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William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

# Nitrous Oxide Enhanced Fires in an Aircraft Lower Deck (LD-3) Sized Steel Test Chamber

July 2023

Final report

U.S. Department of Transportation
**Federal Aviation Administration**

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16. Abstract

The transport of oxidizers and compressed oxygen within aircraft is heavily regulated, largely as a result of the fatal 1996 ValuJet accident. Past Federal Aviation Administration (FAA) studies have found that released oxidizers can exacerbate burning within a halon-suppressed cargo compartment fire, potentially overwhelming the fire suppression system within an aircraft.

Recently, a request was submitted to ship medical devices containing small quantities of gaseous nitrous oxide ($N_2O$). As part of the certification process, the manufacturer of this device completed the PHMSA-required thermal resistance and flame penetration tests; however, the packaging was unable to pass the thermal resistance portion of the required tests and small quantities of $N_2O$ were able to escape. As a result of these initial tests, the manufacturer requested an exemption from this requirement.

PHMSA requested assistance from the FAA Fire Safety Branch to determine if quantities of released $N_2O$ would significantly impact a cargo compartment fire. Although $N_2O$ is not flammable, it is an oxidizing agent that could exacerbate an otherwise controlled cargo compartment fire, and ultimately overwhelm the integrity of the suppression and containment capabilities of the system. Tests were conducted within an aircraft lower deck (LD-3) sized steel test chamber using a fire load of eighteen cardboard boxes filled with shredded paper. During each test, the shredded paper was ignited and the ensuing fire was allowed to develop. Two baseline tests were first conducted, in which the fire within the test chamber was allowed to burn unabated, without introducing $N_2O$. Three subsequent tests were conducted in which various quantities of $N_2O$ gas (5.8 oz, 11.6 oz, and 17.4 oz) were released into the test chamber once the fire was fully developed.

Results indicated that released quantities of $N_2O$ less than or equal to 11.6 oz did not produce a significant reaction within the fire in the test chamber. However, it was observed that as the quantity of released $N_2O$ increased, more significant combustion reactions occurred. Therefore, until further data is acquired, it is recommended that the amount of $N_2O$ be limited to no more than 11.6 oz per Unit Load Device (ULD) for air transport.

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## Acronyms

| **Acronym** | **Definition** |
| --- | --- |
| AXH | FAA Office of Hazardous Materials Safety |
| FAA | Federal Aviation Administration |
| $N_2O$ | Nitrous Oxide |
| PHMSA | The Pipeline and Hazardous Materials Safety Administration |
| ULD | Unit Load Device |

## Executive summary

The transport of oxidizers and compressed oxygen as cargo within an aircraft is heavily regulated, largely as a result of the fatal 1996 ValuJet crash. Past FAA studies have shown that released oxidizers can exacerbate an aircraft cargo compartment fire, even when the fire had been previously suppressed to a controlled level via a suppressing agent such as Halon 1301 (Marker & Diaz, 1999).

The Pipeline and Hazardous Materials Safety Administration (PHMSA) and the FAA Office of Hazardous Materials Safety (AXH) contacted the FAA's Fire Safety Branch to review an applicant's request to ship medical devices containing nitrous oxide ($N_2O$). $N_2O$ is an oxidizing agent that can increase the burning rate of combustible material in the event of a fire. The manufacturer of this medical device had conducted the PHMSA-required flame penetration and thermal resistance tests. However, the proposed packaging could not pass the thermal resistance test, which resulted in a small quantity of $N_2O$ being released. As a result of these initial tests, the applicant requested an exemption from the thermal resistance requirement. In order to evaluate the safety consequences of allowing this exemption, the Fire Safety Branch conducted tests to determine if quantities of released $N_2O$ are a hazard in the event of a fire in the cargo compartment.

Experiments were conducted within a makeshift steel test chamber, resembling a typical LD-3 aircraft unit load device, in which eighteen cardboard boxes filled with shredded paper were used as the fire load. Two baseline tests were conducted without $N_2O$ to determine an average reference point for typical fire intensity. An additional three tests with varying amounts of $N_2O$ gas (5.8 oz, 11.6 oz, and 17.4 oz) released into the steel test chamber were conducted. These values were selected to simulate the release of $N_2O$ stored within 1, 2, and 3 cylinders of the medical device, respectively. Comparisons between the baseline and $N_2O$ tests indicate that $N_2O$ does exacerbate burning depending on the quantity of $N_2O$ released. As the released quantity of $N_2O$ increased, significant reactions were observed to occur within the test chamber. Reactions and temperature changes produced from the $N_2O$ release were observed to last approximately 10 – 60 seconds after the contents within the cylinder were expelled. Temperatures within the test chamber were not found to be uniform, as spikes and decreases in temperatures were observed to be sporadic throughout.

As noted above, released quantities of $N_2O$ less than or equal to 11.6 oz did not produce a significant reaction within the fire in the test chamber. However, since significant combustion reactions were observed as the quantity of released $N_2O$ increased, it is recommended that the

amount of $N_2O$ be limited to no more than 11.6 oz per unit load device (ULD) until further data is acquired.

# 1 Introduction

## 1.1 Background

Nitrous oxide ($N_2O$), a colorless, sweet-tasting gas, commonly known as laughing gas, is a compound that is frequently used within the medical industry. $N_2O$ is a nonflammable gas at room temperature; it is also an oxidizer that can accelerate the burning of combustible material (National Library of Medicine, n.d.). The transportation of oxidizers and pressurized oxygen has been heavily regulated, largely as a result of the 1996 ValuJet crash, to prevent a release during an in-flight cargo compartment fire. Elevated temperatures inside a cargo compartment during a suppressed fire can increase the pressure within a gas cylinder, causing its pressure relief disc to fail and eject the contents within the compartment. Previous FAA studies have shown that a Halon 1301 suppressed cargo compartment fire can be exacerbated when compressed oxygen is released inside, potentially overwhelming the fire suppression system's capability, and impeding an aircraft's ability to make an emergency landing (Marker & Diaz, 1999).

As a result of these previous studies, Pipeline and Hazardous Materials Safety Administration (PHMSA) issued a final Rule on January 31, 2007, under Docket No. RSPA–04–17664 (HM–224B) to enhance the safety standards for transportation of compressed oxygen, other oxidizing gases, and chemical oxygen generators when shipped via air transport:

> The final January Rule amended the HMR to require cylinders of compressed oxygen and chemical oxygen generators to be transported in an outer packaging that: (1) Meets the same flame penetration resistance standards as required for cargo compartment sidewalls and ceiling panels in transport category airplanes; and (2) provides certain thermal protection capabilities so as to retain its contents during an otherwise controllable cargo compartment fire. The outer packaging standard…addresses two safety concerns (1) protecting a cylinder and an oxygen generator that could be exposed directly to flames from a fire and (2) protecting a cylinder and an oxygen generator that could be exposed indirectly to heat from a fire. (Hazardous materials regulations, 2009)

In addition, the final Rule also states: "An outer packaging's materials of construction must prevent penetration by a flame of 1,700 °F for five minutes." (Hazardous materials regulations, 2009). Further, a cylinder of compressed oxygen or another oxidizing gas must remain below the temperature at which its pressure relief device would actuate and an oxygen generator must not activate when exposed to a temperature of at least 400°F for three hours. The 400°F temperature is the estimated mean temperature of a cargo compartment during a halon-suppressed fire. (Hazardous materials regulations, 2009).

The FAA's Office of Hazardous Materials Safety (AXH) and PHMSA representatives contacted the Fire Safety Branch to review a recent applicant's proposal to ship medical devices that contained small quantities of gaseous $N_2O$. The manufacturer of the device had conducted the necessary PHMSA-required flame penetration and thermal resistance tests, but the proposed packaging did not pass the thermal resistance portion of the required tests, which resulted in a small quantity of $N_2O$ being released. The applicant requested an exemption to ship these devices, despite not meeting one of the criteria for acceptance.

The Fire Safety Branch conducted several tests to determine if $N_2O$ gas released into an established fire inside an aircraft lower deck (LD-3) sized test chamber would substantially increase the burning rate and pose a significant safety hazard. This was necessary because no prior research on this topic was available.

## 1.2 Objective

The objective of this experiment was to determine the impact, if any, small quantities of gaseous $N_2O$ has on the intensity of a fully developed fire inside an aircraft lower deck (LD-3) sized test chamber. These tests evaluated the temperatures and flame characteristics of the fire after introducing an unobstructed flow of $N_2O$ gas into the test chamber.

# 2 Experiment setup

## 2.1 Test chamber

Testing was conducted at the FAA William J. Hughes Technical Center within a makeshift aircraft lower deck (LD-3) container constructed of steel. LD-3s are containers commonly used to load and store cargo within the lower lobe of wide body aircraft. For test purposes, an LD-3 container, a type of unit load device (ULD), was used as the basis for the dimensions of the makeshift container. A steel framed container with dimensions of 61 by 60 by 64 inches (169 $ft^3$ interior volume) was constructed and used as the test chamber. The walls of the test chamber were comprised of sheet steel. Eighteen cardboard boxes measuring 18 by 18 by 18 inches were each filled with 2.5 pounds of shredded paper to ensure that the fire load within the test chamber was uniform throughout testing. The boxes were placed in three layers, in a 2 by 3 by 3 orientation. Once the boxes were loaded, a sheet steel door was bolted onto the test chamber. A diagram with the full dimensions of the test chamber is shown in Figure 1.

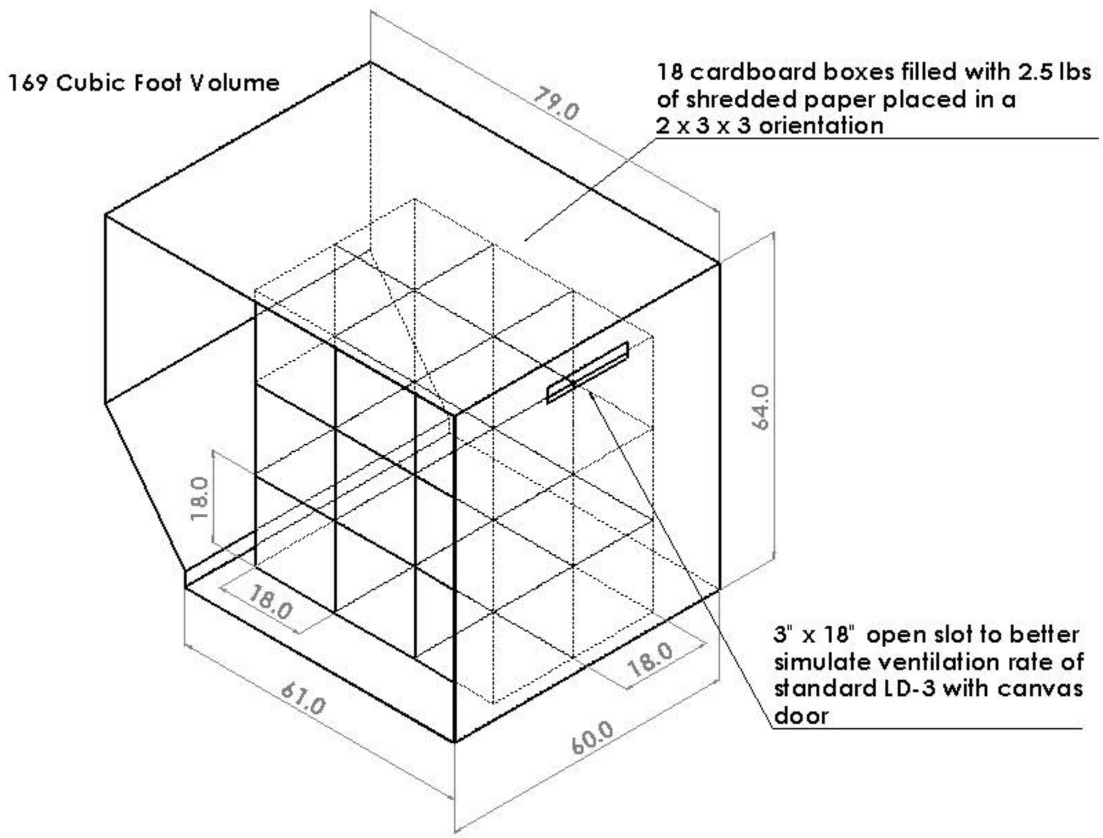


Figure 1. Test chamber setup diagram

Figure 2 shows a picture of the interior of the test chamber and the location in which the $N_2O$ gas was released. The end of the gas line was placed 36 inches from the bottom of the test chamber, between the 2nd and 3rd layers of boxes.

Preliminary testing was conducted to create a baseline fire with adequate oxygen flow to maintain flaming combustion. However, initial tests showed that the test chamber had insufficient oxygen to produce and maintain an open flame. These initial tests produced an oxygen starved, smoldering fire that would not accurately simulate a severe ULD cargo fire. ULD containers are constructed and composed of materials that would allow considerable airflow and would not be as “air tight” as the chamber in the initial tests. For example, some variants of ULD containers utilize a flexible canvas door that would allow significant air circulation during a cargo fire. Modifications to the test chamber were made to more accurately replicate a high intensity ULD cargo fire.

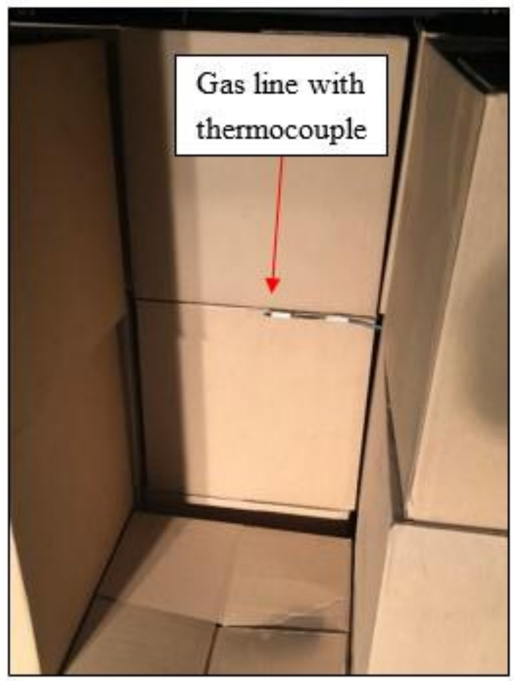


Figure 2. Filled test chamber w/o sealed door (left) and placement of gas line (right)

A 3 by 18-inch slot was added near the top of the container to allow for better circulation of air and exhaust of combustion products within the test container. Furthermore, two forklift slots near the bottom of the container were opened, to improve air intake within the container. These fork-lift slots had been previously closed off with sheet metal during the initial tests.

## 2.2 Experimental setup

In total, seven metal-sheathed, ceramic-packed, 1/16-inch Type K thermocouples were placed throughout the interior of the test chamber to record flame temperatures. Three thermocouples were placed on the back and sidewalls of the test chamber, in the center of their respective walls, 32 inches from the bottom of the test chamber. $N_2O$ is heavier than air so the thermocouples were placed slightly lower than the height at which the gas was released (36 inches from the bottom of the test chamber). The thermocouples were placed 2 inches from their respective walls. Two additional thermocouples were suspended downward 2 inches from the test chamber ceiling. A thermocouple was placed 2 inches away from the end of the $N_2O$ gas line to measure the temperature of the gas release directly. Finally, a thermocouple was placed within the interior of the ignitor box to measure the temperature of the initial ignition source in addition to providing another temperature reading for the lower half of the test chamber. A diagram of the thermocouple setup is shown in Figure 3.

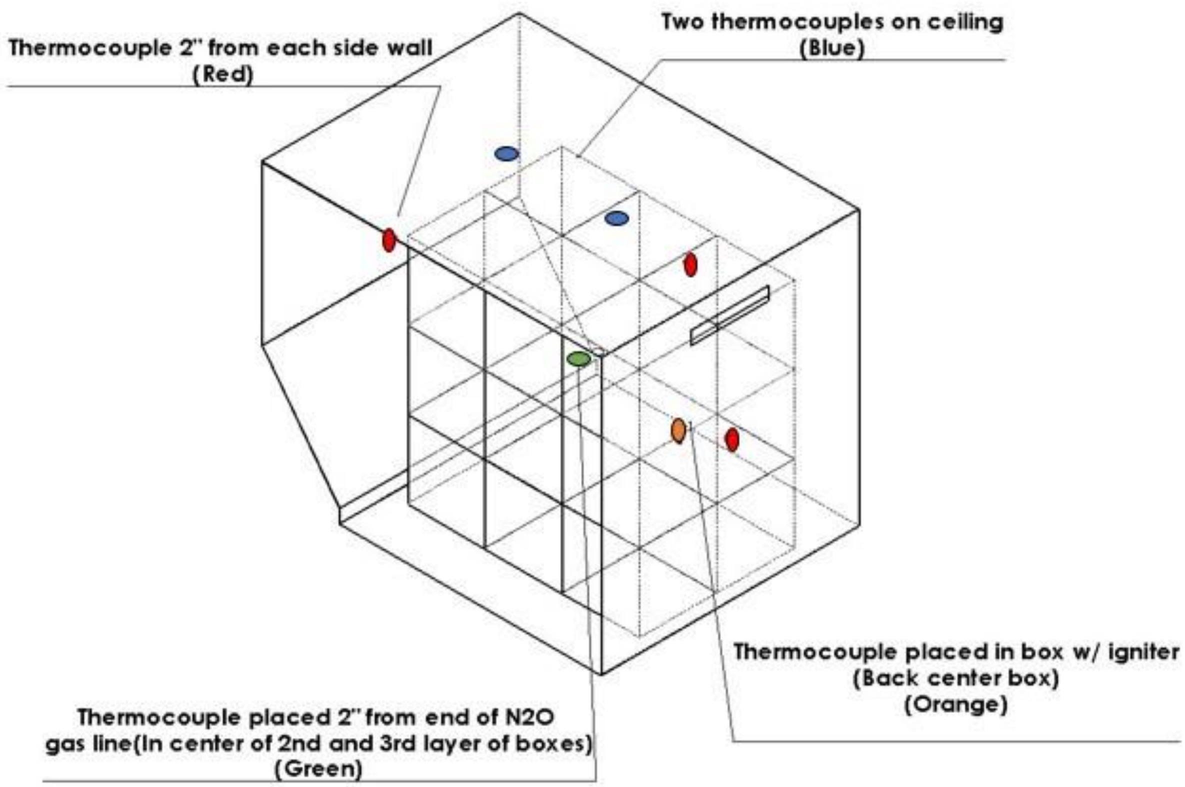


Figure 3. Test chamber thermocouple placements

A nichrome wire wrapped around a paper towel served as the ignition source for the shredded paper, which was placed inside the bottom middle cardboard box. A picture of the nichrome wire ignitor and the interior of the ignition box are shown in Figure 4.

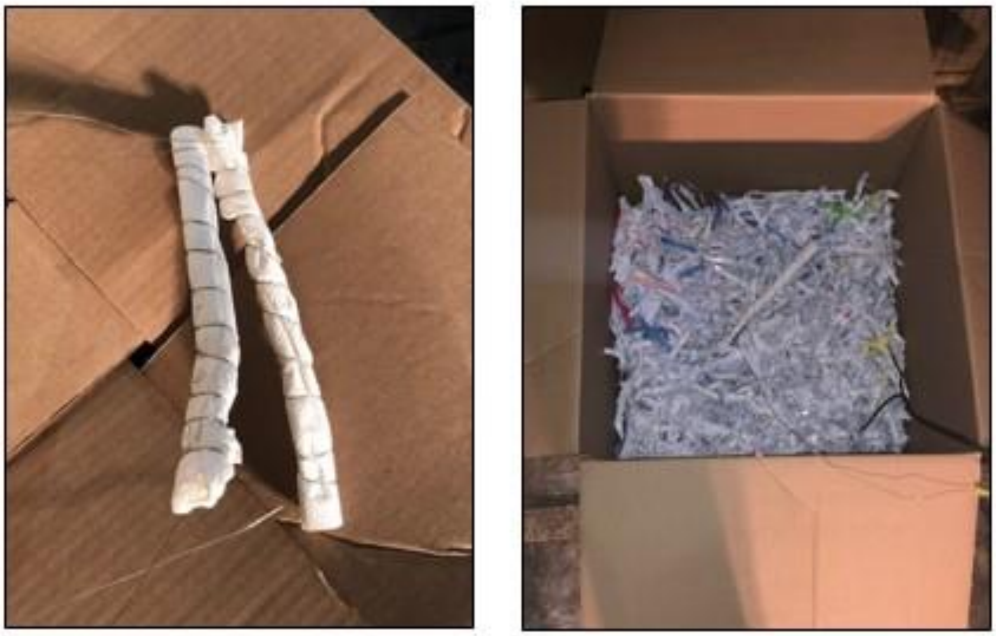

Figure 4. Nichrome wire ignitor and interior of ignitor box

Once the ignitor lit the shredded paper, the fire was allowed to progress until a significant amount of flame was produced, and the thermocouples exceeded temperatures over 1,000°F (537°C).

Two baseline tests were initially conducted to determine average flame characteristics and temperatures within the test chamber. $N_2O$ was not released into the container for the baseline tests, but all other test procedures remained the same. Subsequently, three tests were conducted in which varying amounts of $N_2O$ were discharged into the test chamber. The selected $N_2O$ discharge amounts for each test were approximately 5.8 oz (164.5g), 11.6 oz (329g), and 17.4 oz (493.5g). These values were selected to simulate the amount of $N_2O$ contained within 1, 2, and 3 cylinders of the medical device, respectively. A video camera located outside of the test chamber was used to record the event throughout testing.

Prior to the tests, several 3.78 L (1 gallon) stainless steel cylinders were prepared for storage of the $N_2O$ gas being used. The cylinders were first vacuumed, and then placed on a digital scale to record the empty weight of each. $N_2O$ gas was then transferred into each cylinder until the desired weight was achieved.

One 3.78 L cylinder was used for the storage and release of $N_2O$ in the 5.8 oz (164.5g) test. However, two 3.78 L cylinders were required for the gas storage and transfer in both the 11.6 oz (329g) and 17.4 oz (493.5g) tests.

After the gas transfer was completed, the filled cylinder(s) was bolted down to a stand outside the test chamber. Copper tubing measuring ¼-inch interior diameter was used to transfer the $N_2O$ from the cylinder into the test chamber. An electrically actuated solenoid valve was used to control the flow of gas. A piping tee was used to connect the two cylinders into a single gas line for the 11.6 oz and 17.4 oz tests.

# 3 Test results

## 3.1 Baseline tests

Two baseline tests were conducted to determine the average flame characteristics and flame temperatures in the test chamber without introducing any $N_2O$. Recorded test chamber temperatures for the baseline tests are shown in Figure 5 and Figure 6 respectively. Data was collected for these tests until approximately twenty minutes after the initial ignition.

Temperatures within the test chamber were observed to exceed 1,000°F. It was noted throughout baseline testing that maximum temperatures and flame activity would typically peak 600-900 seconds after initial ignition. Once average temperatures within the test chamber exceeded 1,000°F, temperatures were observed to decrease gradually. Therefore, in order to replicate a “worst case scenario,” it was determined that the gas would be released into the test chamber when the average temperatures were observed to reach approximately 1,000°F.

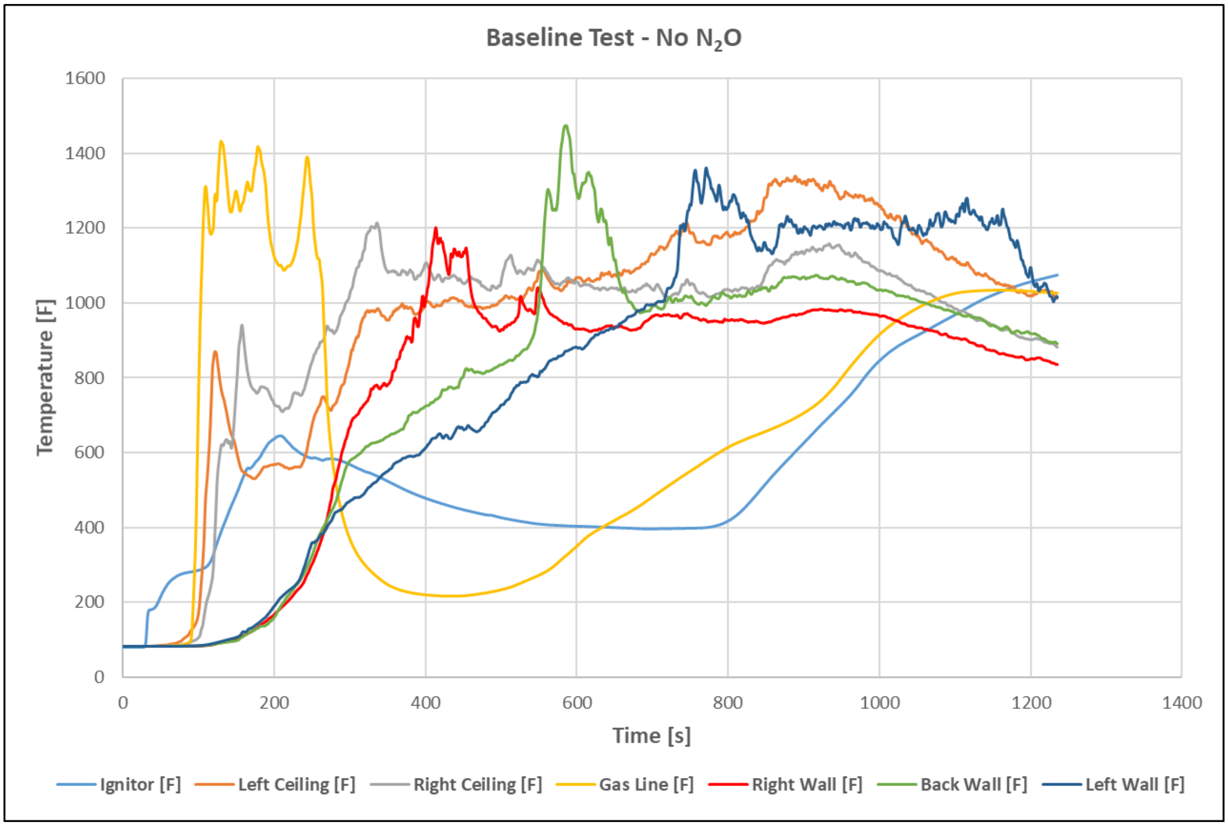


Figure 5. Baseline test 1 temperatures [°F]

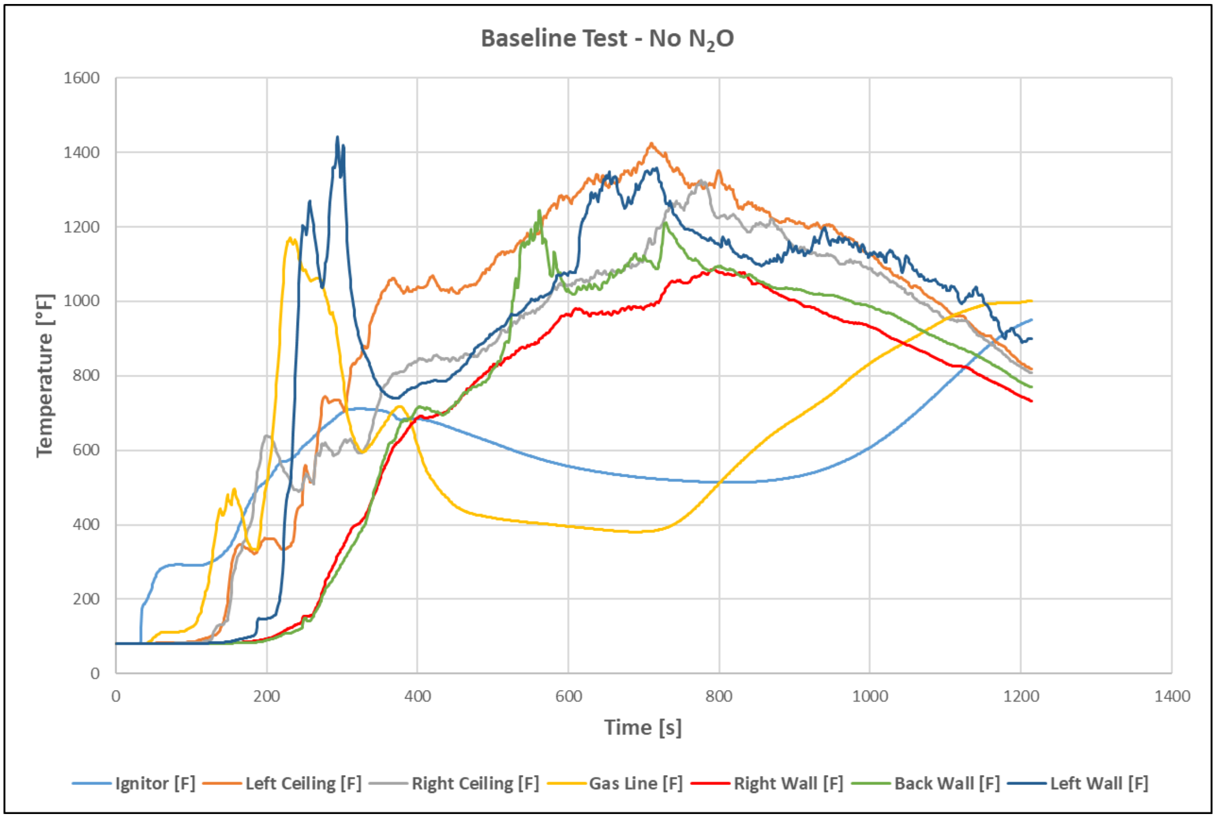


Figure 6. Baseline test 2 temperatures [°F]

## 3.2 $N_2O$ testing

During tests in which $N_2O$ was introduced, the fire was allowed to progress until fully developed and internal temperatures averaging approximately 1,000°F were observed. Once this threshold was met, the gas was released into the test chamber.

### 3.2.1 5.8 oz $N_2O$ test

The first test conducted was the release of 5.8 oz of $N_2O$ into the test chamber. This fire was observed to develop more slowly as compared to previous baseline tests. Significant upticks in temperature did not occur until around 500 seconds after the start of the test. Therefore, additional time was given to allow appropriate fire growth. The $N_2O$ was released around the

1,100 second mark. A graph showing the temperatures of all thermocouples within the test chamber are shown in Figure 7,

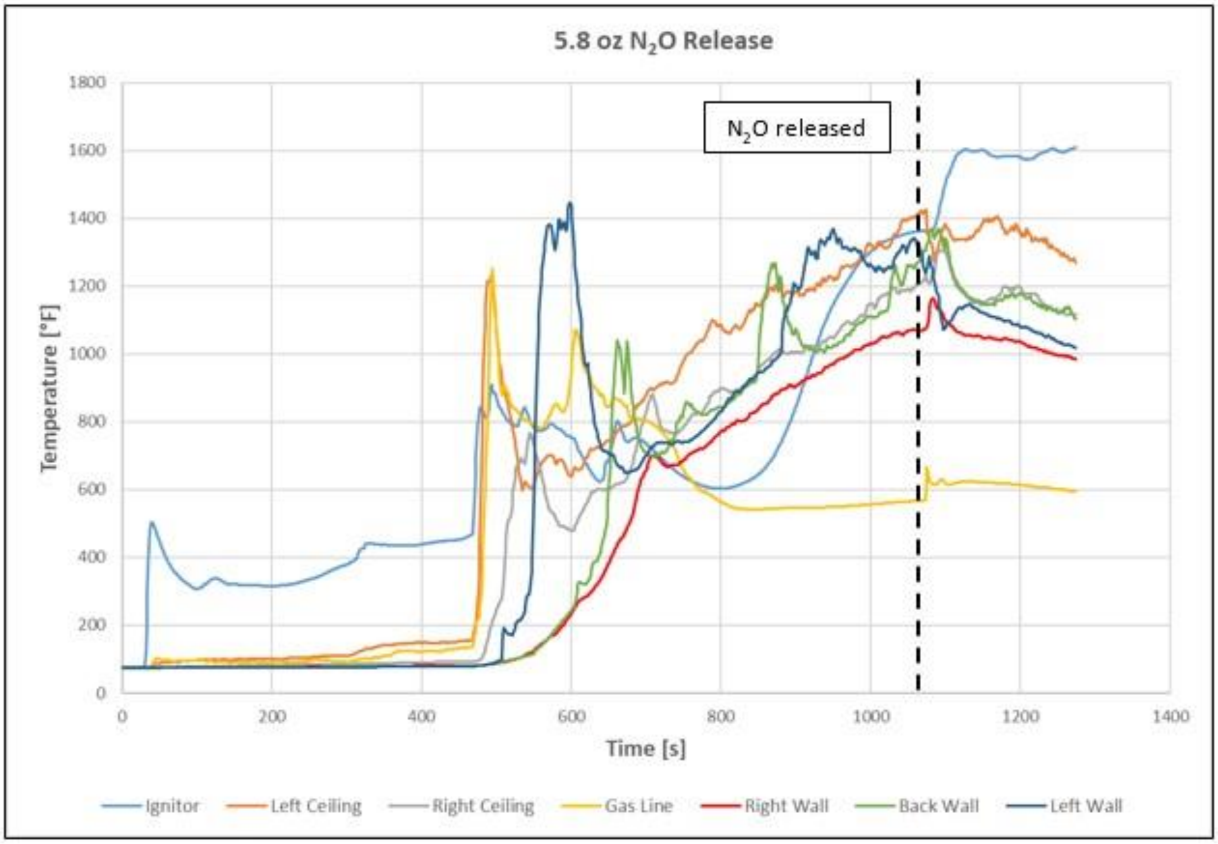


Figure 7. 5.8 oz $N_2O$ test temperatures [°F]

The vertical dashed line indicates the time at which the $N_2O$ was released into the test chamber. Short spikes in temperature (< 90°F) were observed in the thermocouples located near the gas line and the right wall.

A graph showing the average temperature within the test chamber is shown in Figure 8. An additional line is included in the chart, which shows the average temperature excluding the gas line thermocouple, as the gas line thermocouple in later tests skewed the averages.

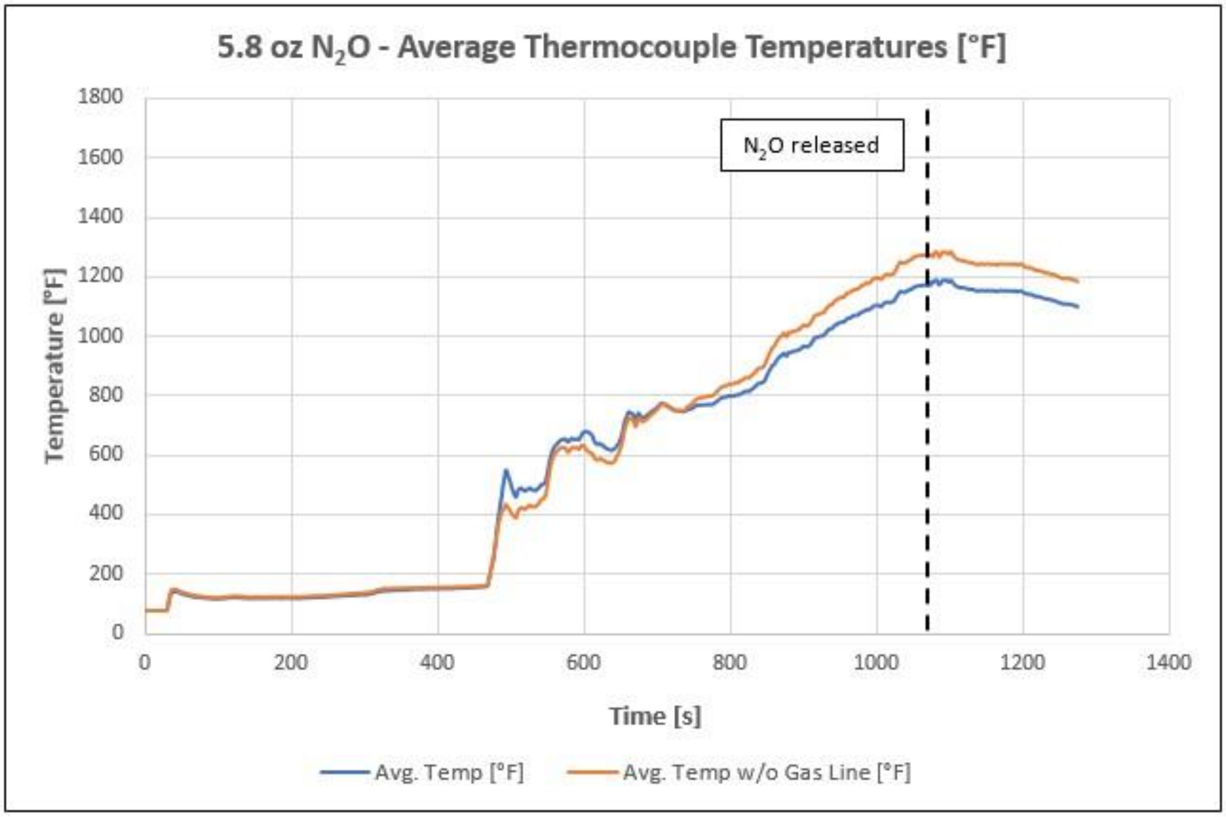

Figure 8. 5.8 oz test average temperatures [°F]

Furthermore, Table 1 shows the change in recorded temperatures (ΔT) both 10 seconds and 20 seconds after the release of $N_2O$ for all thermocouples. The average temperature was observed to increase by approximately 10°F within ten seconds after release.

Table 1. 5.8 oz test temperature Δ [°F]

| **Post $N_2O$ ΔT [°F]** | **10s** | **20s** |
|---|---|---|
| Ignitor | 4.79 | 77.89 |
| Left Ceiling | -127.85 | -89.56 |
| Right Ceiling | 12.61 | 72.81 |
| Gas Line | 46.30 | 58.53 |
| Right Wall | 89.13 | 55.26 |
| Back Wall | 48.32 | 53.06 |
| Left Wall | 1.10 | -113.85 |
| **Avg. ΔT** | 10.63 | 16.31 |
| **Avg. ΔT w/o Gas Line** | 4.68 | 9.27 |

Figure 9 shows the peak reaction observed from the outside of the test chamber during the 5.8 oz test.

For this test, it was observed that only small embers were released from the bottom slots of the test chamber. The duration of the reaction lasted for less than a second following the gas release.

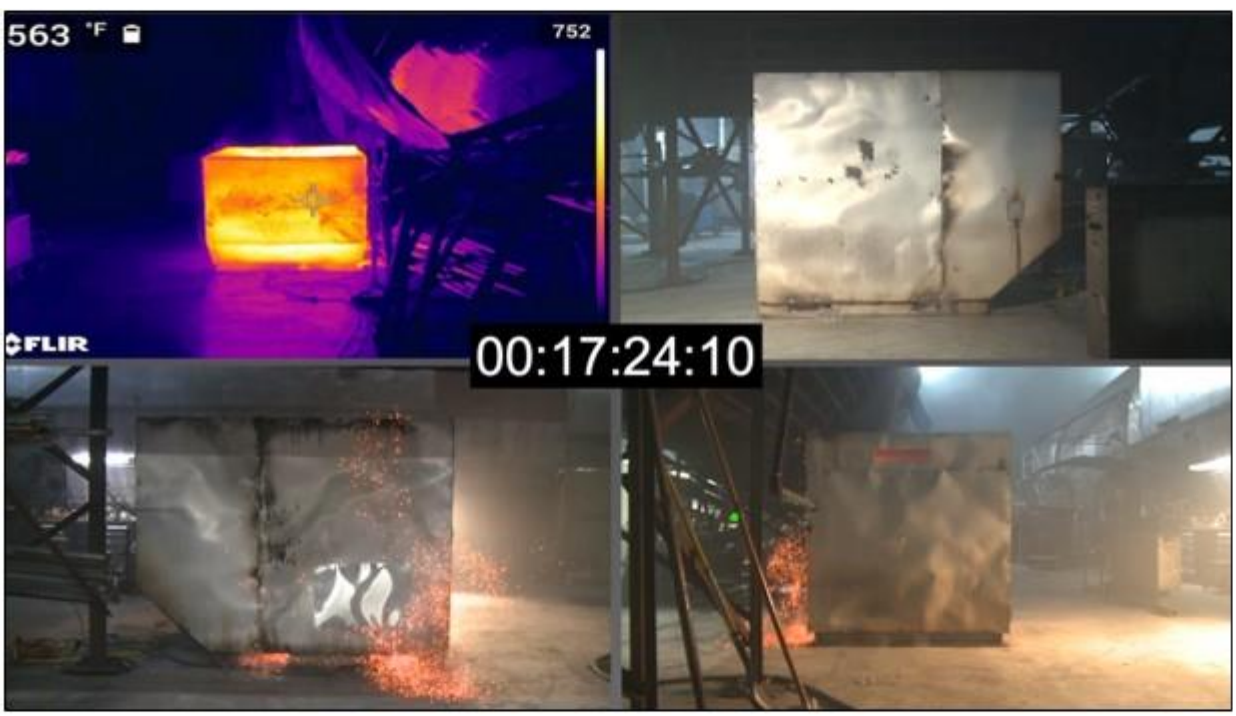


Figure 9. 5.8 oz $N_2O$ test peak reaction

### 3.2.2 11.6 oz $N_2O$ test

The amount of $N_2O$ was increased in the subsequent test to 11.6 oz to simulate the release of two cylinders' worth of gas. Figure 10 shows the temperatures within the test chamber throughout the test.

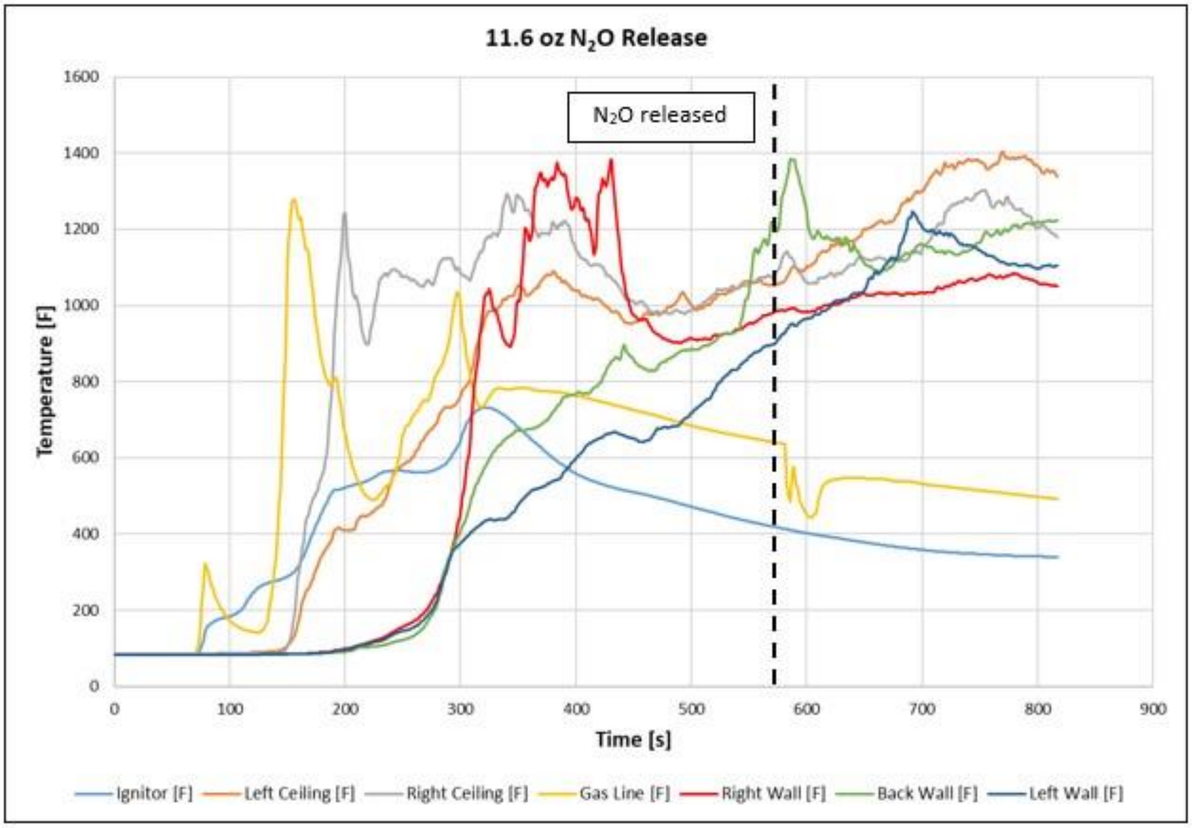


Figure 10. 11.6 oz $N_2O$ test temperatures [°F]

Peaks in temperature were observed to occur in some of the thermocouples throughout the test chamber. Notably, the back wall thermocouple indicated an increase in temperature of approximately 140°F. However, the thermocouple placed directly next to the gas line showed a significant decrease. $N_2O$ is a cryogenic gas, so this temperature decrease may have been a result of the cold gas being expelled from the end of the copper line. Furthermore, the observed decrease in temperature in the gas line thermocouple could be attributed to the expelled gas forcing flames away from this immediate area.

A graph showing the average temperatures within the test chamber is shown in Figure 11, in addition to the average temperature of all thermocouples (excluding the gas line thermocouple).

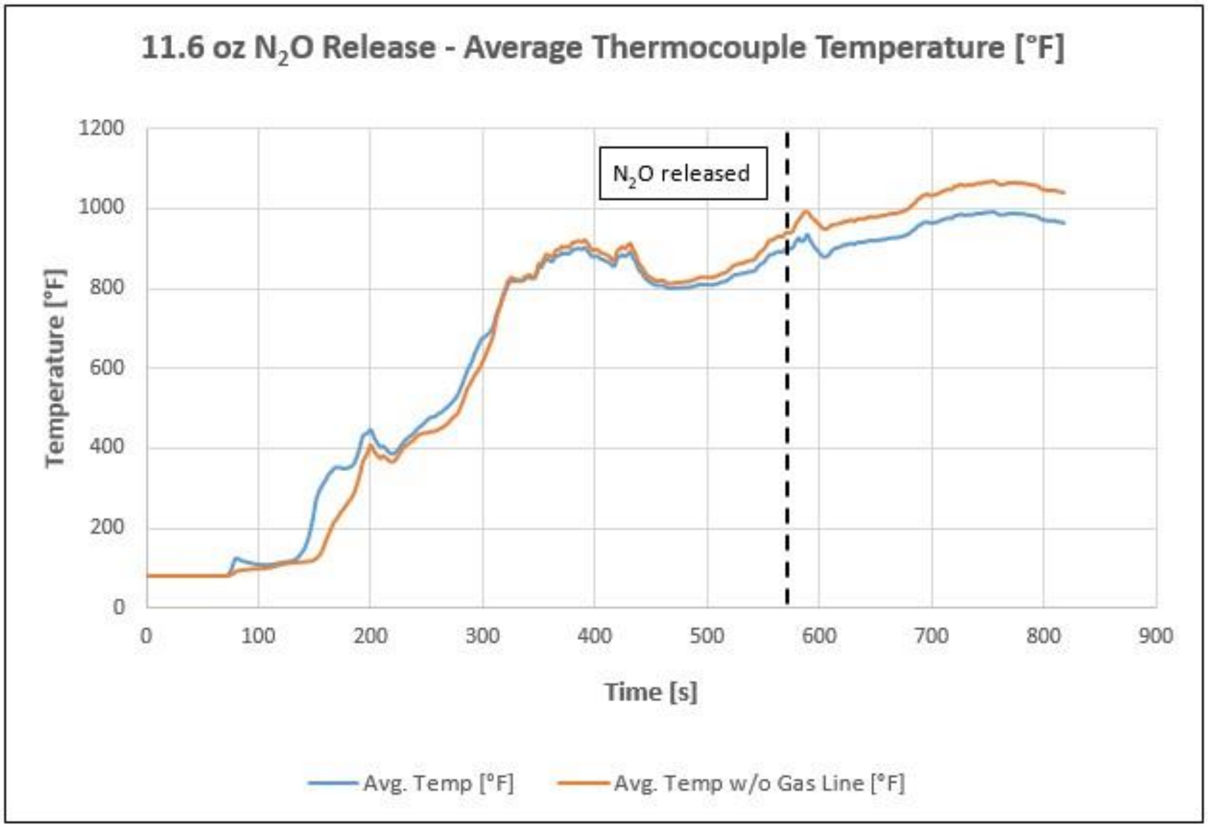


Figure 11. 11.6 oz test average temperatures [°F]

Table 2 shows the change in temperature (ΔT) for all thermocouples within the test chamber both 10 and 20 seconds after release.

Table 2. 11.6 oz test temperature Δ [°F]

| Post $N_2O$ ΔT [°F] | 10s | 20s |
|---|---|---|
| Ignitor | -6.31 | -12.26 |
| Left Ceiling | 39.55 | 32.53 |
| Right Ceiling | 20.10 | -33.68 |
| Gas Line | -112.68 | -169.34 |
| Right Wall | 5.47 | -4.15 |
| Back Wall | 140.72 | 46.68 |
| Left Wall | 34.00 | 47.12 |

| | | |
|---|---|---|
| **Avg. ΔT** | 17.26 | -13.30 |
| **Avg. ΔT w/o Gas Line** | 38.92 | 12.71 |

Figure 12 shows the peak reaction that was observed during the 11.6 oz test. In this test, a small burst of flames and embers escaped from the bottom slots of the test chamber. There was a small but noticeable increase in the amount of flame released compared to the 5.8 oz test. The total visible reaction from outside the test chamber only lasted for approximately 1-2 seconds after the gas was released.


Figure 12. 11.6 oz $N_2O$ test peak reaction

### 3.2.3 17.4 oz $N_2O$ Test

Lastly, a test was conducted in which the amount (17.4 oz) of $N_2O$ was tripled compared to the original amount to simulate the amount of gas that would be released from three cylinders. The recorded temperatures within the container are shown in Figure 13.

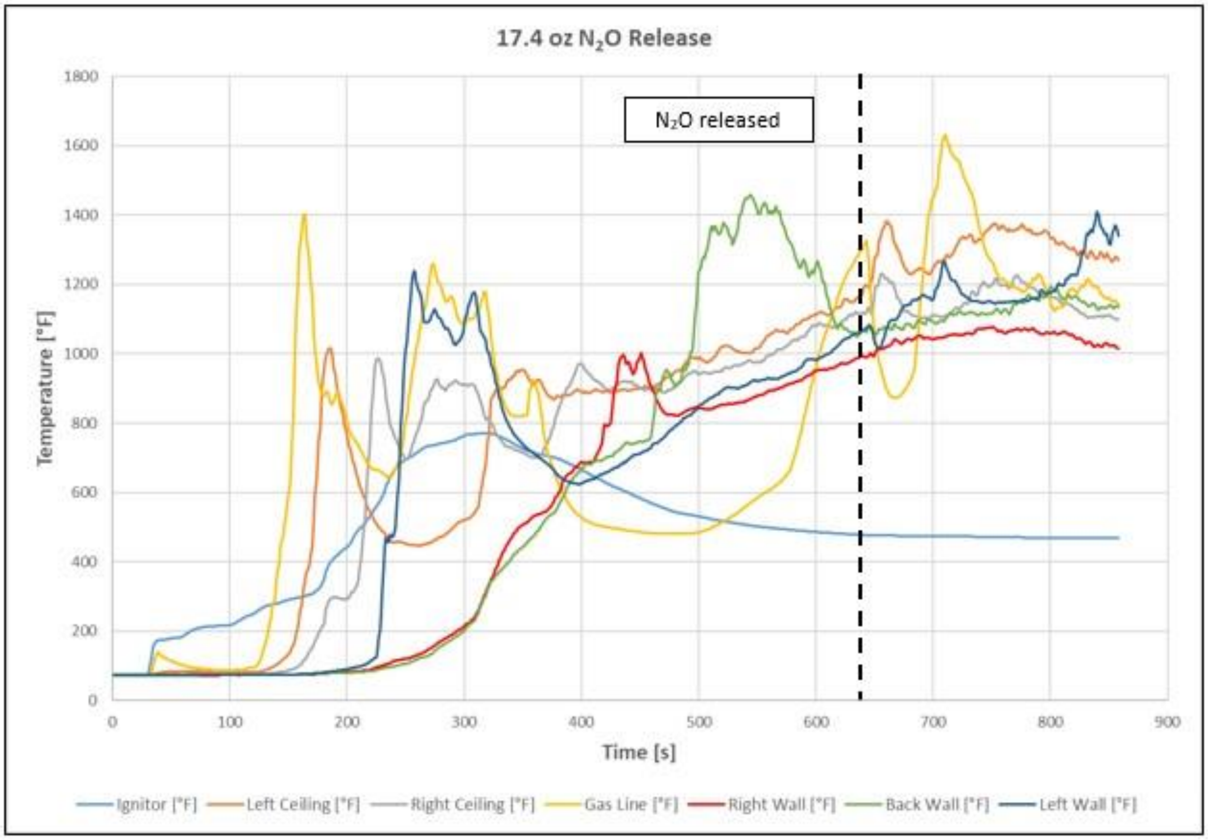

Figure 13. 17.4 oz $N_2O$ test temperatures [°F]

A significant decrease in temperature was observed in the thermocouple placed directly next to the end of the gas line. However, spikes in temperature were observed once again for the thermocouples within the surrounding area. Notably, an increase of 175°F and 85°F was observed for the left ceiling and right ceiling thermocouples, respectively, 20 seconds after gas release.

A graph showing the average temperature measurements and the average temperature measurements excluding the gas line thermocouple is shown in Figure 14. The ~ 400°F decrease in the gas line thermocouple skewed data enough where the average temperature within the test chamber decreased. However, if the gas line thermocouple is excluded, the average test chamber temperature increased by approximately 50°F, 20 seconds after release.

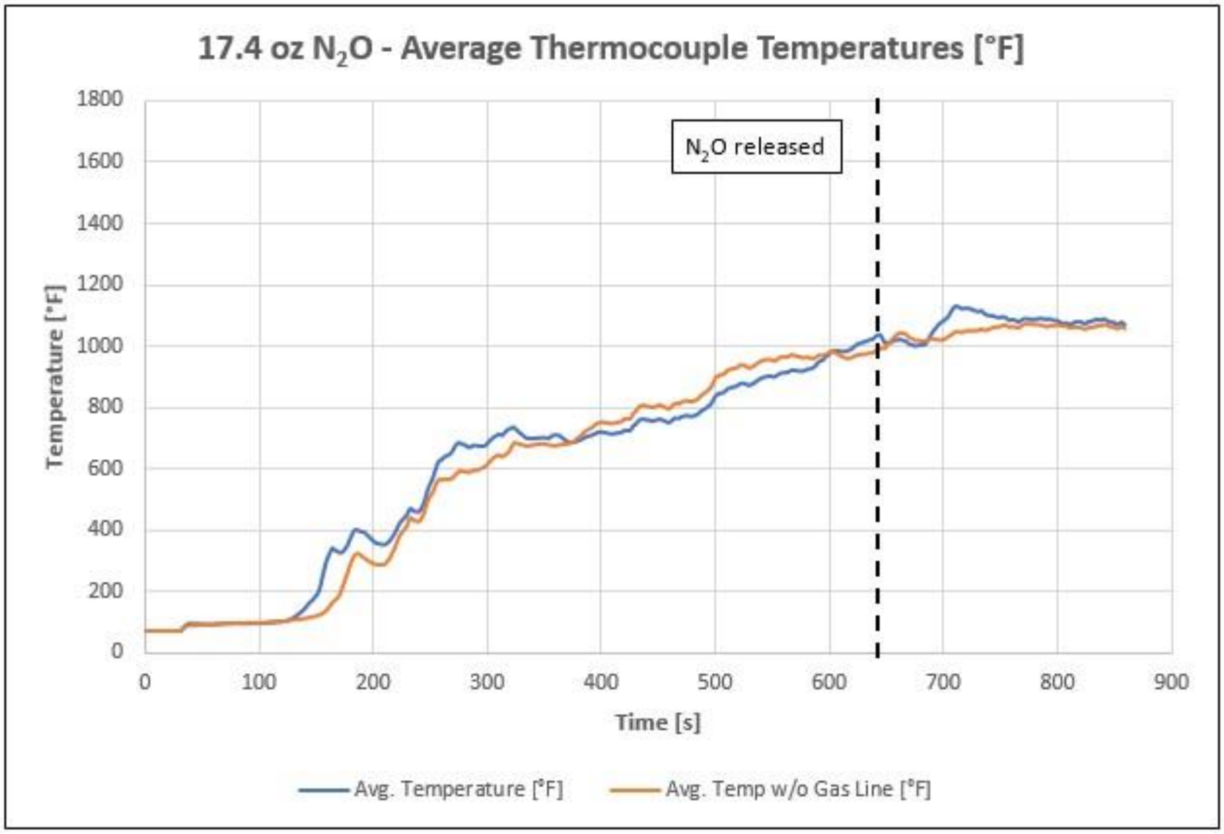


Figure 14. 17.4 oz test average temperatures [°F]

A detailed breakdown of the change in thermocouple temperatures (ΔT) for 10 and 20 seconds after the gas was released is shown in Table 3.

Table 3. 17.4 oz test temperature Δ [°F]

| **Post $N_2O$ ΔT [°F]** | **10s** | **20s** |
|---|---|---|
| Ignitor | -1.05 | -1.85 |
| Left Ceiling | 99.19 | 175.75 |
| Right Ceiling | 75.57 | 85.65 |
| Gas Line | -333.20 | -446.79 |
| Right Wall | 23.59 | 34.35 |
| Back Wall | 4.99 | 9.78 |
| Left Wall | -54.96 | 20.19 |

| | | |
|---|---|---|
| **Avg. ΔT** | -26.55 | -17.56 |
| **Avg. ΔT w/o Gas Line** | 24.55 | 53.98 |

In this test, a substantial amount of flame was observed from the bottom slots of the test chamber after the $N_2O$ was released. This reaction was noted to last for around 10 seconds after the release of $N_2O$. The reaction in this test was more intense compared to previous tests. An image of the peak reaction for this test is shown in Figure 15.


Figure 15. 17.4 oz $N_2O$ test peak reaction

# 4 Summary

Testing indicates that the release of $N_2O$ into an active fire does not produce an explosive condition within the interior of the container, but it does exacerbate burning. This is consistent with previous studies, as it has been noted that $N_2O$ is an oxidizer, but not flammable. Fire exacerbation from within the test chamber was observed to become more severe as the amount of $N_2O$ released into the test chamber increased.

For all three tests, a sharp increase in temperature was observed immediately after the release of $N_2O$. This increase was not uniform throughout all thermocouples – surges in temperature were observed in varying areas throughout testing. Changes in temperature for the thermocouple closest to the $N_2O$ gas line were inconsistent throughout testing. A small increase in temperature was observed for the 5.8 oz test, however, the tests with higher levels of $N_2O$ (11.6 and 17.4 oz) released inside the test chamber were found to produce a significant decrease in recorded temperature for the gas line thermocouple. This decrease may have been due to the cryogenic temperature of the $N_2O$ gas when first released. Furthermore, the drop in temperature may have been caused from the force of the released gas pushing away flame near the gas line discharge point.

Reactions in both flame activity and temperature were observed to vary depending on the quantity of released $N_2O$. Visible flames were observed being released from the bottom air slots for a sustained amount of time (~10 seconds) for the 17.4 oz test. On the other hand, a visible reaction was noted only for a short duration (< 2 seconds) for the 5.8 and 11.6 oz tests. Increases in temperature were witnessed for approximately 10-15 seconds after release in the 5.8 oz $N_2O$ test. Temperature spikes were observed to last 20-25 seconds after gas release for the 11.6 oz and 17.4 oz tests.

Tests results provided a clear trend; increasing the quantity of $N_2O$ released produced reactions that were more violent. However, the exact upper limit of $N_2O$ that could become a significant safety hazard is unknown. Additional testing data would be needed to determine the amount at which aircraft fire suppression systems would be deemed ineffectual. Therefore, until further data is acquired, it is recommended that the amount of $N_2O$ be limited to no more than 11.6 oz per ULD for air transport.

# 5 References

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