GII, LLC Explosion

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Limitations

At the request of Reserve Management Group (RMG), Exponent, Inc. (Exponent) investigated an explosion that occurred at the GII, LLC (GII) facility in Chicago, Illinois, on May 18, 2020. The purpose of the investigation was to determine the root cause of the incident and to provide recommendations intended to prevent the recurrence of a similar incident. Exponent investigated specific issues relevant to this incident as requested by GII and RMG. The scope of services performed during this investigation may not adequately address the needs of other users of this report, and any re-use of this report or its findings, conclusions, or recommendations presented herein are at the sole risk of the user. The opinions and comments formulated during this assessment are based on observations and information available at the time of the investigation. No guarantee or warranty as to future life or performance of any reviewed condition is expressed or implied.

The findings presented herein are made to a reasonable degree of engineering certainty. We have made every effort to accurately and completely investigate all areas of concern identified during our investigation. If new data become available or there are perceived omissions or misstatements in this report regarding any aspect of those conditions, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

Executive Summary

At the request of RMG, Exponent conducted an investigation of the incident that occurred at the GII, LLC (GII) facility in Chicago, Illinois. The purpose of the investigation was to determine the root cause of the incident and to provide recommendations intended to prevent the recurrence of a similar incident. Exponent's analysis was conducted in a manner consistent with the guidelines presented in NFPA 921 Guide for Fire and Explosion Investigations, 2017 edition and utilized the scientific method to evaluate the potential causes and contributing factors to the event.

Exponent collected data relating to the event through the performance of on-site inspections, collection and testing of components from the system, analysis of relevant documents and process data, and combustion calculations. Based on the available information provided and collected to date, multiple hypotheses for the cause of the explosion were developed and analyzed. To determine the cause of the explosion, two questions must be answered: 1) What was the ignition source? and 2) What was the source of fuel? The evidence clearly indicates that the RTO was the ignition source. The hypothesis that the event was ignited at the shredder was refuted. The hypothesis that methane from the RTO burner was the source of the explosion was also refuted. The only remaining hypothesis, that a flammable gas was released in the shredder and ignited at the RTO, was unable to be refuted and remained as possible. However, no affirmative physical evidence of either a shredded container or specific flammables in the process stream was able to be identified. According to NFPA 921, the industry standard guide for fire and explosion investigations, it is improper to offer a conclusion based on a lack of supportive evidence, therefore the cause of the explosion (the source of fuel) must be undetermined.[1]

Engineering and administrative controls were proposed for both the RTO and the release of flammable gases in the shredder. Engineering controls for reducing the risk of explosion included the installation of a combustible gas monitor near the shredder and a bypass vent near the RTO. Administrative controls for reducing the risk of explosion include efforts to further reduce the likelihood of introducing a flammable material into the shredder stream. GII currently has a robust screening process for the removal of flammable containers; however, GII intends to send a written reminder to their suppliers to emphasize, once again, the importance of the segregation of flammable materials from the other scrap material. This communication will include specific visual examples of flammable materials that need to be segregated and will also be distributed as a flyer to suppliers.

[1] NFPA 921, Guide for Fire and Explosion Investigations, 2017 edition, 19.6.5

Introduction

At the request of RMG, Exponent conducted an investigation of the incident that occurred at the GII facility in Chicago, Illinois. The purpose of the investigation was to determine the root cause of the incident and to provide recommendations intended to prevent the recurrence of a similar incident. Exponent's analysis was conducted in a manner consistent with the guidelines presented in NFPA 921 Guide for Fire and Explosion Investigations, 2017 edition and utilized the scientific method to evaluate the potential causes and contributing factors to the event.

Facility overview

GII is a metal recycling facility that processes metal products such as discarded demolition materials, automobiles, and appliances. Exponent's analysis focused on the metal shredding process and the associated equipment. A simple schematic of the process is shown in Figure 1.

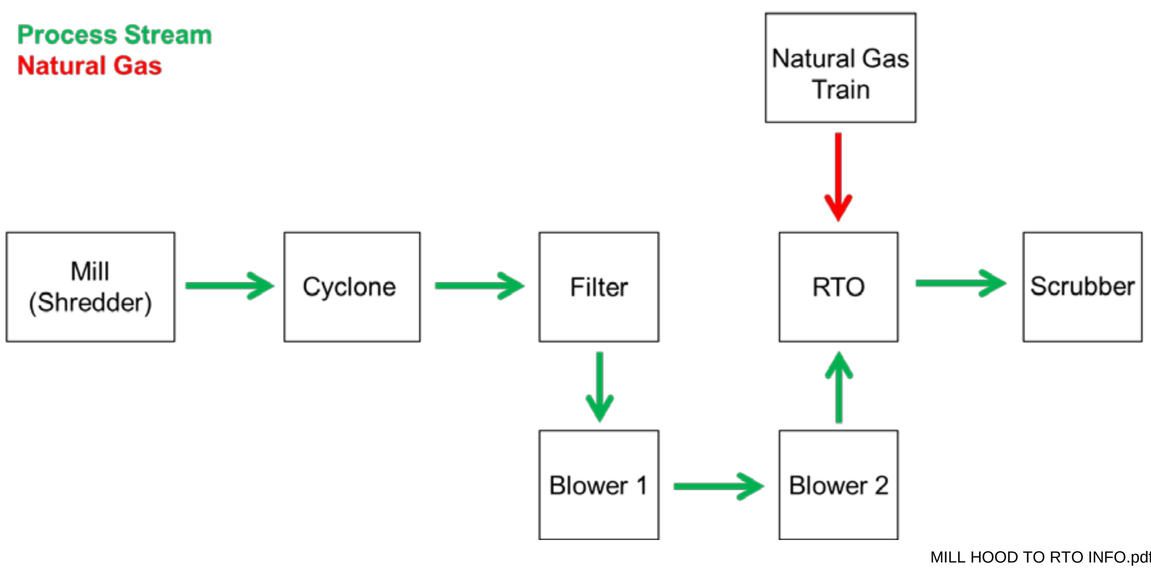

Figure 1. Simple schematic of system.

The metal to be shredded was conveyed into the shredder enclosure, where a hammer mill reduced the large metal components into smaller pieces. Water mist was sprayed into the shredder enclosure and a hood was positioned above the shredding process. Air was drawn from the shredder hood, through a cyclone, and into a roll-media filter by a blower. From there, the process stream was conveyed by a second blower into the regenerative thermal oxidizer (RTO) and finally into a wet scrubber. The RTO and wet scrubber were installed and brought online by Catalytic Products International (CPI) in August of 2019.[2]

Incident overview

On Monday, May 18, 2020, an explosion occurred at the GII facility causing damage to the RTO, the roll-media filter, the ducting between them, the blower located adjacent to the RTO, and surrounding areas. An aerial view of the facility is shown in Figure 2.

2 RTO Commissioning document, dated August 2019.

Figure 2. Aerial view of the GII facility with the RTO location outlined in yellow, the filter in blue, and the shredder in green. The approximate camera location related to the video is circled in red.

A video camera captured the incident and its approximate location is indicated in Figure 2. The first indication of explosion appeared to be located at or near the RTO as shown in Figure 3.

Screenshot from ACC Export – 2020-05-18 avi 10.53.24 AM.avi

Figure 3. Screenshot from provided video at 9:10:09:833 AM. The approximate location of the RTO is circled in yellow, the filter in blue, and the shredder in green. A first appearance of flame above the RTO is visible in the enlarged inset outlined in red.

Shortly afterwards, a jet of flame was observed exiting the ductwork at the elbow down into the filter as shown in Figure 4. This was followed shortly thereafter by an explosion at the filter and visible clouds of dust or smoke emanating from the cyclone and adjacent ducting explosion vents.

Screenshot from ACC Export – 2020-05-18 avi 10.53.24 AM.avi, cropped

Figure 4. Cropped screenshot from provided video at 9:10:10:033 AM. Jet of flame at the duct work elbow indicated with a red arrow. Approximate locations of the shredder (green), filter (blue), and RTO (yellow) are circled.

A few seconds after the initial explosion, flames were visible at the RTO before self-extinguishing in a matter of seconds. The force of the explosion ejected two of the four poppet actuators from their fixture on the RTO. The blower shroud, from the blower adjacent to the RTO, was visible traveling toward the filter. A relatively consistent plume was visible exiting the wet scrubber during the time prior to the explosion.

Activities prior to incident

On May 14, 2020, the Thursday before the incident, GII had difficulties bringing the RTO up to its operating temperature. According to interviews performed on site with a GII employee, Jeff Jones, it was explained that they were unable to start the RTO on Thursday morning and consequently did not run the shredder. He reported that he spent time that day on the phone with CPI troubleshooting at their direction. Specifically, he recalled being told to clean the flame detectors. He also repeatedly reset and restarted the RTO and observed a low flame signal on the burner controller. He recalled getting a "flame safety fault" every time he restarted.

A CPI technician, Ross Kozmin, arrived at the GII facility around 4 p.m. Just before his arrival, GII had successfully restarted the RTO and they ran the process until approximately 7:45 p.m. At that time, they shut down the RTO in order to further troubleshoot with Mr. Kozmin. According to the CPI Daily Work Sheet[3] and an interview with Mr. Jones, Mr. Kozmin checked the burner tuning and manually adjusted the second main gas regulator. Mr. Kozmin also

[3] 2020 05 JHA Daily, dated May 14, 2020.

reportedly brought a flame detector with him, which he used to sequentially replace the existing flame detectors. A similar task was described relating to the burner controllers; however, no additional detail on the reason for the replacement of the flame detector or burner controllers has been provided.

At the end of Mr. Kozmin's visit, Mr. Jones asked him to return the RTO to the condition it was before the service visit. The CPI work order states that Mr. Kozmin "found burner control on side B to be faulting" and that he found the air control valve to be corroded. Mr. Jones recalled being told to purchase a new burner controller, which he did on Friday morning.

Before the new burner controller was installed, GII was able to restart the RTO on Friday morning. According to the provided data, shown in Figure 5, the RTO remained at its operating temperature, approximately 1800°F, from Friday, May 15, at 9 a.m. through Sunday, May 17, at 8 a.m. At 8 a.m. on Sunday, May 17, the RTO was apparently turned to the "bottle-up" setting and the temperature decreased until Monday morning.

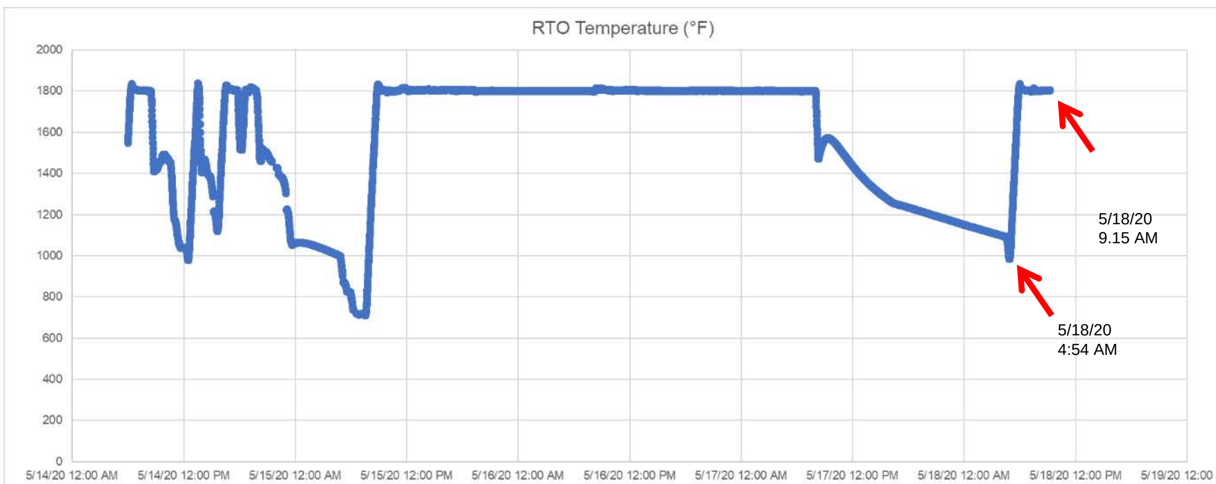

Figure 5. Provided data for the RTO temperature from Thursday, May 14, 2020 through Monday, May 18, 2020.

On the morning of Monday, May 18, 2020, the data shows that the RTO was started at approximately 5 a.m. and that it reached a steady temperature of approximately 1800°F by about 6 a.m. The temperature held relatively steady until the incident occurred at approximately 9:15 a.m. Slight fluctuations in the temperature were observed to be within 15°F over the three-hour period prior to the incident. These fluctuations are consistent with the previous start-up temperature profile.

Engineering analysis

Exponent’s analysis of the incident that occurred at the GII facility in Chicago, Illinois, was conducted in a manner consistent with the guidelines presented in NFPA 921 Guide for Fire and Explosion Investigations, 2017 edition and utilized the scientific method to evaluate the potential causes and contributing factors to the event. The scientific method is a structured approach that involves the generation of hypotheses, and collection and analysis of data, and testing of the proposed hypotheses for an incident’s cause. This methodology aims to challenge hypotheses presented in the investigation and test them through reasoning in an attempt to refute hypotheses that are inconsistent with the incident facts.

Data collection

Exponent was first contacted on the day of the incident, May 18, 2020, and first arrived on site for an initial inspection on May 19, 2020. The initial inspection included discussions and interviews with GII employees as well as a visual documentation of the damaged equipment and overall process. It is unclear what activities occurred on site between the time of the incident and Exponent’s arrival on the morning of May 19, 2020.

Exponent led a joint inspection on June 2-3, 2020, where further visual documentation was performed. The control panel was powered to collect any available data and artifacts were collected from the RTO. A list of collected artifacts is available in Appendix A.

A joint artifact exam was performed at Exponent’s facility on June 19, 2020. The retained artifacts were visually documented and tested for functionality when possible. An additional joint site inspection was performed on June 24, 2020, in order to test the flame detectors and burner controllers. The human machine interface module (HMI) was removed and eventually transferred to CPI in an effort to recover any additional available data.

Throughout the course of the investigation, documents, data, images, and videos were requested, provided, and reviewed.

Observations of Damage

During Exponent’s initial site examination on May 19, 2020, damage was observed to the RTO, roll-media filter, the blower adjacent to the RTO, and the ducting associated with these components. The RTO housing was deformed and damaged. The south end of the RTO is shown in Figure 6 and can be seen to be bulged outward.

Figure 6. Photograph of the south end of the RTO. Access door was opened after the incident.

The top of the RTO housing was also bulged outwards and the rear of the RTO housing was separated as shown in Figure 7.

D18689-0061

Figure 7. Photograph of the north end of the RTO.

Two of the poppet actuators, originally located on the top of the south end of the RTO, were found on the ground nearby. Additionally, the two poppet valves on the south side of the RTO were observed to be domed as shown in Figure 8. When compared with the north poppet valves, it was evident that the south poppet valves had been deformed during the explosion. Based on the damage, it appeared that the south poppet valves were situated in the down position at the time of the explosion. The explosion forced the south poppet valves upwards, accelerating them, and ultimately causing them to contact the upper valve seat that resulted in the deformation. According to the principle of conservation of momentum, if an object is accelerated by a certain force over a given period of time, deceleration of the same object over a shorter period of time requires a proportionally larger force. Unlike the north poppet valves that only had the force of the gas pressure acting on them, the south poppet valves were subjected to a much larger force due to the rapid deceleration upon contact with the valve seat. This event also forced the two poppet actuators to be separated and propelled upwards.

D18689-0030 (top, cropped) and D18689-0019 (bottom, cropped)

Figure 8. Photographs of one of the south poppet valves (top) and one of the north poppet valves (bottom). The south poppet valve appears to be deformed as indicated by the dotted yellow line whereas the north poppet valve is flat.

The video also captured the top of the blower shrouding as it was projected from the area. Figure 9 depicts the damaged blower and the damage to the adjacent elbow in the ducting that connects to the filter.

D18666-0013

Figure 9. Photograph of the blower adjacent to the RTO. The green ducting on the right was the elbow of the ducting connecting the filter and the RTO. The fresh air damper is visible in the bottom left corner of the image.

The explosion panels on the filter had been released during the incident and the elbow in the ducting directing downward into the filter was also damaged. No visible damage was observed on the cyclone or other portions of the ductwork; however, clouds of dust or smoke were observed to exit the cyclone and ductwork explosion vents in the video. The fresh air damper was originally located on the ductwork above the elbow shown in Figure 9, and had separated from the duct and fallen to the ground near the RTO.

The observed damage and the events depicted in the video indicated that the explosion originated at the RTO. The housing of the RTO was bulged outwards, the south poppet valves had evidence of a force directed upwards from the inlet manifold, and first visible signs of escaped flame were near the RTO in the video. The explosion appeared to propagate upstream, exiting at both elbows in the ducting between the RTO and releasing the explosion panels on the filter. The video showed a pressurization of the ductwork between the filter and the cyclone and between the cyclone and shredder near the end of the event.

RTO operation

A brief overview of the RTO operation will be helpful to put the following analysis in context. A screenshot from a CPI video is shown in Figure 10 and depicts a simplified diagram of the RTO. The subject RTO contained two burners and two sets of poppet valves instead of the single set of poppet valves shown in the diagram. Based on the observations of damage to the south poppet valves described above, the configuration shown in Figure 10 was likely the configuration of the subject RTO at the time of the incident (assuming that the left and right sides of Figure 11 correspond to the respective north and south sides of the subject RTO).

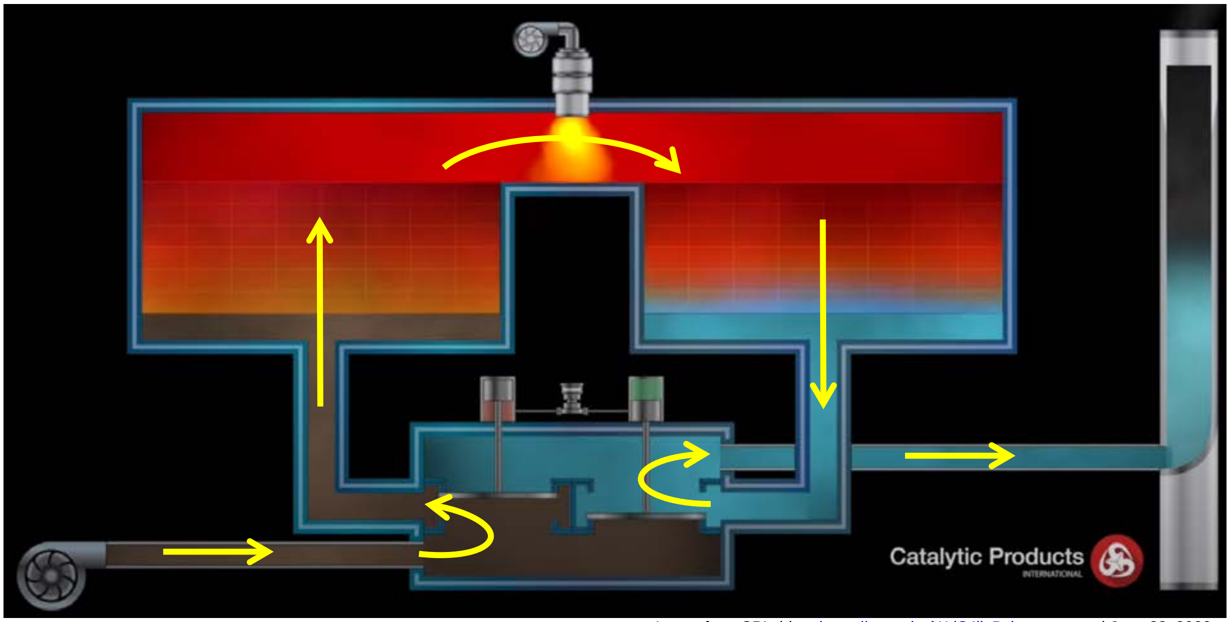

Image from CPI video, https://youtu.be/WdS4ijpByho, accessed June 28, 2020

Figure 10. Screenshot from a video describing RTO operation on CPI's website. Yellow arrows were added by Exponent to show the flow for the depicted configuration.

Process flow from the shredder (by way of the cyclone and roll-media filter) entered the RTO through a blower, shown in the lower left-hand corner of the image. The process stream was directed by the position of the poppet valves to enter one of the two media chambers. The media chambers were filled with ceramic bricks that have 2.9 mm channels in them for the process stream to flow through. [4] In the configuration shown in Figure 10, the process flow entered the poppet housing and since the left (red) poppet valve was up and the right (green) poppet valve was down, the flow entered the bottom of the left media chamber. The process flow was warmed by the hot ceramic media and reached the combustion chamber where the natural gas burners continued to heat the system. The process stream then flowed down through the right ceramic media chamber and was cooled. The stream then flowed through the right (green) poppet valve and out to the wet scrubber.

[4] LA10-43-cell-300mm-Material-Specification-Sheet-2016.pdf.

The poppet valves pneumatically switched position every three minutes so that the flow through the RTO was reversed. The subject RTO operated at approximately 1800°F and 56,000-66,000 standard cubic feet per minute.[5,6]

The two natural gas burners were fed by a single natural gas train. The main portion of the natural gas train contained two pressure regulators, two blocking valves, and a modulating control valve. A pilot gas line branched off and contained a pilot gas regulator and two pilot blocking valves. The burners each had their own flame detector.

Combustion air was also provided to the burners from a 25 horsepower blower.[7] Combustion air was controlled using a single modulating valve for both burners. Three manual valves on the combustion air system were all found to be in the open position.

The control system for the RTO consisted of the following key components: a set of Honeywell flame scanners, an Allen-Bradley CompactLogix Programmable Logic Controller (PLC), an Allen-Bradley PanelView Plus Human-Machine Interface (HMI), and a Honeywell Graphic Recorder (Chart Recorder).

The control system monitored various sensors, including nine temperature sensors for the interior of the RTO, an inlet temperature sensor, and outlet temperature sensor, flame sensors (scanners), poppet valve positions, supply gas pressure switches, a combustion air pressure switch, fan motor contactors, gas valve positions and more. The control system used these inputs to determine when a fault has occurred and closed the main gas blocking valves when the certain conditions are detected.[8] For example, based on our review, the control system would stop fuel flow when the flame signal was lost from either sensor. Further, the system used these inputs to control the temperature of the RTO by modulating the gas and air valves.

Testing results

Exponent hosted a joint artifact examination of the retained artifacts on June 19, 2020. A protocol from that inspection can be found in Appendix B and the common scribe notes of the testing results can be found in Appendix C. The goal of the testing was to determine whether the equipment was functioning properly.

All three gas regulators from the RTO gas train were found to be set at pressures in agreement with the RTO Commissioning document. The gas blocking valves on the main and pilot lines were found to be functioning as expected. The temperature sensors from the combustion chamber, media chamber, inlet, and outlet were all found to be functioning as expected. The combustion gas modulating control valve performed as expected.

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5 RTO Commissioning document, dated August 2019.

6 Mostardi Platt, Compliance Emissions Test Report, January 13, 2020.

7 D18666 – 0362.jpg.

8 Where needed for our analysis, the control system operation (wiring and logic) was reviewed; however, an exhaustive review of the logic and controls of the RTO was not performed as part of this investigation.

The gas modulating control valve functioned; however, the low fire switch was always closed and did not open during the full travel of the modulating valve. Low fire switches are typically used to inform the control system that the modulating valve is in the appropriate position to start the burner. However, for this RTO, the low fire switch was also used as part of determining when to enter Self Sustain Mode. The potential effects of this finding are explained in the Root Cause section below.

The control system was configured to turn off the burners if a loss of flame signal was detected by either flame detector. One flame scanner, FS1, was configured to directly turn off the burners, while the other flame scanner, FS2, performed this action through the PLC. Both flame detectors were tested at another joint inspection on site at GII using the burner controllers on June 24, 2020, and subsequently tested on June 27, 2020. FS1, which was the main burner control module, was found in a lockout state and did not drive the flame scanner to look for flame signal. However, upon performing a reset through pins 3 and 5 of the plug-in module, the scanner detected flame and drove the sensor shutter for the periodic test cycle.[9] FS2, which serves as a secondary flame sensing relay, detected flame and drove the sensor shutter for its periodic test cycle. Once reset, no anomalies were discovered in the operation of these components. The six previous fault codes were also recovered from the burner control module. These are presented in Table 1 below and discussed in the Root Cause section below.

Table 1. Fault history captured from FS1.

History	Hours	Delta Hours	Cycles	Delta Cycles	Code	Meaning	Where in Sequence	System Failure[10]
Current	2247		307					
H1	2247	0	307	0	33	Pre-Ignition Interlock Fault	PostPurge 00:05	Pre-Ignition Interlock fault.
H2	2242	5	306	1	33	Pre-Ignition Interlock Fault	PostPurge 00:05	Pre-Ignition Interlock fault.
H3	2193	54	303	4	19	Main Flame Ignition	RUN	Flame was lost during MFEP or the first 10 seconds of the RUN state.
H4	2193	54	300	7	28	Pilot Flame Fail	Pilot Ignition 00:10	Pilot flame failure.
H5	2193	54	298	9	19	Main Flame Ignition	RUN	Flame was lost during MFEP or the first 10 seconds of the RUN state.
H6	2193	54	297	10	19	Main Flame Ignition	RUN	Flame was lost during MFEP or the first 10 seconds of the RUN state.

Combustion Analysis

An analysis of combustion conditions was performed in order to analyze the possible fuel source for the explosion. The intent of the following calculations was not to specifically model the incident in its entirely, but simply to provide bounding guidance to determine whether various hypotheses were possible or impossible. Scenarios involving both natural gas from the RTO and other fuels from the shredder were examined.

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9 This behavior is consistent with the safety shutdown (lockout) feature of the burner control. Burner controls require a reset once entering a lockout mode and do not energize the gas valves until the fault is cleared and control sequence is restarted.

10 Honeywell RM7800E,G,L,M; RM7840E,G,L,M 7800 SERIES Relay Modules, 32-00143-01, M.S. 12-17 and Honeywell 7800 SERIES S7800A Keyboard Display Module, 65-0090-6, M.S. Rev. 5-06.

Flammable mass calculations were performed to conservatively estimate the amount of flammable gas or vapor needed to cause the observed damage for a variety of potential fuels. Natural gas from the RTO, and propane, acetylene, and gasoline from the shredder were used as exemplar fuels.

Next, the theoretical expansion of hot combustion gases was estimated in order to conservatively estimate how far the flames could have traveled through the process. A comparison of flame speeds for natural gas were compared with the speed of the process stream in the duct work in order to analyze the potential path of the explosion. Finally, an evaluation of the quenching distance was also performed to determine whether a flame could pass through the ceramic media chamber.

Volumes of various portions of the system were calculated based on provided drawings. Within the RTO, three separate volumes were considered. As shown in Figure 11, three subdivisions within the RTO were made. The combustion chamber, or plenum, was designated as the open area at the top of the RTO where the natural gas burners operated. The media chambers were defined as the areas of the RTO housing the ceramic media and the poppet housing area was defined as the manifolds above and below the poppet valves. Since it is likely that the poppet valves were both forced into the up position during the explosion, which would isolate the exhaust half of the manifold, half of the total poppet housing volume was used for purposes of the combustion analysis.

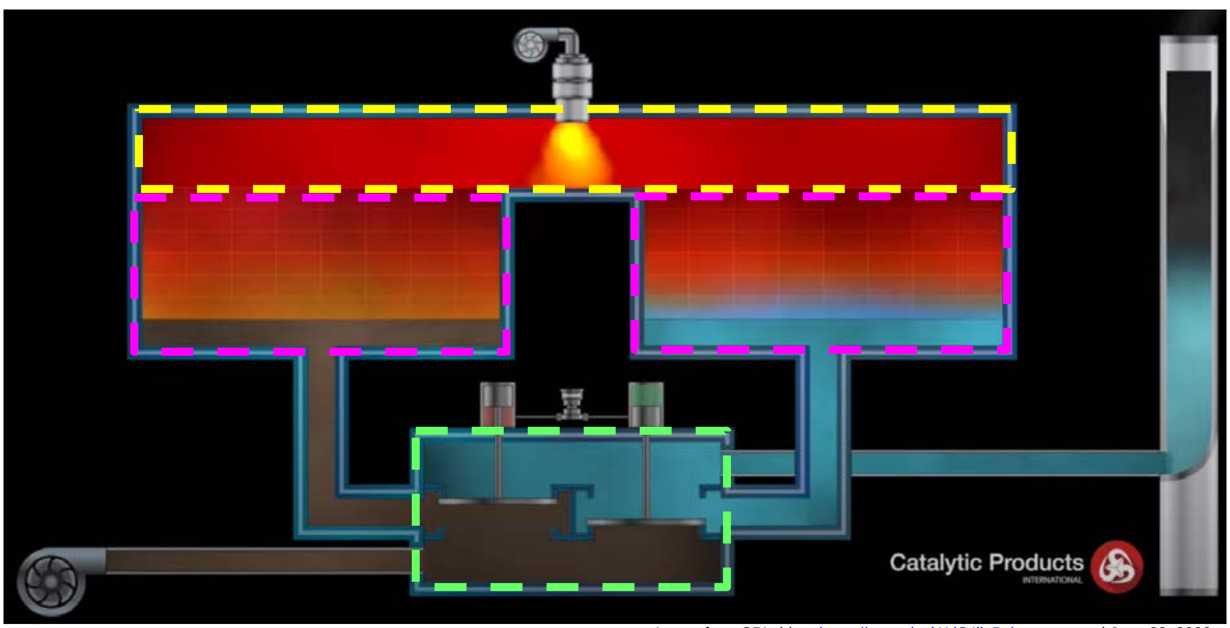

Image from CPI video, https://youtu.be/WdS4ijpByho, accessed June 28, 2020

Figure 11. Drawing of the RTO with the combustion chamber indicated in yellow, the media chambers indicated in pink, and the poppet housing indicated in green.

Volumes of duct work between the RTO, roll-media filter, cyclone, and shredder were estimated based on provided drawings. Similarly, the volumes of the cyclone, roll-media filter, and shredder hood were estimated for the analysis.

Flammable mass calculations

The damage caused by an explosion depends on many factors including the fuel composition, the fuel concentration and distribution, the discharge rate and location of the fuel release, the size and shape of the compartment space, the presence or absence of mechanical ventilation, and the location of the ignition source. Within the RTO, complicating factors of a high momentum gas source (the burner), the large ventilation source (the process stream), and the multi-compartment nature of the geometry make a precise calculation difficult. Therefore, combustion calculations were performed to establish or refute the feasibility of certain scenarios. These calculations provided a sound, scientific basis for testing hypotheses. However, these calculations are not intended to be a reconstruction of the actual conditions leading to the accident.

First, a release of natural gas from the RTO burners into the combustion chamber was considered. In order to calculate a conservative value for the potential flammable mass needed, a partial volume explosion technique was used.[11] This method assumes that a portion of the total volume was filled with a stoichiometric mixture of fuel and air, that there was no ventilation in the volumes, and that the methane and air were well mixed when ignited. Three different volumes were considered: the combustion chamber alone, the combustion chamber and the media chambers, and the total volume of the RTO (the combustion chamber, media chambers, and poppet housing). Based on guidance from NFPA 921 and for purposes of this calculation, the observed damage to the RTO was assumed to be caused by a 2.3-3 psig overpressure event.[12]

Table 2 shows the results of this calculation. The "Lower Damage Limit" corresponds to an overpressure of 2.3 psi whereas the "Upper Damage Limit" corresponds to an overpressure of 3 psi. The fill time is calculated based on the maximum natural gas flow rate of 15,000 SCFH (250 scfm).[13]

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[11] Ogle RA. Explosion hazard analysis for an enclosure partially filled with a flammable gas. Process Safety Progress 1999; 18:170–177.

[12] NFPA 921, 2017 edition, Table 23.14.4.1.5(b) Property Damage Criteria.

[13] 18-10089-310 R02.pdf.

Table 2. Minimum methane volumes and respective fill time required by the partial fill explosion model for three different volumes within the RTO.

	Methane volume to cause damage (standard cubic ft)	Fill Time at Max Flow Rate (seconds)	Fill Time at Half Max Flow Rate (seconds)
Enclosure Volume of initial explosion	**Lower Damage Limit - Upper Damage Limit**	**Lower Damage Limit - Upper Damage Limit**	**Lower Damage Limit - Upper Damage Limit**
Combustion Chamber	5.2 – 6.8	1.3 - 1.6	2.5 - 3.2
Combustion Chamber and Media Chamber	15 - 19	3.6 - 4.6	7.1 - 9.3
Combustion Chamber, Media Chamber and Poppet Housing	19 - 24	4.5 - 5.8	9.0 - 12

The results of the calculations indicated that enough methane to cause the observed damage could have flown into the combustion chamber in seconds. However, these calculations assumed that there was no ventilation, no combustion of the fuel, and that the fuel and air were well mixed when ignited. In the subject explosion, there was a constant flow of approximately 56,000-66,000 standard cubic feet per minute (scfm) of process stream flowing through the RTO.[14] The RTO was also at a high temperature, which would have made it difficult to accumulate enough methane in a well-mixed state without combusting it. The conclusion drawn from these calculations of minimum flammable mass is that an explosion of methane from the burner in the RTO was possible.

Similar calculations were made to assess the feasibility of typical flammable gases: propane and acetylene. As above, these calculations were performed to establish or refute the feasibility of certain scenarios and are not intended to be a reconstruction of the actual conditions leading to the accident. The same partial volume explosion method was used, again assuming the explosion was ignited by the RTO. In addition to the previously considered enclosure volumes, the volume of the duct network prior to the RTO was also considered as the flammable gas would be expected to flow through that network to reach the RTO. The results of these calculations are shown in Table 3. As with methane, the overpressures for lower and upper damage limits were 2.3 psi and 3 psi.

[14] Mostardi Platt, Compliance Emissions Test Report, January 13, 2020.

Table 3. Minimum flammable gas volumes of propane and acetylene required for reaching overpressure damage limits.

	Propane volume (standard cubic ft)	Acetylene volume (standard cubic ft)
Enclosure Volume of initial explosion	**Lower Damage Limit - Upper Damage Limit**	**Lower Damage Limit - Upper Damage Limit**
Combustion Chamber	2.2 – 2.8	4.9 – 6.3
Combustion Chamber and Media Chamber	6.2 – 8.1	14 - 18
Combustion Chamber, Media Chamber and Poppet Housing	7.8 - 10	17 - 23
Combustion Chamber, Media Chamber, Poppet Housing and pre-RTO ducting	16 - 21	35 - 46

The calculations showed that fairly small volumes of propane and acetylene were required to cause the observed damage. A typical barbeque propane tank holds approximately 170 standard cubic feet of propane and a larger lift truck style propane tank holds approximately 280 standard cubic feet. The amount required to create the observed damage, was less than 10 standard cubic feet. Similarly, welding rigs typically hold an acetylene cylinder with 10-140 standard cubic feet of gas. The minimum amount calculated to create the observed damage to the RTO was between 5-25 standard cubic feet. Assuming the flammable gases could have reached the RTO, had a full container of propane or acetylene been shredded, they would have contained sufficient flammable mass to cause the observed damage.

In addition to acetylene and propane, gasoline was also considered as a potential fuel source from the shredder due to the potential shredding of gasoline tanks in automobiles. Unlike acetylene and propane, which are gases at ambient conditions, gasoline is a volatile liquid which must be evaporated before it can form an explosive mixture. An estimation of the evaporation of gasoline is complex and depends on many variables such as the surface area of liquid, vapor pressure of the gasoline constituents, and the heat transfer rate between the liquid gasoline and the surroundings. Experiments in the literature for measuring the mass loss rate for gasoline in an open container in ambient conditions (approximately 70ºF) resulted in a measured mass loss of 3.5 grams per second.[15] Although the shredder was at a higher than ambient temperature which would increase evaporation rate, the application of water sprays in the shredder would likely lower the evaporation rate of gasoline. Another physical mechanism that could create an ignitable mixture of gasoline and air is the atomization of the gasoline liquid into liquid droplets during the shredding process. These liquid droplets could become fluidized in the shredder and transported downstream through the ductwork towards the RTO. Atomization could serve as a feasible mechanism for creating an ignitable mixture of gasoline and air. Even if the shredding environment increased the evaporation of gas through an elevated temperature or aerosolization,

[15] Zinke et al. Proc Safety Prog. 2019; e12128. The mass loss is based on gasoline in a 0.6 m diameter open cylinder.

subsequent contact with cooler air and surfaces downstream of the shredder could result in condensation of the evaporated gasoline.

The partial volume explosion method was used to estimate the volumes of liquid gasoline that would be capable of causing the observed damage to the RTO. The results of these calculations are shown in Table 4. It was assumed that the liquid volumes of gasoline fully evaporated to vapor and were well mixed with air. Based on an estimated evaporation rate of 3.5 g/s, between one and eight minutes would be required to evaporate enough gasoline vapor to fulfill the partial volume explosion criterion. This long evaporation time would not allow sufficient gasoline vapors to accumulate, reach the RTO, and cause the observed damage. However, the atomization of gasoline during the shredding process might be capable of producing an ignitable mixture.

Table 4. Liquid volumes and evaporation times for gasoline based on the partial volume explosion method.

	Liquid Gasoline Volume Required (gallons)	**Evaporation Time (minutes)**
Enclosure Volume of initial explosion	**Lower Damage Limit - Upper Damage Limit**	**Lower Damage Limit - Upper Damage Limit**
Combustion Chamber	0.07 - 0.09	0.9 - 1.1
Combustion Chamber and Media Chamber	0.19 - 0.25	2.4 - 3.2
Combustion Chamber, Media Chamber and Poppet Housing	0.24 - 0.32	3.1 - 4.0
Combustion Chamber, Media Chamber, Poppet Housing and pre-RTO ducting	0.50 - 0.65	6.2 - 8.1

Expansion calculations

As described above, the video of the explosion as well as the observed damage indicated that flame and combustion products reached at least to the filter and potentially farther upstream to the cyclone. Had an explosion of methane from the RTO burners caused the explosion, the combustion products from that event would need to have been capable of filling at least the volumes of the RTO, the ducting between the RTO, and the filter to cause the observed damage. A rough estimate of expansion volume from the combustion of methane and air can be calculated using the expansion ratio.[16] For methane/air mixtures, which have an expansion ratio of 7.4, the combustion products will have a volume of 7.4 times the initial fuel/air volume.[17]

[16] NFPA 921, Guide for Fire and Explosion Investigations, 2017 edition, 28.8.2.1.5 Expansion Ratio.

[17] NFPA 921, Guide for Fire and Explosion Investigations, 2017 edition, Table 23.8.2.1.4.

First, the minimum flammable masses calculated above were used to estimate the associated combustion product volumes. These results are shown in Table 5.

Table 5. Expanded volumes of combustion products calculated for methane volumes in Table 1.

	Methane volume to cause damage (standard cubic ft)	**Methane/Air Volume (standard cubic ft)**	**Expanded Volume after combustion (standard cubic ft)**
Enclosure Volume of initial explosion	**Lower Damage Limit - Upper Damage Limit**	**Lower Damage Limit - Upper Damage Limit**	**Lower Damage Limit - Upper Damage Limit**
Combustion Chamber	5.2 – 6.8	55 - 71	400 - 530
Combustion Chamber and Media Chamber	15 - 19	160 - 200	1200 - 1500
Combustion Chamber, Media Chamber and Poppet Housing	19 - 24	200 - 260	1500 - 1900

The expanded combustion product volumes range between approximately 400 and 2000 standard cubic feet. When compared to the volume of the RTO, nearly 10,000 cubic feet, it is clear that the conservative flammable masses calculated above are insufficient to cause visible flame to propagate upstream and enter the filter. However, these flammable masses were calculated as minimum flammable masses to cause the damage.

A more appropriate calculation is to calculate the minimum flammable mass required to produce a combustion product volume large enough to reach the points observed in the video. The resulting time to fill the RTO with that mass of methane through the burner was also calculated. These results are shown in Table 6.

Table 6. Expansion volumes and corresponding methane volumes needed for reaching parts upstream of RTO.

	Expansion volume needed (standard cubic ft)	**Methane/Air Volume needed (standard cubic ft)**	**Methane volume needed (standard cubic ft)**	**Fill Time at Max Flow Rate (seconds)**	**Fill Time at Half Max Flow Rate (seconds)**
To reach blower 2	9800	1300	130	30	61
To reach blower 1	11800	1600	150	36	73
To reach filter	16000	2200	210	49	99
To reach cyclone	16400	2200	210	50	101
To reach shredder	19300	2600	250	60	119

In order for a methane/air explosion to initiate in the RTO and create enough combustion products to reach the filter, the burner would need to be receiving methane through a fully open gas train for one to two minutes. The methane would need to accumulate in the RTO and not be passed out to the wet scrubber with the exhaust or consumed by combustion. Based on the above analysis of the RTO control system, gas train components, and an understanding of the system operation, it was not possible to collect a minute's worth of methane flow in the RTO while the process stream was running and the RTO was at the high steady state temperature of 1800°F.

Residence Time

Based on flow rate of 56,000 scfm,[18] volumetric average residence times for the process stream were calculated for major components of the RTO. This can be understood to conservatively approximate the time the process stream would spend in the RTO before being exhausted to the wet scrubber. The estimated RTO residence time, based on the entire volume of the RTO, was approximately 11 seconds. The portion in the combustion chamber was estimated to be three seconds.

The operation of the RTO included a reversal of flow every three minutes by the changing poppet valve positions. During the flow reversal, it was possible for a portion of the process stream to have approximately double the residence time. Even then, the residence time is conservatively estimated to be approximately 22 seconds for the entire RTO.

Natural gas flow into the RTO from the burner occurred at approximately the half way point for the process flow through the RTO as is shown in Figure 10. This would mean a conservative approximation for the residence time of any unburnt natural gas from the burner would be between 5-17 seconds. This number is still well below the minimum time needed to accumulate the amount of gas calculated above to result in the observed damage to the system.

Quenching Distance

Calculations were performed to determine whether a natural gas flame was capable of propagating through the ceramic media. Quenching distance is a theoretical minimum separation between two flat parallel plates that would allow a flame to pass through.[19] Any separation less than the quenching distance would result in extinguishment of the flame. The quenching distance is dependent on many factors including the type of fuel, fuel-oxidant ratio, temperature of the channel, and materials from which the channel is constructed.

For methane, the primary component of natural gas, quenching distances have been measured to be as low as 2 mm for stoichiometric conditions, with greater quenching distances for lean or rich conditions.[20] This is comparable with the cell size for the media in the RTO (2.9 mm).[21] The reported quenching distances in the literature are typically based on experiments performed at ambient temperature conditions. Heating the channel to a higher temperature would result in a lower quenching distance.[22] Ceramic channels will also have a lower quenching distance than

[18] Mostardi Platt, Compliance Emissions Test Report, January 13, 2020.

[19] C.K. Law, *Combustion Physics*, 2006, p. 305.

[20] M. Fukuda et al., Bulletin of the JSME, Vol. 24, No. 193, 1981.

[21] LA10-43-cell-300mm-Material-Specification-Sheet-2016.pdf.

[22] H. Yang, et al. (2011) Combustion Science and Technology, 183: 5, 444–458.

that of steel, which is typically used in the published experiments. Other simple hydrocarbons, such as propane, can also be reasonably assumed to have similar quenching distances.[23]

Given the cell size of the media in the RTO, the elevated temperature of the media during RTO operation, and construction of media from ceramic material, the propagation of a natural gas flame through the ceramic media cannot be refuted. It is possible that a natural gas flame could have traveled through the ceramic media.

Flame speed

Since video of the incident showed flow of combustion products upstream opposite the direction of the process flow, a comparison of flame speed and average flow velocity of the process stream was performed. The process velocity in the duct leading up to the RTO from the filter is nominally 21 m/s (4100 fpm).[24] Thus, for a flame front to travel in the upstream direction, it would be necessary for the flame speed to exceed the process velocity. While laminar flame speeds of commonly used fuels are smaller in comparison to the process velocity (as low as 0.4 m/s for methane to as high as 1.5 m/s for acetylene), flow conditions during the explosion would have been highly turbulent and would have resulted in a turbulent flame condition. Turbulent flame speeds for a given fuel can be orders of magnitude higher than laminar flame speeds depending on the flow conditions. As an example, methane/air flames have been shown to reach turbulent flame speeds of up to 130 m/s (25,600 fpm) from turbulence produced by obstructions in the flow.[25] In order for a flame to reach these speeds, it would need to be sustained by a sufficient source of fuel and air.

The nominal flow rate for the process stream was 56,000 scfm before reaching the second blower. A consistent plume was visible exiting the wet scrubber prior to the incident, indicating that flow was proceeding through the RTO. For a turbulent flame to propagate upstream toward the filter, it would require either a flammable mixture in the process stream or a fuel/air flow rate greater than 56,000 scfm. The natural gas train was designed to provide a maximum flow rate of 250 scfm. At stoichiometric conditions (9.5% methane, 90.5% air) this would result in a total flow rate of approximately 2600 scfm. Thus, the natural gas train would not have been able to sustain a turbulent flame traveling upstream against the normal process stream.

Summary of Calculation Conclusions

Combustion analyses were performed to assess potential fuels and explosion pathways. Minimum flammable mass calculations indicated both the methane from the burner and flammable gases from the shredder could have produced enough fuel for the observed explosion damage at the RTO. Although evaporation of gasoline at the shredder would not be sufficiently fast, mechanical atomization of gasoline by the hammer mill may be capable of producing an ignitable mixture. Calculations of quenching distance related to the ceramic media indicated that it was possible for a flame of methane, or other similar gases, to flow through the ceramic media. Additionally, maximum flame speeds for methane found in the literature were higher

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[23] C.K. Law, *Combustion Physics*, 2006 p. 306.

[24] Based on diameter from "MILL HOOD TO RTO INFO.pdf" and a nominal flowrate of 56,000 scfm.

[25] I.O. Moen et al., Combustion and Flame 39: 21-32 (1980) 21.

than the velocity of the process stream. However, the maximum flow rate of natural gas from the natural gas train was insufficient to sustain a flame traveling in the upstream direction.

The calculation of the expansion of combustion products indicated that the minimum flammable masses needed to result in the observed damage to the RTO were insufficient to produce the observed flames and damage to the ducting and filter. Furthermore, the minimum amount of flammable mass needed to produce the observed flames and damage upstream at the filter and beyond, would have required one to two minutes of methane flowing into the RTO and accumulating without losses to the exhaust or combustion. The analysis showed that it was not possible for the explosion to originate from methane flowing through the burners of the RTO.

Root Cause of Explosion Event

Throughout the data gathering and analysis process, hypotheses for the root cause of the explosion were generated and assessed. The discussion of these hypotheses below is based on the available data and information gathered to date. The limited process data available and loss of alarm messages during the explosion necessarily constrained the conclusions that could be drawn from this information. At this stage in the analysis, it was assumed that the wiring in the field at the time of the explosion matched the provided drawings and that the logic provided was the correct logic as was running in the PLC. This section will serve as a summary of the hypotheses developed and analyzed.

The surveillance video captured images of flame venting from the equipment and ductwork during the explosion. These images, in conjunction with the observed mechanical damage to equipment and ductwork, indicate a combustion explosion. Three factors are required for combustion: fuel, oxidizer, and an ignition source. These three factors are known as the fire triangle. The fire triangle implies that three kinds of hypotheses must be considered to evaluate the cause of the explosion.

The first step in the determination of the root cause of the explosion is to identify the ignition sequence. As described above, the video indicated that the explosion was initiated at the RTO and propagated upstream toward the shredder. The progression of the explosion and the observation of flames is consistent with a deflagration (propagating flame) involving a diffuse fuel such as a flammable gas or vapor. The RTO operated at high temperatures (ceramic media temperatures in excess of 1500°F) and could have acted as an ignition source for a variety of fuels. However, the observation of the first flame at the RTO only indicated the location of ignition. It did not indicate the source of fuel. Based on the design of the shredder system and its air pollution control equipment, it was concluded that there were two potential sources of the fuel for a deflagration: the RTO and the shredder.

The next stage of hypothesis development focused on identifying the scenarios under which a fuel source for the explosion could develop. The stack tests performed on the shredder indicated the presence of organic chemicals.[26] However, the concentrations measured were on the order of 100 times too small to support combustion (147 to 269 ppm total hydrocarbons as propane

[26] RK & Associates, Shredder Emissions Test Report - Total Hydrocarbons, Particulate, and Metals, June 25, 2018.

[corrected] versus the lower flammability limit of propane: 21,000 ppm).[27] Thus, the normal emissions of the shredder were not considered to be a reasonable source of fuel for the explosion. The RTO utilized a natural gas burner. The first scenario considered was the potential malfunction of the fuel gas train leading to an accumulation of unburnt natural gas that then experienced a delayed ignition. The second scenario considered the possibility that a flammable gas or vapor was released in the shredder. Given the great diversity of metal items processed at a scrap metal facility, the shredder had the potential to shred items that contained flammable liquids or gases. These two fuel sources provided the framework for the rest of the hypothesis development.

The final factor to consider was the oxidizer source. Air was abundantly available throughout the process stream, from the shredder to the RTO. There was no indication of another oxidizer being present. Therefore, it was concluded that air was the oxidizer for this combustion explosion.

Natural gas hypotheses

There were no reported external leaks in the gas train for the RTO and the damage to the equipment was clearly internal. Therefore, for natural gas to have fueled the explosion, it would have needed to flow through the gas train and enter the combustion chamber. The data provided indicates that the RTO measured temperature was near 1800°F for approximately three hours prior to the explosion. Based on this data, the RTO appeared to be in steady state, which would have eliminated any pilot, purge, or other start-up problems. No functionality problems were observed with the temperature sensors that would have indicated an error with the steady state determination.

Additionally, the gas regulators, gas valves, flame detectors, and combustion air valves functioned appropriately during Exponent's testing. The main gas modulating control valve did have an anomalous result relating to the low fire signal; however, this related to start up and would not have affected steady-state operation. Based on the testing performed on the gas train components, a physical failure of the gas train components was refuted as a cause of the explosion.

In the days leading up to the explosion, there were indications of potentially unstable combustion at the RTO. The "post established flame loss" alarm message was observed multiple times during troubleshooting on the Thursday before the incident. That alarm message indicated that a flame sensor did not detect a flame when it expected to. This may have indicated that the flame had extinguished, that there was a barrier to detection (such as a dirty or failed flame detector), or that the flame was unstable and intermittent. Mr. Jones, with GII, also reported seeing a lower than usual flame signal on the burner controller during troubleshooting. This could have been an indication of unstable combustion and a weak flame signal.

When CPI was troubleshooting on site, their work order indicated they checked the burner tuning. However, when CPI left the GII facility, the RTO had not yet been restarted successfully and CPI had concluded that the burner controller was not working. It is unknown whether the

[27] C.K. Law, Combustion Physics, 2006 p. 347.

burner was successfully tuned during CPI's visit. In Exponent's testing, the flame detectors and burner controllers functioned as expected once the burner controllers were reset. During their visit on the Thursday before the incident, CPI also changed the main gas pressure regulator as part of troubleshooting. Exponent confirmed that the gas regulators were at their commissioned levels at the time of their examination. No visual indications that the combustion air modulating valve linkage had been changed from its original setting were observed.

The RTO had been successfully operated for over 50 hours after the troubleshooting with CPI and before the explosion. Unfortunately, only one set of temperature data was recorded and available for analysis after the incident. It is Exponent's understanding that the RTO Temperature shown in Figure 5 was recorded as the highest temperature of nine different temperature sensors in the RTO once every 10 seconds. No data specific to a single temperature sensor were available for analysis to determine whether relevant temperature anomalies existed in the RTO that may point to unstable or poor quality combustion. Additionally, no data on poppet valve position, gas or combustion air valve position, blower activity, flame signal, or pressure data were recorded or available for analysis.

Based on the observed explosion damage, Exponent calculated the quantity of natural gas required under a variety of potential circumstances. The accumulation of unburnt natural gas in the RTO would have required a flow of gas for a specific duration of time. Exponent also calculated the average residence time of gas within the combustion chamber. A comparison of the natural gas flow times versus the residence time of the process stream clearly indicated that it was not possible to accumulate the quantity of natural gas needed to create the observed explosion damage. Thus, the calculations indicated that the RTO was not likely to be the source for fuel for the explosion.

The damage to the poppet valves indicates that the pressure in the entrance side of the poppet housing was greater than the pressure in the exit side of the poppet housing and was suggestive of an explosion in the inlet side of the RTO. As described above, and shown in Figure 8, the south poppet valves were forced upwards by the explosion. This observed damage is not consistent with a fuel cloud ignited within the combustion chamber. If the explosion had occurred in the combustion chamber, the overpressure damage to the poppet valves would indicate a downwards motion. Thus, the damage done to the poppet valves does not support the hypothesis of natural gas from the RTO being the fuel for the explosion.

The potential effects of the low fire switch being closed regardless of the actual position of the gas modulating valve were analyzed. Typical burner controls use the low fire switch to determine whether conditions are appropriate for light-off. In this particular application, the low fire switch is also used as a permissive to enter the RTO's Self-Sustain Mode. This mode is described on page 3 of the manual with the following text:[28]

[28] RTO O&M Manual.pdf, pdf page 18.

OX_STEP 95 – The RTO will go into **SELF SUSTAIN MODE** when one of the RTO thermocouples exceeds the set point and the low fire start switch is made for a preset time. If (1) of the thermocouples (TE190, TE191, TE192, TE196, TE197, TE199, TE200, TE201, TE203) rise above an adjustable set point from a secured screen for 30 seconds and the gas CV low fire input, the main gas valves are turned off. When the valves are de-energized we do not look at the main gas valve open and main block valve open limit alarms. The system will continue to run this way until the hottest thermocouple drops below a set point temperature plus self-sustain value (adjustable from secured screen) for 15 seconds. At this point the main gas valves are re-energized and the sequence returns to OX_STEP 90.

Given the finding of the low fire switch always being closed, this mode of the RTO was analyzed in our work. When the RTO was in self sustain mode, control relay 1312 is energized, which caused the block valves to be de-energized.[29] However, the pilot flame remained energized during this mode.[30] If the pilot flame was lost and the flame scanner no longer detected the presence of flame, the burner would have shut off. When the RTO enters this mode, it also turned the modulating gas valve to its lowest setting. Based on this analysis, self-sustain mode required a flame to be present to maintain the pilot. Thus, unburned fuel was not entering the RTO. This is also supported by the temperature data, which indicated a temperature of approximately 1800°F. Had unburned fuel and air been exposed to that temperature, it likely would have combusted.

The fault history from FS1 was evaluated in the context of the RTO operation leading up to the explosion. H1 is the most recent fault code stored in FS1 and its time stamp and cycle count match the current time stamp and cycle count of the controller. It is likely the result of a loss of field wiring or flame present on FS2 during the incident and occurred after the unit shutdown (post purge). H2 occurred 5 hours before the current time, which is not concurrent with the time of the explosion. H3 through H6 are the oldest fault codes and occurred 54 hours of operation prior to the current time. This time frame is consistent with troubleshooting activity that took place Thursday evening.

Based on the observed damage, the testing of the RTO components, the calculations of combustion product expansion and flame speed, and analysis of the available data, the hypothesis that natural gas from the RTO gas train caused the explosion was refuted.

Exponent next considered the hypothesis that the explosion fuel came from the shredder.

Fuel from the shredder hypotheses

GII had a robust system for removing compressed gas containers from their process stream. The program included efforts to educate suppliers, reward suppliers for compliance, notify suppliers for non-compliance, as well as employed inspectors to search the incoming stream for these materials. However, according to interviews with plant personnel, containers containing flammable gases or liquids were inadvertently passed through the shredder on occasion. Based

[29] See electrical schematic diagram page 6 of 24.

[30] Burner control FS1 is a RM7800 M 1011. See 32-00143.pdf (RM7800E,G,L,M; RM7840E,G,L,M 7800 SERIES Relay Modules). Pdf pages 8 and 13 demonstrate that this version of the controller maintains the pilot valve during the entire call for heat.

on their experiences, if a pressurized container, such as a propane tank, was shredded, there would be a noticeable pressure release event in the shredder. They reported that if a container of flammable liquid, such as an automobile gas tank, was shredded, they expected a small ignition event at the shredder. This is because the shredding process was violent and produced sparks and hot pieces of metal. No pressure release event or fire was reported at the shredder at the time of the incident.

The shredder also contained a water spray system to cool the shredder and control dust emissions. The water spray may have also displaced air around the hammer mill. For flammable gases or vapors to be ignited, they must both encounter an ignition source and be mixed appropriately with oxygen.[31] At least at the point of release, the flammable mixture is likely to be too rich to be ignited.

However, if a flammable vapor or gas had been released in the shredder, it would have become diluted with fresh air as the fuel traveled down the duct and through the filter. Downstream from the shredder the flow would have encountered a cyclone and large filter enclosure on the way to the RTO. The turbulent flow in the ducting, the swirling flow in the cyclone, and the expansion into the larger area of the filter would all have promoted mixing and dilution of the flammable gas or vapor with the surrounding air. Therefore, a fuel cloud that would be too rich to ignite at the shredder could have been diluted and mixed to an ignitable concentration as it traveled downstream from the shredder. This scenario is consistent with the physical evidence.

The observed damage to the poppet valves is consistent with an explosion scenario wherein a cloud of flammable gas entered the RTO at the poppet housing entrance and flowed upwards into the hot ceramic media. In this scenario, the leading edge of the flammable cloud would be where it entered the hot ceramic media. The flame would then flash back, igniting ever-increasing amounts of fuel. This scenario would lead to a greater overpressure on the entrance side of the poppet housing compared to the pressure on the exit side of the poppet housing.

There is no physical evidence that a fuel container was shredded shortly before the time of the explosion. However, according to the calculations described above, typical commercially available flammable gas containers hold sufficient amounts of fuel to have reached flammable levels within the ducting and RTO. For gasoline, a liquid fuel, the evaporation rate was shown to be incapable of allowing enough vapor to have accumulated and cause the observed damage; however, aerosolization of the gasoline may have resulted in a flammable mixture reaching the RTO.

At the time of the explosion, combustible gases were not measured in the ductwork or shredding systems, so no confirmation that a combustible gas was present can be performed. Thus, the inference that the explosion fuel was released by the shredder cannot be concluded to within a reasonable degree of engineering certainty.

While the analysis shows it is possible that fuel from the shredder ignited in the RTO and caused the observed damage, no affirmative physical evidence of a shredded container or

[31] Autoignition of fuel and air mixtures can occur at sufficiently high temperatures without a piloted ignition source.

specific flammables in the process stream was able to be identified. The type of hypothetical container, the type of fuel contained within it, and the amount of fuel contained within it all remain unknown. Although the "process of elimination is an integral part of the scientific method," selecting a conclusion "for which no supporting evidence exists" is considered an inappropriate use of the scientific method and is often referred to as *negative corpus*.[32] NFPA 921, the industry accepted guide for fire and explosion investigation, cautions investigators against the use of negative corpus and states (***emphasis added***):

> 19.6.5.1 Cause Undetermined. In the circumstance where all hypothesized fire causes have been eliminated and the investigator is left with no hypothesis that is evidenced by the facts of the investigation, the only choice for the investigator is to conclude that the fire cause, or specific causal factors, remains undetermined. ***It is improper to base hypotheses on the absence of any supportive evidence. That is, it is improper to opine a specific fire cause, ignition source, fuel or cause classification that has no evidence to support it even though all other such hypothesized elements were eliminated.***

Therefore, the fuel source of the explosion is undetermined.

In conclusion, the determination of the fundamental causes of the explosion begin with the determination of three factors: the fuel, the oxidizer, and the ignition source. The fuel source did not come from the RTO (specifically, the natural gas used to fire the RTO burner). It may have come from the shredder (a container of flammable material fed to the shredder), but that hypothesis is not supported by the available evidence. The oxidizer was the ambient air. The ignition source was determined to be the hot internal components of the RTO.

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[32] NFPA 921, Guide for Fire and Explosion Investigations, 2017 edition, 19.6.5 Appropriate Use.

Mitigation strategies

As described above, the cause of the explosion was undetermined. However, a release of flammable gas from the shredder was found to be possible. Meaningful mitigation strategies can be deployed, both related to the shredder and the RTO, to reduce the risk of future incidents.

According to the hierarchy of hazard control, engineering controls are preferred to administrative controls.[33] However, when used together, the combination of both engineering and administrative controls can form the basis for a robust safety management program. This analysis will discuss both engineering and administrative types of controls as they can both be used to reduce the overall risk of explosion.

Engineering controls

Engineering controls are physical additions or modifications to the process used to reduce the risk of a specified hazard. These may include sensors, control systems, or other physical pieces of equipment introduced in the system. They may also include changes to logic, processes, or settings for equipment.

Although the incoming stream of metal to the shredder was monitored for items such as propane tanks and other compressed gas containers, the facility personnel reported that occasionally they would experience a small deflagration or pressure release event in the shredder when one of these types of components was shredded. According to their experience, the events were confined to the shredder and did not propagate into the RTO. At the time of the incident, the system at GII did not monitor combustible gas levels and it cannot be confirmed that flammable gases from shredded components flowed to the RTO. A combustible gas detector, located in the system near the shredder, would provide this information in the future.

The engineering controls proposed by GII would include a PrevEx Flammability Analyzer, both to monitor whether combustible gases are entering the product stream and to control a bypass vent downstream to divert the process stream if an explosive atmosphere is detected.[34] The flammability analyzer will be installed on the process ducting near the shredder enclosure and the bypass vent will be located upstream of the RTO inlet fan. The PrevEx flammability analyzer features a malfunction relay if the status of the analyzer is compromised by a loss of fuel, air, sample flow, or power, which will trigger a bypass event. GII will also confirm the functionality of the analyzer and bypass system upon commissioning and on a quarterly basis thereafter.

The position of the bypass damper will also be monitored and the data stored with the data from the flammability analyzer. Should the flammable gas setpoint be reached, the bypass damper

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[33] ANSI/ASSE Z590.3 -2011, Prevention through Design Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes.

[34] RK & Associates, Proposed Shredder LEL Monitor and RTO Bypass Stack GII, LLC – 1909 North Clifton Avenue – Chicago, Illinois, dated June 25, 2020.

will divert the flow away from the RTO, the poppet valves will close, the natural gas supply for the RTO will be shut off, and the shredder feed will be stopped. This system of detector and diverter would reduce the risk of a flammable mixture being ignited by the RTO.

The RTO already contained a sophisticated control system to prevent an accumulation of natural gas in the equipment. The double blocking valves, flame detectors, and purging logic all worked to reduce the risk of a natural gas explosion in the RTO. Eleven temperature sensors, multiple valve position sensors, pressure sensors, and others were input into the RTO system at the time of the incident; however, only a single temperature value set was stored in the process data. Monitoring of additional sensors may aid in better understanding the condition of the RTO. Trends in data from these sensors could be useful in scheduling maintenance, improving efficiencies, and in analyzing RTO performance. These data could also be useful in troubleshooting problems and in identifying any future near miss situations.

Additionally, the alarm messages that were temporarily stored in the HMI at the time of the incident, were lost when the system lost power. Had these alarm messages been available for analysis after the incident, it could have aided in the investigation. Similar to the collection of more sensor data, a record of alarm messages may be useful in troubleshooting, analyzing RTO performance, and in scheduling maintenance.

Administrative controls

Administrative controls can be used to further reduce the risk of a hazard by modifying or introducing procedures. These can be actions for employees to perform or avoid, protocols for equipment operation, or corporate policies.

Administrative controls can be implemented to reduce the likelihood of introducing a flammable material into the shredder stream. The objective here is the prevention of flammable material containers from entering the shredder. This includes flammable pressurized liquids (propane), flammable gases (acetylene or other compressed gases), and flammable liquids (portable fuel containers for gasoline). GII already has a robust program to remove these materials from the shredder stream. The program includes efforts to educate suppliers, reward suppliers for compliance, notify suppliers for non-compliance, and the employment of inspectors to search the incoming stream for these materials. GII has found that accepting compressed gas containers separately incentivizes customers to indicate their location, as opposed to a refusal to accept, which may result in obfuscation. Signage, shown in Figure 12, identifies typical cylinder shapes and indicates that they will be paid for.

Figure 12. Signage from GII regarding compressed gas cylinders.

Additionally, a team of at least eight inspectors search for materials to segregate from the incoming stream. According to GII, they are tasked with removing prohibited materials, including pressurized cylinders, gasoline containing items, and other flammable containers (such as paint thinner, aerosols, and adhesives). Inspectors are instructed to err on the side of removal of items and their work is continually reviewed by a supervisor. Based on documentation from May and June of 2020, GII disposed of over 200 compressed gas cylinders that they had successfully segregated from their shredder feed.[35] Additionally, GII requires their automotive suppliers to sign a Drain Statement, certifying that the vehicles have been drained of fluids prior to their delivery.[36] GII is proud of the relationships they have built between their inspectors and suppliers and the positive impact that has had on compliance regarding prohibited materials.

GII has made considerable effort to reduce the risk of flammable containers from entering the process stream; however, on occasion, containers do make it into the shredder. Exponent recommends the current policies and procedures remain in place. GII intends to also send a written notice to their suppliers to reemphasize the importance of the segregation of flammable materials from the other scrap material. This communication will include specific visual examples of flammable materials that need to be segregated. The visual examples of flammable materials will be printed as a flyer for distribution to current suppliers and will also be part of the new supplier signup process. GII will also enhance their signage regarding flammable materials.

For the RTO, administrative controls could be used to ensure that periodic maintenance of the equipment is performed. The RTO manual includes weekly, monthly, semi-annual, and annual maintenance and inspection checklists. These could be used to ensure continued proper operation of the RTO. At the time of the incident, GII LLC utilized CPI to assist them with maintenance and troubleshooting. A continuation of this relationship, or a relationship with other maintenance providers, could help mitigate the risk of explosion by routine checks of system functionality and necessary repairs. Should unstable or poor quality combustion be identified during routine maintenance or checks, or through the monitoring of RTO data, the system should be shut down and the combustion improved before continued operation.

[35] AmeriGas Cylinder exchange receipt, dated May 28, 2020, and Gateway Cylinder bill of lading, dated June 3, 2020.

[36] GII, LLC Drain Statement, Rev. October 2019.

Summary and conclusions

At the request of RMG, Exponent conducted an investigation of the incident that occurred at the GII, LLC (GII) facility in Chicago, Illinois. The purpose of the investigation was to determine the root cause of the incident and to provide recommendations intended to prevent the recurrence of a similar incident. Exponent's analysis was conducted in a manner consistent with the guidelines presented in NFPA 921 Guide for Fire and Explosion Investigations, 2017 edition and utilized the scientific method to evaluate the potential causes and contributing factors to the event.

Exponent collected data relating to the event through the performance of on-site inspections, collection and testing of components from the system, analysis of relevant documents and process data, and combustion calculations. Based on the available information provided and collected to date, multiple hypotheses for the cause of the explosion were developed and analyzed. To determine the cause of the explosion, two questions must be answered: 1) What was the ignition source? and 2) What was the source of fuel? The evidence clearly indicates that the RTO was the ignition source. The hypothesis that the event was ignited at the shredder was refuted. The hypothesis that methane from the RTO burner was the source of the explosion was also refuted. The only remaining hypothesis, that a flammable gas was released in the shredder and ignited at the RTO, was unable to be refuted and remained as possible. However, no affirmative physical evidence of a shredded container or specific flammables in the process stream was able to be identified. According to NFPA 921, the industry standard guide for fire and explosion investigations, it is improper to offer a conclusion based on a lack of supportive evidence, therefore the cause of the explosion (the source of fuel) must be undetermined.[37]

Engineering and administrative controls were proposed for both the RTO and the release of flammable gases in the shredder. Engineering controls for reducing the risk of explosion included the installation of a combustible gas monitor near the shredder and a bypass vent near the RTO. Administrative controls for reducing the risk of explosion include efforts to further reduce the likelihood of introducing a flammable material into the shredder stream. GII currently has a robust screening process for the removal of flammable containers; however, GII intends to send a written reminder to their suppliers to emphasize, once again, the importance of the segregation of flammable materials from the other scrap material. This communication will include specific visual examples of flammable materials that need to be segregated and will also be distributed as a flyer to suppliers.

[37] NFPA 921, Guide for Fire and Explosion Investigations, 2017 edition, 19.6.5

Appendix A

Artifact List

Field Number	Evidence ID No.	Item Name	Date of Removal	Date of Receipt
1	270480	Booster fan pressure switch	6/2/2020	6/2/2020
2	270481	Oxidizer inlet pressure transducer	6/2/2020	6/2/2020
3	270482	Inlet temperature sensor	6/2/2020	6/2/2020
4	270483	Outlet temperature sensor	6/2/2020	6/2/2020
5	270484	Top of RTO southwest temperature sensor	6/2/2020	6/2/2020
6	270485	Top of RTO southeast temperature sensor	6/2/2020	6/2/2020
7	270486	Top of RTO northwest temperature sensor	6/2/2020	6/2/2020
8	270487	Flame detector south	6/2/2020	6/2/2020
9	270488	Flame detector north	6/2/2020	6/2/2020
10	270489	Combustion air pressure switch	6/2/2020	6/2/2020
11	270490	South ignitor	6/2/2020	6/2/2020
12	270491	North ignitor	6/2/2020	6/2/2020
13	270492	Temperature sensor north bottom (TE 199)	6/2/2020	6/2/2020
14	270493	Temperature sensor north middle (TE 197)	6/2/2020	6/2/2020
15	270494	Temperature sensor north top (TE 196)	6/2/2020	6/2/2020
16	270495	Temperature sensor south top (TE 200)	6/2/2020	6/2/2020
17	270496	Temperature sensor south bottom (TE 203)	6/2/2020	6/2/2020
18	270497	Temperature sensor south middle (TE 201)	6/2/2020	6/2/2020
19	270498	Differential pressure transmitter (PIT 259)	6/2/2020	6/2/2020
20	270499	Fresh air damper	6/3/2020	6/4/2020
21	270500	Main gas line between burners	6/3/2020	6/4/2020
22	270501	Pilot gas line between burners	6/3/2020	6/4/2020
23	270502	Pilot valve line	6/3/2020	6/4/2020
24	270503	Pilot regulator	6/3/2020	6/4/2020
25	270504	Pilot pressure gauge	6/3/2020	6/4/2020
26	270505	Pilot hand valve	6/3/2020	6/4/2020
27	270506	Main 2nd regulator	6/3/2020	6/4/2020
28	270507	Main gas vent line piece	6/3/2020	6/4/2020
29	270508	Main gas line with trap	6/3/2020	6/4/2020
30	270509	Main gas double block	6/3/2020	6/4/2020
31	270510	Main gas line with control valve	6/3/2020	6/4/2020
32	270511	Main gas 1st regulator	6/3/2020	6/4/2020
33	270512	South poppet positioner	6/3/2020	6/4/2020
34	270513	North poppet positioner	6/3/2020	6/4/2020
35	270514	Disconnect from combustion air fan	6/3/2020	6/4/2020
36	270515	South burner	6/3/2020	6/4/2020
37	270516	North burner	6/3/2020	6/4/2020
38	270517	Combustion air manifold	6/3/2020	6/4/2020
39	270518	Poppet positioner 1	6/3/2020	6/4/2020
40	270519	Poppet positioner 2	6/3/2020	6/4/2020

Field Number	Evidence ID No.	Item Name	Date of Removal	Date of Receipt
41	270795	Combustion air blower	6/3/2020	6/4/2020
42	270796	Combustion air blower cap	6/3/2020	6/4/2020
43	271558	FS1 burner controller	6/19/2020	6/19/2020
44	271559	FS2 burner controller	6/19/2020	6/19/2020

Appendix B

Inspection Protocol from 6/19/2020

Exponent®

External Memorandum

To:	Mark Weintraub
From:	Suzanne Smyth, Ph.D., PE, CFI
Date:	June 15, 2020
Project:	2004542.000
Subject:	Inspection Protocol – GII, LLC

Examination location: Exponent's Naperville warehouse located at 670 West 5th Avenue #120, Naperville, IL

Inspection date: June 19, 2020

Start time: 9am

This examination protocol contains activities that may be completed during the examination of the artifacts listed below. Documentation may be performed by notes, sketches, photographs, or video (without sound). Sound recording of the proceedings or related discussions is not permitted unless the recording party specifically receives agreement from all other parties present. Exponent will retain possession of all artifacts examined.

All interested parties are invited to submit suggested modifications, additions, and deletions to this protocol. The absence of such suggestions by any party will be interpreted as agreement by that party with this protocol and employed examination procedures.

This protocol may be modified based on examination findings. All parties present at the examination will be given the opportunity to provide input regarding modifications to this protocol. Modification of the protocol will occur with the reasonable agreement of all parties present. However, Exponent reserves the right of final decision should an impasse develop regarding agreement of all parties. Written objection to the final decision will be the responsibility of the objecting party.

All attendees will be required to sign a Lab Access Agreement and a COVID-19 Visitor Questionnaire. Exponent will also require a face covering, adherence to social distancing, and healthy hygiene during the inspection, as detailed in the COVID questionnaire document.

Protocol Steps

1. Visual examination of the retained artifacts.
2. Gas Regulators
    a. Pilot regulator
        i. Connect the regulator to an air pressure supply at 10 psi.
        ii. Measure the pressure downstream of the regulator.
    b. 1st stage main gas regulator
        i. Connect the regulator to an air pressure supply at 20 psi.
        ii. Measure the pressure downstream of the regulator.
    c. 2nd stage main gas regulator
        i. Connect the regulator to an air pressure supply at 10 psi.
        ii. Measure the pressure downstream of the regulator.
3. Main gas control valve
    a. Energize the control valve and monitor position indicator on control valve for position as the control current is increased.
4. Combustion air control valve
    a. Energize the control valve and monitor position indicator on control valve for position as the control current is increased.
    b. Consider repeating at different linkage positions
5. Flame detector
    a. Energize the flame detectors and, apply a propane torch flame in front of the detector, and monitor the response of the detectors.
6. Booster Fan Pressure Switches and Combustion Air Pressure Switch
    a. For each pressure switch, connect a meter to the NC, NO, and COM contacts, and measure the resistance.
    b. For each pressure switch, connect the switch to an air supply and monitor the connection between the contacts as the pressure is raised from 0” WC to above the setpoint (1” WC for PDS252, 20” WC for PSH248, and 6” WC for PDS217).
7. Main gas block valves – pressure switches
    a. For both pressure switches, connect a meter to the NC, NO, and C contacts, and measure the resistance.
    b. While monitoring the contacts on the pressure switches, raise the pressure above the setpoint of 190” WC.
    c. Drop the pressure below 190” WC, monitor the contacts. Continue to lower the pressure to below 21” WC.
8. Main gas block valves - operation
    a. Connect a meter to the NC, NO, and C contacts for the proof of closure switch, and measure the resistance.
    b. Energize the valves, monitor the contacts for the proof of closure switch, and the position of the valves.
9. Pilot valves

    a. Introduce pressure to the pilot valves, energize them, and monitor valve positions.

10. Temperature Sensors
    a. For each temperature sensor, monitor the voltage output of the sensor as a flame is brought near the sensor.
11. Poppet positioner sensors
    a. Energize sensors, place metal in front of sensor, and monitor response.
12. Siemens Sitrans P DS III Transmitters
    a. Energize transmitters, apply differential pressure, and monitor responses.
13. Fresh air damper
    a. Visual inspection. Consider energizing and monitoring response.

Appendix C

Testing Results from 6/19/2020

Exponent

Project Name GII, LLC Explosion Inv. Project Number 2004542.000

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Pilot Regulator (270503)

Upstream Pressure: 10 psi Downstream Pressure: 2 psi

1st Stage Main Gas Regulator Regulator (270511)

Upstream Pressure: 20 psi Downstream Pressure: 10 psi

2nd Stage Main Gas Regulator Regulator (270506)

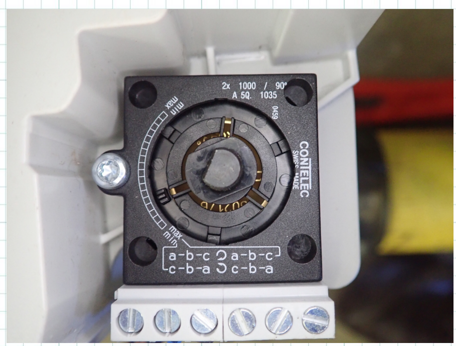
Upstream Pressure: 10 psi Downstream Pressure: ~5 psi

- Notes for 2nd stage main gas regulator:
  - Lock nut on regulator stem is loose
  - Downstream pressure feedback must be connected, otherwise upstream and downstream pressure are equivalent

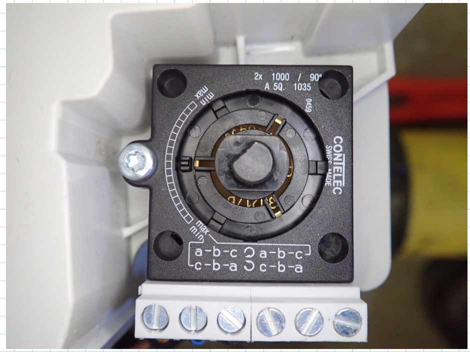
Main Gas Control Valve (270510)

4 mA: Angle= -12

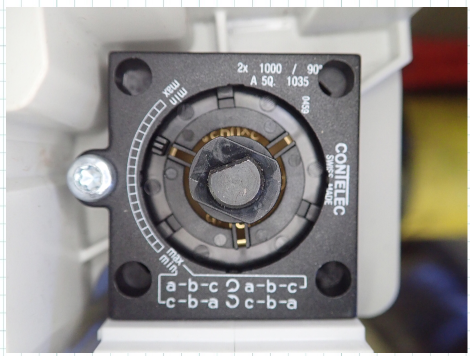
8 mA: Angle= 25



12mA: Angle = 50



16 mA: Angle = 70



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Project Name GII, LLC Explosion Inv. Project Number 2004542.000

Author M. Walters Date 6/19/20

20 mA: Angle: 90

- Terminals 3 and 4 remain made for full range of motion from 4 to 20 mA
- Maintains position when power removed

Combustion Air Control Valve (270517)

Starting angle: 70

4 mA: Past Open, physically wide open

8 mA: On the open label

12 mA: Angle ≈ 60

16 mA: Angle = 42

20 mA: Angle = 30

- Went to 24 mA → no change
- Return to 4 mA → return to 20 mA → Open loop: Returns to past open
- Loss of AC: holds position

Flame Detector South (270487) and Flame Detector North (270488)

- Unable to test, plan to test at GII, LLC site

Booster Fan Pressure Switch PSH 248 (270480)

At Ambient Pressure-

COM to NC: Closed COM to NO: Open

Compressed air applied-

COM to NC: Open COM to NO: Closed

- After pressure removed, COM to NC reading resistance of ~130 Ω
- Cycled pressure again and switch behaved normally

Booster Fan Pressure Switch PDS 252 (270480)

At Ambient Pressure-

COM to NC: Closed COM to NO: Open

Compressed air applied-

COM to NC: Open COM to NO: Closed

- Had to pull slight vacuum when pressure removed to reset switch
  → Repeated test and same behavior persisted

Combustion Air Pressure Switch PDS 217 (270489)

At Ambient Pressure-

COM to NC: Closed COM to NO: Open

Compressed air applied-

COM to NC: Open COM to NO: Closed

- Returned to normal settings after pressure removed

Main Gas Double Block Valve SOV 134 (270509)

Pressure Switch

At Ambient Pressure-

C to NC: Closed C to NO: Open

Compressed air applied-

COM to NC: Open COM to NO: Closed

- Returned to normal state when pressure removed

Actuator

~11 seconds to actuate

NC is closed, NO is open

Main Gas Double Block Pressure Switch BV 137 (270509)

At Ambient Pressure-

C to NC: Closed C to NO: Open

At ~7 psi-

C to NC: Open C to NO: Closed

- Returned to normal state after pressure removed

Actuator

~15 seconds to actuate

NC is closed, NO is open

Pilot Valves (270502)

- Both valves actuate when energized

Temperature Sensors

270482 (Inlet T): Lower Element - 75.8°F (RT), Similar when switched to this element
Upper Element - 76.1°F (RT), Raised to >200°F w/ propane

270483 (Outlet T): Lower Element - 74.3°F (RT), Similar when switched to this element
Upper Element - 74.5°F (RT), Raised to >200°F w/ propane

270484 (Top RTO SW): Lower element - 74.7°F (RT), Similar when switched to this element
Upper element - 74.7°F (RT), Raised to >200°F w/ propane

270485 (Top RTO SE): Lower element - 74.8°F (RT), Similar when switched to this element
Upper element - 74.9°F (RT), Raised to >200°F w/ propane

270486 (Top RTO NW): Lower element - 74.9°F (RT), Similar when switched to this element
Upper element - 75.0°F (RT), Raised to >200°F w/ propane

270492 (TE 199): Lower element - 75.3°F (RT), Similar when switched to this element
Upper element - 75.4°F (RT), Raised to >200°F w/ propane

270493 (TE 197): Lower element - 74.8°F (RT), Similar when switched to this element
Upper element - 74.8°F (RT), Raised to >200°F w/ propane

270494 (TE 196) Lower element - 74.8°F (RT), Similar when switched to this element
Upper element - 74.8°F (RT), Raised to >200°F w/ propane

270495 (TE 200) Lower element - 74.5°F (RT), Similar when switched to this element
Upper element - 74.7°F (RT), Raised to >200°F w/ propane

270496 (TE 203) Lower element - 75.7°F (RT), Similar when switched to this element
Upper element - 75.9°F (RT), Raised to >200°F w/ propane

270497 (TE 201) Lower element - 74.5°F (RT), Similar when switched to this element
Upper element - 74.8°F (RT), Raised to >200°F w/ propane

Poppet Positioner (270512)

ZSH523: Wire 34 operates (cylinder retract, switch open)
ZSL522: Wire 35 Operates (cylinder extend, switch closed)

Poppet Positioner (270513)

ZSH503: Wire 26 operates (cylinder retract, switch open)
ZSL502: Wire 25 Operates (cylinder extend, switch closed)

PIT 249 (270481)

Starting: -1.46" H_2O (no pressure) → 6.3 mA
5.5" H_2O with pressure → 12.82 mA

PIT 259 (270498)

Starting: 0.45" H_2O (no pressure) → 4.8 mA
4.55" H_2O → 6.44 mA
~22" H_2O → 15.6 mA (gauge reads 0.5 psi)