force Weapons Laboratory: Kirtland Air Force Base, New Mexico, July 1974. [Online]. Available: https://www.freelists.org/archives/arocket/01-2014/pdfEE82jaPU9W.pdf. [Accessed 28 January 2017].

[117] State of California: Division of Occupational Safety and Health, "Inspection Report: 0950625, Inspection Nr.: 310821103," 2008.

[118] Scaled Composites, LLC, "News Release," 1 August 2008. [Online]. Available: http://www.scaled.com/images/uploads/news/airelease_8_1_08.pdf. [Accessed 28 January 2017].

[119] D. Messier, "What Scaled, Virgin & Peter Diamandis Said After Last Fatal SpaceShipTwo Program Accident," 4 December 2014. [Online]. Available: http://www.parabolicarc.com/2014/12/04/peter-diamandis-virgin-galactic-fatal-spaceshiptwo-accident/. [Accessed 28 January 2017].

[120] Parker Hannifin Corporation, "Parker O-Ring Handbook: ORD 5700," 2007. [Online]. Available: http://www.parker.com/literature/O-Ring%20Division%20Literature/ORD%205700.pdf. [Accessed 28 January 2017].

[121] Pensacola News Journal, "Jesse Graham Folmar 1984 - 2016," 2016. [Online]. Available: http://www.legacy.com/obituaries/pensacolanewsjournal/obituary.aspx?n=jesse-graham-folmar&pid=181233037&fhid=5666. [Accessed 29 January 2017].

[122] Center for Chemical Process Safety, "20 Elements of Risk Based Process Safety (RBPS)," [Online]. Available: http://www.aiche.org/academy/courses/ela120/20-elements-risk-based-process-safety-rbps. [Accessed 29 January 2017].

[123] Levante-emv, "One Killed in an Explosion at a Moncada Factory," 7 September 2012. [Online]. Available: http://www.levante-emv.com/sucesos/2012/09/07/muerto-explosion-fabrica-moncada/934209.html. [Accessed 21 January 2017].

[124] USDOL, "1910.105: Nitrous Oxide," [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9751.

[125] USDOL, "1910.119 App A: List of Highly Hazardous Chemicals, Toxics and Reactives (Mandatory)," [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9761.

[126] USDOL, "Accident Search Results: Nitrous Oxide," [Online]. Available: https://www.osha.gov/pls/imis/AccidentSearch.search?acc_keyword=%22Nitrous%20Oxide%22&keyword_list=on. [Accessed 22 January 2017].

[127] USFDA (and others), "Guideline on General Principles of Process Validation," May 1987. [Online]. Available: http://www.pharmanet.com.br/pharmanet/pv.htm. [Accessed 22 January 2017].

[128] USDOL, "Inspection 100395516 - John H. Corbit, Inc.," 13 January 1988. [Online]. Available: https://www.osha.gov/pls/imis/establishment.inspection_detail?id=100395516. [Accessed 21 January 2017].

[129] USEPA, "List of Regulated Substances Under the Risk Management Plan (RMP) Rule," [Online]. Available: https://www.epa.gov/rmp/list-regulated-substances-under-risk-management-plan-rmp-program.

[130] USDOL, "Nitrous Oxide in Workplace Atmospheres (Passive Monitor)," May 1994. [Online]. Available: https://www.osha.gov/dts/sltc/methods/inorganic/id166/id166.html. [Accessed 22 January 2017].

[131] USDOL, "Process Safety Management Guidelines for Compliance: OSHA 3133," 1994 (Reprinted). [Online]. Available: https://www.osha.gov/Publications/osha3133.pdf. [Accessed 22 January 2017].

[132] USDOL, "Process Safety Management: OSHA 3132," 2000 (Reprinted). [Online]. Available: https://www.osha.gov/Publications/osha3132.pdf. [Accessed 22 January 2017].

[133] USDOL, "Standard Interpretations," 23 March 2000. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=23722. [Accessed 22 January 2017].

[134] USDOL, "Standard Interpretations," 29 November 2005. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=25164. [Accessed 22 January 2017].

[135] USDOL, "Updating OSHA Standards Based on National Consensus Standards," 24 November 2004. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=FEDERAL_REGISTER&p_id=18260. [Accessed 22 January 2017].

[136] USCSB, "What do the Status Designations for Each Recommendation Mean?," [Online]. Available: http://www.csb.gov/recommendations/faq/#52.

[137] USCSB, "Board Member Poje Testifies in New Jersey on Reactive Hazards," 17 March 2003. [Online]. Available: http://www.csb.gov/board-member-poje-testifies-in-new-jersey-on-reactive-hazards/. [Accessed 29 January 2017].

[138] Center for Chemical Process Safety, "CCPS By-Laws-Amended November 5, 2007," 5 November 2007. [Online]. Available: http://www.aiche.org/ccps/about/by-laws#Article%20III%20Section%201. [Accessed 29 January 2017].

[139] A. E. Summers, "ISA 84 – The Standard for Safety Instrumented Systems," [Online]. Available: http://sis-tech.com/wp-content/uploads/2011/05/ISA_84_-_The_Standard_for_Safety_Instrumented_Systems.pdf. [Accessed 22 January 2017].

[140] Michigan Technological University, "Department of Chemical Engineering: Daniel A. Crowl," [Online]. Available: http://www.mtu.edu/chemical/department/faculty/crowl/. [Accessed 21 January 2017].

[141] laprovincia, "One Dead and Five Injured by gas Explosion," 8 September 2012. [Online]. Available: http://www.laprovincia.es/sucesos/2012/09/08/muerto-cinco-heridos-explosion-gas/481842.html. [Accessed 21 January 2017].

[142] Business Wire, "Airgas Helps Fuel SpaceShipOne's Ansari X Prize Victory; Offers Congratulations to Customer Scaled Composites," 5 October 2004. [Online]. Available: http://www.businesswire.com/news/home/20041005006014/en/Airgas-Helps-Fuel-SpaceShipOnes-Ansari-Prize-Victory.

[143] Knights Arrow, "Observations and Comments on Cal/OSHA Report (Inspection No. 31081103) on Fatal Accident at Mojave Test Site of Scaled Composites at the Mojave Air and Space Port, 26th July 2007," [Online]. Available: http://www.knightsarrow.com/rockets/scaled-composites-accident/.

[144] NBC News, "Spaceship Builder Faces Fines for Fatal Blast," 18 January 2008. [Online]. Available: http://www.nbcnews.com/id/22733186/ns/technology_and_science-space/t/spaceship-builder-faces-fines-fatal-blast/#.WI7WFfKJXeR. [Accessed 29 January 2017].

[145] State of Delaware, "Department of State: Division of Corporations," [Online]. Available: https://icis.corp.delaware.gov/Ecorp/EntitySearch/NameSearch.aspx. [Accessed 29 January 2017].

[146] Compressed Gas Association (CGA), "Standard for the Installation of Nitrous Oxide Systems at Customer Sites," 1964.

[147] Compressed Gas Association (CGA), "Cleaning Equipment for Oxygen Service," 2009.

[148] Compressed Gas Association (CGA), "Safety and Reliability of Industrial Gases, Equipment, and Facilities Seminar," 16-17 October 2013. [Online]. Available: https://web.archive.org/web/20131414034200/http:/www.cganet.com/events/2013safetyandreliability/2013PreliminaryProgram.php. [Accessed 29 January 2017].

[149] A. Hopkins, "Lessons from Esso's Gas Plant Explosion at Longford," [Online]. Available: http://www.futuremedia.com.au/docs/Lessons%20from%20Longford%20by%20Hopkins.PDF. [Accessed 29 January 2017].

[150] Compressed Gas Association (CGA), CGA G-8.3–2016: Safe Practices for Storage and Handling of Nitrous Oxide, Second ed., 2016.

[151] Compressed Gas Association (CGA), "CGA G-4.1–2009: Cleaning Equipment for Oxygen Service," 2009.

[152] Compressed Gas Association (CGA), "Publications," [Online]. Available: https://www.cganet.com/customer/Publication.aspx. [Accessed 30 January 2017].

[153] G. Floreancig, "Total Enclosed Fan Cooled vs Open Drip Proof (TEFC vs ODP)," 27 June 2011. [Online]. Available: https://www.youtube.com/watch?v=8raG1ZxunA8. [Accessed 30 January 2017].

[154] Faircloth & Roberts Metallurgical Services, LLC, "L160812-RPT-102," Mobile, 2016.

[155] Compressed Gas Association (CGA), "CGA G-8.1–2013: Standard for Nitrous Oxide Systems at Customer Sites," 2013.

[156] Compressed Gas Association (CGA), "CGA G-8.4–2016: Safe Practices for the Production of Nitrous Oxide from Ammonium Nitrate," 2016.

[157] Compressed Gas Association (CGA), "Safety Bulletin: Nitrous Oxide Security and Control," Chantilly, May 2014.

[158] Compressed Gas Association (CGA), "CGA P-2–2013: Characteristics and Safe Handling of Medical Gases," Chantilly.

[159] Center for Chemical Process Safety, "CCPS Process Safety Glossary," [Online]. Available: http://www.aiche.org/ccps/resources/glossary. [Accessed 1 February 2017].

[160] TNO, "About TNO," [Online]. Available: https://www.tno.nl/en/about-tno/. [Accessed 2 February 2017].

[161] D. Burgener, "Liquid Nitrous Oxide Pump Related Incidents & Best Practices for Prevention," in *Safety and Reliability of Industrial Gases, Equipment, and Facilities Seminar: Octoberr 16-17, 2013*, Tampa, Florida, 2013.

[162] Smith Precision Pumps, "AL-105: Field Adjustmentt of "WW-Series" Bypass Valves," [Online]. Available: http://www.smithpumps.com/literature/downloads/?file=AL-105.pdf. [Accessed 1 February 2017].

[163] Serta, "What's the Difference Between PSI, PSIA, & PSIG," 12 March 2015. [Online]. Available: http://www.setra.com/blog/the-difference-between-psi-psia-psig/2015/03/12. [Accessed 29 January 2017].

[164] American Gas Association (AGA), "AGA Website," [Online]. Available: https://www.aga.org/. [Accessed 29 January 2017].

[165] American Conference of Governmental Industrial Hygienists (ACGIH), "About ACGIH," 2017. [Online]. Available: http://www.acgih.org/about-us/about-acgih. [Accessed 29 January 2017].

[166] Asia Industrial Gases Association (AIGA), "AIGA Web Site," 2017. [Online]. Available: http://www.asiaiga.org/. [Accessed 29 January 2017].

[167] American Petroleum Institute (API), "About API," 2017. [Online]. Available: http://www.api.org/about. [Accessed 29 January 2017].

[168] American Petroleum Institute (API), "Procedures for Standards Development," June 2016. [Online]. Available: http://mycommittees.api.org/standards/Reference/API%20Procedures%20for%20Standards%20Development-2016.pdf. [Accessed 29 January 2017].

[169] State of California: Department of Industrial Relations, "Cal/OSHA," 2017. [Online]. Available: http://www.dir.ca.gov/dosh/. [Accessed 29 January 2017].

[170] Center for Chemical Process Safety (CCPS), "CCPS," [Online]. Available: https://www.aiche.org/ccps. [Accessed 29 January 2017].

[171] TimeandDate.com, "CDT - Central Daylight Time / Central Daylight Saving Time (Daylight Saving Time)," 2017. [Online]. Available: https://www.timeanddate.com/time/zones/cdt. [Accessed 29 January 2017].

[172] USGPO, "Electronic Code of Federal Regulations," 1 February 2017. [Online]. Available: http://www.ecfr.gov/cgi-bin/ECFR?page=browse. [Accessed 2 February 2017].

[173] Compressed Gas Association (CGA), "CGA Web Site," [Online]. Available: https://www.cganet.com/. [Accessed 2 February 2017].

[174] USCSB, "U.S. Chemical Safety Board Web Site," [Online]. Available: http://www.csb.gov/. [Accessed 2 February 2017].

[175] USDOT, "U.S. Department of Transportation Web Site," [Online]. Available: https://www.transportation.gov/. [Accessed 2 February 2017].

[176] European Industrial Gases Association (EIGA), "EIGA Web Site," [Online]. Available: https://www.eiga.eu/index.php?id=291. [Accessed 2 February 2017].

[177] USEPA, "U.S. Environmental Protection Agency Web Site," 1 February 2017. [Online]. Available: https://www.epa.gov/. [Accessed 2 February 2017].

[178] USFDA, "U.S. Food & Drug Web Site," 30 January 2017. [Online]. Available: http://www.fda.gov/. [Accessed 2 February 2017].

[179] State of Florida, "The Official Portal of The State of Florida," 2 February 2017. [Online]. Available: http://www.myflorida.com/. [Accessed 2 February 2017].

[180] FTC, "Federal Trade Commission," [Online]. Available: https://www.ftc.gov/. [Accessed 2 February 2017].

[181] International Society of Automation (ISA), "ISA Web Site," [Online]. Available: https://www.isa.org/. [Accessed 2 February 2017].

[182] International Organization for Standardization (ISO), "ISO Web Site," [Online]. Available: http://www.iso.org/iso/home.html. [Accessed 2 February 2017].

[183] Japan Industrial and Medical Gases Association (JIMGA), "JIMGA Web Site," [Online]. Available: http://www.jimga.or.jp/front/bin/cglist.phtml?Category=6943. [Accessed 2 February 2017].

[184] Cornell University Law School, "Maximum Allowable Working Pressure," [Online]. Available: https://www.law.cornell.edu/cfr/text/46/54.10-5. [Accessed 2 February 2017].

[185] Washington State Department of Labor & Industries, "Management of Change," [Online]. Available: http://www.lni.wa.gov/safety/grantspartnerships/partnerships/vpp/pdfs/vppmocbestpractices.pdf. [Accessed 2 February 2017].

[186] National Fire Protection Association (NFPA), "NFPA Web Site," [Online]. Available: http://www.nfpa.org/. [Accessed 2 February 2017].

[187] Pumpschool.com, "Understanding Net Positive Suction Head," 2007. [Online]. Available: http://www.pumpschool.com/applications/npsh.pdf. [Accessed 2 February 2017].

[188] USNTSB, "NTSB Web Site," [Online]. Available: http://www.ntsb.gov. [Accessed 2 February 2017].

[189] Valve Magazine, "Introduction to Pressure Relief Devices - Part 1," [Online]. Available: http://www.valvemagazine.com/magazine/sections/back-to-basics/7322-pressure-relief-devices-part-1.html. [Accessed 2 February 2017].

[190] USDOL, "Process Safety Management of Highly Hazardous Chemicals," 8 February 2013. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9760. [Accessed 2 February 2017].

[191] USDOL, "Process Safety Management," 2000. [Online]. Available: https://www.osha.gov/Publications/osha3132.html. [Accessed 2 February 2017].

[192] C. McLaren, "Safety Management Systems Update," 26 August 2016. [Online]. Available: http://www.texasgas.com/wp-content/uploads/2016/08/Safety-Management-Systems_TGA-TRRC_08.26.2016-PHMSA-Chris-McLaren.pdf. [Accessed 2 February 2017].

[193] Chemours, "Teflon PTFE Coating, Extrusion and Molding," 2017. [Online]. Available: https://www.chemours.com/Teflon_Industrial/en_US/products/product_by_name/teflon_ptfe/. [Accessed 2 February 2017].

[194] USDOL, "Background on Recognized and Generally Accepted Good Engineering Practice," 11 May 2016. [Online]. Available: https://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=30785 . [Accessed 2 February 2017].

[195] USEPA, "Risk Management Plan (RMP) Rule," 21 December 2016. [Online]. Available: https://www.epa.gov/rmp. [Accessed 2 February 2017].

[196] USDOL, "Hazard Communication Safety Data Sheets," [Online]. Available: https://www.osha.gov/Publications/HazComm_QuickCard_SafetyData.html. [Accessed 2 February 2017].

[197] Instrument and Control Engineering for Process Industries, "Safety Instrumented System (SIS)," [Online]. Available: http://instrumentationportal.com/2011/instrument-glossary/glossary-s/safety-instrumented-system-sis/. [Accessed 2 February 2017].

[198] FAA, "Safety Management System (SMS)," 5 July 2016. [Online]. Available: https://www.faa.gov/about/initiatives/sms/. [Accessed 2 February 2017].

[199] Electrical Engineering Portal (EEP), "7 Most Common Motor Enclosure Types Defined by NEMA Standards," 9 August 2013. [Online]. Available: http://electrical-engineering-portal.com/7-most-common-motor-enclosure-types-defined-by-nema-standards. [Accessed 2 February 2017].

[200] USA.gov, "About the United States," [Online]. Available: https://www.usa.gov/about-the-us. [Accessed 2 February 2017].

[201] Centers for Disease Control and Prevention (CDC), "The National Institute for Occupational Safety and Health (NIOSH)," 30 January 2017. [Online]. Available: https://www.cdc.gov/niosh/index.htm. [Accessed 2 February 2017].

[202] Bakersfield.com, "Three Injured in Mojave Explosion Recovering," 1 August 2007. [Online]. Available: http://www.bakersfield.com/news/three-injured-in-mojave-explosion-recovering/article_24a39a28-c51f-5d3a-8444-25b550590d86.html.

[203] Beaver County Times, "Powerful Explosion Hits Plant," November 6, 1980. [Online]. Available: https://news.google.com/newspapers?nid=2002&dat=19801106&id=dFkuAAAAIBAJ&sjid=1dkFAAAAIBAJ&pg=1387,1217420. [Accessed 21 January 2017].

[204] D. Long and T. Heidermann, "Flame Arresters for Plants Handling Acetylene and Ethylene Oxide," in *IChemE: Hazards XXI: Symposium Series No. 155*, 2009.

[205] National Fire Protection Association, "Guide for Fire & Explosion Investigations," 2014. [Online]. Available: http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code&code=921. [Accessed 2 February 2017].

[206] National Institute of Standards and Technology (NIST), "Nitrogen Dioxide," 2016. [Online]. Available: http://webbook.nist.gov/cgi/cbook.cgi?ID=C10102440&Units=SI. [Accessed 2 February 2017].

[207] National Institute of Standards and Technology (NIST), "Nitric Oxide," 2016. [Online]. Available: http://webbook.nist.gov/cgi/cbook.cgi?ID=C10102439&Units=SI. [Accessed 2 February 2017].

[208] National Institute of Standards and Technology (NIST), "Nitrous Oxide," 2016. [Online]. Available: http://webbook.nist.gov/cgi/cbook.cgi?Name=nitrous+oxide&Units=SI. [Accessed 2 February 2017].

[209] National Institute of Standards and Technology, "Tetrafluoroethylene," 2016. [Online]. Available: http://webbook.nist.gov/cgi/cbook.cgi?Name=Tetrafluoroethene&Units=SI. [Accessed 2 February 2017].

[210] Internal Revenue Service (IRS), "Limited Liability Company (LLC)," 8 July 2016. [Online]. Available: https://www.irs.gov/businesses/small-businesses-self-employed/limited-liability-company-llc. [Accessed 2 February 2017].

[211] International Society for Pharmaceutical Engineering (ISPE), "Good Manufacturing Practice (GMP) Resources," 2017. [Online]. Available: http://www.ispe.org/gmp-resources. [Accessed 2 February 2017].

[212] Canadian Centre for Occupational Health and Safety (CCOHS), "How do I Work Safely With - Flammable and Combustible Liquids (Static Electricity)," 30 September 2008. [Online]. Available: https://www.ccohs.ca/oshanswers/prevention/flammable_static.html. [Accessed 25 January 2017].

[213] American Society for Quality (ASQ), "Learn About Quality: Failure Mode Effects Analysis (FMEA)," 2016. [Online]. Available: http://asq.org/learn-about-quality/process-analysis-tools/overview/fmea.html. [Accessed 2 February 2017].

[214] Air Liquide, "Air Liquide Completes Acquisition of Airgas," 23 May 2016. [Online]. Available: https://www.airliquide.com/media/air-liquide-completes-acquisition-airgas. [Accessed 21 January 2017].

[215] AIGA, "Safe Practices for Storage and Handling of Nitrous Oxide," [Online]. Available: http://www.asiaiga.org/uploaded_docs/AIGA%20055_14%20Installation%20guide%20for%20stationary%20electric%20motor%20driven%20centrifugal%20liquid%20oxygen%20pumps.pdf. [Accessed 21 January 2017].

[216] AmeriGas, "AmeriGas Web Site," 2017. [Online]. Available: https://www.amerigas.com/. [Accessed 4 February 2017].

[217] Association of Oil Pipe Lines (AOPL) and American Petroleum Institute (API), "Safety Management Systems," December 2012. [Online]. Available: http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/Pipeline/2%20SafetyMgt_PAC_RGM.ppt. [Accessed 5 February 2017].

[218] American Petroleum Institute (API), "Pressure-Relieving and Depressuring Systems: API Standard 521," January 2014.

[219] American Petroleum Institute (API), "ANSI/API Recommended Practice 1173: Pipeline Safety Management Systems," 2015.

[220] International Society of Automation (ISA), "Products Landing: ISA-84," [Online]. Available: https://www.isa.org/store/products/?mstype=Publications&ms_product_type=Standards&mssearch=ISA-84#/2b74cfb1cb8ac00c1f7844ab64d0518e. [Accessed 14 February 2017].

[221] USDOL, "Accident Report Detail: Accident: 201089349 - Three Employees Killed Three Injured In Explosion," 26 July 2007. [Online]. Available: https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=201089349. [Accessed 18 February 2017].

[222] USDOL, "Fatality and Catastrophe Investigation Summaries," [Online]. Available: https://www.osha.gov/pls/imis/accidentsearch.html. [Accessed 18 February 2017].

[223] U.S. Department of Health and Human Services, Food and Drug Administration, Center for Drug Evaluation and Research (CDER), Center for Biologics Evaluation and Research (CBER), Center for Veterinary Medicine (CVM), "Guidance for Industry: Process Validation: General Principles and Practices," January 2011. [Online]. Available: https://www.fda.gov/downloads/drugs/guidances/ucm070336.pdf. [Accessed 18 February 2017].

[224] FTC, "Appendix A: Gases Locations," [Online]. Available: https://www.ftc.gov/system/files/documents/cases/160513americanair-appendixa_0.pdf. [Accessed 21 January 2017].

[225] Emerson, "See How a Flame Arrestor Works," [Online]. Available: http://www2.emersonprocess.com/en-US/divisions/regulator-technologies/Documents/animations/TypeArrestor_EN.swf?_ga=1.47987495.1093675283.1474291775. [Accessed 22 January 2017].

[226] W. Schmidt, "Burning Steel Wool: Comparing Four Grades of Steel Wool to see Which Burns the Best," 2015. [Online]. Available: https://www.youtube.com/watch?v=xVd9vWhSzN0. [Accessed 22 January 2017].

[227] "Graphic of Close-Coupled Pump," [Online]. Available: http://img.weiku.com/a/017/155/EAZ_Close_Coupled_In_line_Centrifugal_Water_Pump_6137_1.jpg. [Accessed 22 January 2017].

[228] "CSB Safety Video: Reactive Hazards: Dangers of Uncontrolled Chemical Reactions," Sandy Gilmour Communications LLC., July 2007. [Online]. Available: https://www.youtube.com/watch?v=sRuz9bzBrtY. [Accessed 21 January 2017].

[229] USCSB, "Final Investigation Report: Chevron Richmond Refinery: Pipe Rupture and Fire: Chevron Richmond Refinery #4 Crude Unit: Richmond, California: August 6, 2012: 2012-03-I-CA," 2015. [Online]. Available: http://www.csb.gov/assets/1/19/Chevron_Final_Investigation_Report_2015-01-28.pdf. [Accessed 19 February 2017].

[230] USCSB, "Hazard Investigation: Improving Reactive Hazard Management: 2001-01-H," 2002. [Online]. Available: http://www.csb.gov/assets/1/19/ReactiveHazardInvestigationReport.pdf. [Accessed 22 January 2017].

[231] USCSB, "Investigation Report: Catastrophic Rupture of Heat Exchanger (Seven Fatalities): Tesoro Anacortes Refinery: Anacortes, Washington: April 2, 2010: 2010-08-I-WA," 2014. [Online]. Available: http://www.csb.gov/assets/1/7/Tesoro_Anacortes_2014-May-01.pdf. [Accessed 19 February 2017].

[232] USCSB, "Investigation Report: Volume 4: Drilling Rig Explosion and Fire at the Macondo Well," 2016. [Online]. Available: www.csb.gov/file.aspx?DocumentId=742. [Accessed 22 January 2017].

[233] USCSB, "Key Lessons for Preventing Incidents from Flammable Chemicals in Educational Demonstrations: Eliminating Flash Fire Hazards by Substituting or Minimizing the use of Flammable Chemicals and Performing an Effective hazard Review Will Prevent Injuries," 2014. [Online]. Available: http://www.csb.gov/key-lessons-for-preventing-incidents-from-flammable-chemicals-in-educational-demonstrations/. [Accessed 19 February 2017].

[234] USCSB, "Recommendations: Improving Reactive Hazard Management," [Online]. Available: http://www.csb.gov/recommendations/?F_InvestigationId=78. [Accessed 19 February 2017].

[235] USCSB, "Tesoro Martinez Refinery: Process Safety Culture Case Study: Martinez, California: February 12, 2014 and March 10, 2014 Sulfuric Acid Release Incidents," 2016. [Online]. Available: http://www.csb.gov/assets/1/19/Tesoro_Martinez_Final_Case_Study1.pdf. [Accessed 19 February 2017].

[236] USCSB, "Williams Geismar Olefins Plant: Reboiler Rupture and Fire: Geismar, Louisiana," 2013. [Online]. Available: http://www.csb.gov/assets/1/7/Williams_Case_Study_2016-10-19.pdf. [Accessed 19 February 2017].

[237] BTC Instrumentation, "Cavitation in a Water Pump," 30 November 2012. [Online]. Available: https://www.youtube.com/watch?v=eMDAw0TXvUo. [Accessed 22 January 2017].

[238] FM Global, "Property Loss Prevention Data Sheets: Explosion Protection Systems: 7-17," 2012. [Online]. Available: fmglobal.com. [Accessed 19 February 2017].

[239] British Standard, "Flame Arresters - Performance Requirements, Test Methods and Limits for Use," 2001.