Air-Conditioning, Heating and Refrigeration Technology Institute

Final Report

AHRTI Report No. 9007-2

Benchmarking Risk by Whole Room Scale Leaks and Ignitions Testing of A3 Refrigerants

Final Report Preface

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By

AHRTI 9007-02 Project Monitoring Subcommittee

Prepared for

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Preface by AHRTI Project Monitoring Subcommittee

Background

Environmental concerns raised by high global warming potential (GWP) refrigerants have triggered a series of activities around the world to implement low GWP refrigerants, including the Kigali amendment to the Montreal Protocol requiring a global Hydrofluorocarbon (HFC) phasedown, effective January 1, 2019. HFCs are the most common high-GWP refrigerants used today. The State of California has an increasing need for transitioning to environmentally friendly low GWP refrigerants to meet its goal of 40 percent HFC emissions reductions by 2030 required by Senate Bill (SB) 1383, Lara 2016, "Short-lived Climate Pollutants: methane emissions: dairy and livestock; organic waste: landfills (ARB, 2016b; SB 1383, 2016). To date, most promising low-GWP refrigerants are flammable, particularly in the air-conditioning sector. The safe use of these refrigerants in the field requires a timely revision of relevant safety standards and codes. However, there is a lack of publicly available technical knowledge on how to safely use flammable refrigerants and set proper refrigerant charge quantity limits. To advance the understanding of a complete suite of low-GWP flammable refrigerants safety, on a national and international scale, the California Air Resources Board (CARB) sponsored the Air-Conditioning, Heating, and Refrigeration Technology Institute (AHRTI) to conduct refrigerant R-290 (i.e. propane) leak and ignition tests. This project is part of a larger collaborative research program jointly funded by the Air-Conditioning, Heating, and Refrigeration Institute (AHRI), American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE), the U.S. Department of Energy (DOE) and CARB. The program's goal is to generate publicly available technical data to support relevant standards and codes revisions toward the safe use of flammable refrigerants classified as A2L and A3 per ASHRAE Standard 34.

Objectives and Methods

The objective of this project was to conduct refrigerant R-290 (propane) leak and ignition testing under whole room scale conditions to develop data and insight into the risks associated with the use of Class A3 refrigerants and to generate technical data to support revisions of relevant safety standards.

The entire project included parametric testing to investigate how key variables (refrigerant charge amount, release rate and height etc.) influence the 'ignition event' under whole room scale scenarios. It involved releasing liquid R-290 refrigerant into spaces with a variety of viable ignition sources present. The testing scenario simulated a Packaged Terminal Air Conditioner (PTAC) and a mini-split air conditioner (AC) in a typical motel room and a single door reach-in cooler and a three-door reach-in cooler in a convenience store. All the tests were conducted by AHRTI's subcontractor, Underwriter's Laboratories (UL) under the supervision of AHRTI and CARB. Tests were performed at the UL facility in Northbrook, IL. AHRTI assembled a Project Monitoring Subcommittee (PMS) to design and guide the testing. The PMS consists of CARB staff, technical experts from the HVACR industry and representatives from relevant safety standards committees/working groups (WGs).

The PMS designed the testing scenario according to the existing requirements or proposed requirements in the IEC Standards 60335-2-40 (for air-conditioning products) and IEC 60335-2-89 (for commercial refrigeration products), and their equivalent North American version published by UL. However, there were some differences between the IEC standards and the testing scenario followed. For example, the air-conditioning equipment testing final discharge rates were based on the finding (documented in this report) that the mass flow rate of liquid propane is 49% of the R-32 liquid mass flow rate at the same saturation temperature and orifice size. These values were selected so that comparisons could be made between the A2L and A3 i.e. propane refrigerant tests in the 9007-01 and 9007-02 programs. As with the 9007-01 program, leak rates were almost always higher than the rate corresponding to total loss of charge in four minutes that was generally considered by the IEC/UL 60335-2-40. Generally, this means the scenarios are more severe than they would have been with four-minute leaks. The reason of using a leak rate higher than what was considered in the standards was that the industry was trying to understand what the worst-case scenarios would be in terms of ignition event severity so that the industry can build resolutions upon it to effectively mitigate the risk.

The R290 charge amounts used in the testing had their bases in either existing or proposed limits for A3 refrigerants. In the absence of recommended limits for A3 refrigerants, the formulas for A2L refrigerants were used on the assumption that limits for A3's would follow the same formula. This approach allowed the project to assess safety factors for refrigerant charge quantity and mitigation criteria including mitigation response time and airflow rate for mixing and threshold for performing a certain safety test for commercial refrigerators.

Applicability to Relevant Standards

The project generated a large set of R290 dispersion and ignition data at different release amounts. The results provide useful information to product safety standards IEC/UL 60335-2-40, IEC/UL 60335-2-89, and to the application standard ASHRAE Standard 15. Over the course of the project, the test results were presented to the working groups of the IEC SC61C/WG4 and IEC SC61D/WG16 while they were revising the contents related to using A3 refrigerants in the IEC 60335-2-89 and IEC 60335-2-40 respectively.

<u>IEC/UL 60335-2-40</u>

The PTAC and mini-split unit testing was designed to assess the R290 charge levels according to the then current proposed "Preliminary Comment Draft" of 3rd Edition UL 60335-2-40 (dated Nov 22, 2017) which was based on the 6th Edition of IEC 60335-2-40. According to the draft UL 60335-2-40, the charge limit for R290 is 114g regardless of the room size for direct systems; however, the IEC standard 60335-2-40 Edition 6.0 allows higher charges. The IEC standard allows R290 charges up to 152g without room size restriction. Charges higher than 152g are correlated to the room area and equipment installation height for an unventilated room.

Both PTAC and mini-split AC tests indicated that the flammable region can extend outside the product casing and be easily ignited. This is also true for floor level release at the current charge limit of 114g without room size restriction defined by UL. The mini-split AC testing demonstrated that the maximum allowable charge (325g) per the test room area ($19m^2$) calculated using IEC 60335-2-40 caused R290 to build up a flammable region around the unit vicinity at floor level and caused ignition when an ignition source was present.

Both IEC and UL 60335-2-40 specify requirements for equipment using A2L refrigerants with incorporated circulation airflow, which includes an incorporated fan to be either continuously operated or initiated by a refrigerant detection system. This concept is to ensure circulation airflow prevents refrigerant stagnation so that the equipment can use a higher refrigerant charge than those without this feature.

At present, neither the IEC nor UL 60335-2-40 has specified such requirements for A3 refrigerants that would allow higher A3 refrigerant charge quantity. The IEC has established a WG (SC61D/WG16) to develop additional requirements for A3 refrigerants including the incorporated airflow concept. This project used the existing requirements for A2Ls in terms of determining charge quantity, minimum airflow rate and refrigerant detection system response time for R290 tests to assess the applicability of these requirements for A3 refrigerants.

The PTAC testing demonstrated that ignition can even happen while the PTAC fan is kept constantly on at low speed setting during the refrigerant release. This indicates that 1) the safety factor in the calculation of refrigerant quantity may not be enough; and 2) the mitigation using air flow may require a higher air flow rate than the A2L refrigerants to mitigate A3 refrigerants for floor mounted products.

The mini-split testing showed no ignitions in tests where the fan was running continuously before the start of the refrigerant discharge. However, the ignition occurred where the fan was energized 15s after the start of the refrigerant discharge (simulating a delay caused by a refrigerant detection system detecting and responding to a leak event in 15 seconds). This indicated that a higher air flow rate and/or faster response time would be required for A3 refrigerants compared to A2L refrigerants.

The different behavior between the PTAC and mini-split unit was primarily because they have different installation height. The mini-split-unit was installed at 1.8 meters above the floor. When the R290 leaked from the indoor unit, it mixed with room air while falling to the floor level due to the gravity effect (R290 is heavier than air). The PTAC was installed close to the floor level, the leaked R290 accumulated at the floor level without having a chance to mix with the air in the room.

IEC 60335-2-89

The reach-in cooler testing was designed to assess the R290 charge levels according to the latest draft IEC 60335-2-89 Edition 3 Committee Draft for Vote (CDV) (dated on April 20, 2018), which subsequently progressed to the Final Draft International Standard (FDIS) stage and was approved by a vote of IEC SC61C on April 12th, 2019.

The FDIS requires the performance of the “door-opening test” and imposes mandatory minimum floor area warnings for all self-contained reach-in coolers containing more than 150g of A3 refrigerant. Consistent with current IEC and UL 60335-2-89 standards, the draft standard has no additional requirements for self-contained reach-in coolers having flammable refrigerant charges less than 150g. The previous draft had waived the door opening test if the refrigerant charge per refrigerating circuit does not exceed a threshold of (5 x LFL [kg/m³] x refrigerated volume [m³]). The door-opening test involves releasing refrigerant in a critical leak location inside the refrigerated space and opening the cooler door or drawer at the end of the leak. The concentration of leaked refrigerant in the proximity must be below a certain value within a specified amount of time (current FDIS is below 50% LFL in 5 minutes) to avoid potential ignition.

Reach-in coolers testing has revealed that both the single door unit and 3-door unit with R290 charge of 114g can fail the “door opening test”, and cause ignitions when the ignition source was present at the floor monitoring location. This result should be weighed in the context of real-world experience and field data with similar <150g equipment installed in the U.S. and around the world as permitted under current standards, including in both household refrigerators and existing reach-in commercial coolers that have already been widely adopted using R290 or R600a.

The three-door unit with 200g R290 failed the “door-opening test” which would have not been required to be performed due to the cooler size being below the threshold for the “door-opening” test (200g is well below 5*LFL*cooler’s internal volume). An ignition source was present at the monitoring location in front of the cooler. The resulting deflagration had a flame boundary velocity of approximately 40% of the speed of sound. This indicates an event approaching the deflagration to detonation transition, from a subsonic propagating combustion reaction to a supersonic propagation with shock wave mechanisms. Due to the severity of the event, higher charge level was not conducted for internal release tests. Because of the test results, the final FDIS for IEC 50335-2-89 that was previously approved has removed the exemption and requires the open-door test for all reach-in coolers having charge larger than 150g.

The draft standard does not specify requirements on mitigation method(s). An “external release” test of a three-door reach-in cooler, with condensing unit underneath the food storage compartment, was conducted using approximately 400g of R290. This charge level was set according to the 2-89 CDV rules relating to room size. As above, an ignition source was present. There was an appreciable floor area with R290 concentration at or near the lower flammability limit when the condenser fan was in off mode. A significant fire event did occur. The test was repeated with the condenser fan in operating mode. No ignition occurred. This indicated that using condenser fan to provide ample air circulation would effectively reduce the ignition risk, especially for condensing units located at the bottom of the cooler.

Conclusions

According to the testing results, the following findings are recommended to the relevant standard committees for consideration. All the events that occurred in the testing were low probability events which were forced to occur to understand worse case scenarios and standards should take into account not only the severity of the ignitions that occurred during the testing, but also the probability of those ignitions.

IEC/UL 60335-2-40

- Raising the current charge limit (114g for R290) per UL 2-40 should be carefully considered especially for floor or near floor mounted products.
- Any potential ignition sources should be avoided underneath installed units and near the projected area at floor level.

- Air flow requirements as a mitigation method should be carefully considered in relation to sensor response times, the amount of refrigerant, and perhaps type of refrigerant (A2Ls vs A3s).

IEC/UL 60335-2-89

- The criteria used for requiring the door-opening test to be performed should be revisited. Empirical validation should guide the selection of criteria. The test also requires that the concentration of refrigerant not exceed 50% of LFL within five minutes of the door having been opened. Extending this time period may be another way that the test could be made more conservative; that is, extending the time period in which refrigerant could build up.
- Any potential ignition sources should be avoided around the unit at floor level.
- Additional mitigation requirement should be assessed to further allow higher charge, such as using fan circulation to dilute leaked refrigerant or shut-off valves to limit the leaked refrigerant quantity.
- The condenser fan being on had a positive effect in reducing the likelihood of an ignition event.
- This study and the National Fire Protection Association (NFPA) A3 study showed that external leaks that occur higher up in elevation on the cooler cabinet are much less likely to produce a flammable cloud near floor level. The standards committees might consider having different requirements between condensing units high up on the cabinet and condensing units lower or at floor level. This assumes the condenser assembly is the highest probability leak location. However, this assumption needs to be confirmed from the field data.

The testing was focused on understanding R290 ignition risk (in terms of the event severity) following either existing or proposed standards. It is not designed to address the probability of the refrigerant ignition event. Some tested ignition events represented the worst-case scenarios with low probability of occurrence. Ignition sources were simultaneously placed where flammable mixtures were most likely to occur. Therefore, some low probability events were forced to occur. The requirements in safety standards should consider the combination of potential event severity and the probability of an ignition event. Therefore, the adoption of the test results to relevant standards will eventually rely on these committees because individual members have different acceptable thresholds for a harmful event severity and likelihood.

The future work should include a thorough evaluation of:

- Mitigation concepts using airflow circulation and ventilation and shut-off valves.
- The probabilistic distribution of real world ignition sources in terms of ignition energy, quantity, spatial location throughout the room, and activation frequency.
- The probabilistic distribution of different refrigerant release scenarios, across a range of leak rates and total refrigerant charge released.
- The unique and complex commercial kitchen applications should be studied for IEC/UL 60335-2-89 because there are typically several adjacent ignition sources and within a very crowded space.

- Risk assessment on ignition probability using existing market results. Many R290 units are in use around the world and real world performance should be taken into account for existing systems.

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Executive Summary

Background

Research was conducted under contract with Air-Conditioning, Heating and Refrigeration Technology Institute (AHRTI) relative to ignition of propane refrigerant (A3 flammability class) released through leaks in refrigerant systems in a test room and document the severity of fire events. The test methodology used for release of the refrigerant was similar to the previous AHRTI 9007-1 [1] investigation focused on ignition testing of A2L refrigerants. Also, similar to the investigation on A2L refrigerants, this investigation focused on ignition of flammable refrigerant concentrations resulting from a range of leak rate conditions (i.e., rate and location).

The objectives of this investigation were as follows:

- Investigate and document the fire hazard of propane refrigerant (A3 flammability class) under whole room conditions .
- Provide test data to support future revisions of safety standards.

The probability of available specific energy sources and their ability to ignite propane-air mixtures was outside the scope of this investigation.

Safety and Test Facilities

Safety of personnel and facilities was the first concern of this project since propane refrigerant has much higher burning velocity and heat of combustion as compared to A2L refrigerants. This creates the potential for overpressure events (deflagrations) or detonations. A special facility was developed for this test program to minimize overpressures through the use of deflagration vents. Additionally, a step-wise or titration approach of increasing discharge amounts was used to explore the limits of discharge quantities that may lead to deflagration events. In one test series, it was necessary to stop the series short of the final refrigerant discharge quantity goal due to overpressure damage to the test facility.

For each igniter test, a concentration test was performed without use of the ignition sources. This test provided information on refrigerant concentrations in the test room, and also informed testing personnel of the need for either repairs (e.g. damaged door gaskets) or additional preparation and safety precautions for the ignition test.

Since intentional releases of propane were critical to the program, safety considerations dictated the use of CP grade propane (99% minimum propane) with an odorant instead of refrigerant grade propane (R-290: 99.5% minimum propane) which has no odorant.

Task 1 Parametric Testing

Task 1 testing was performed in 2.4 x 3.6 x 2.4 meter high facility as specified in ISO 9705 [2]. The room was modified with deflagration vents and access doors for the purpose of the test program.

The following three factors were selected for variation in the investigation:

- Release height (0.2 and 1.8 m)
- Discharge quantity (25% and 50% of lower flammability limit (LFL) when mixed in the entire room volume)
- Release rate (Low and High).

Final discharge rates were based on the finding (documented in this report) that the mass flow rate of liquid propane is 49% of the R-32 liquid mass flow rate at the same saturation temperature and orifice size. These values were selected so that comparisons are possible between the A2L and propane refrigerant Task 1 tests in both research programs.

The tests resulted in consistent ignition when propane was discharged at the 0.2 m height, regardless of discharge rate, while ignition at the 1.8 m height was dependent on placement of electric arc ignition source at similarly high elevation in the test room. The concentration tests at the 1.8 m height showed dispersal of concentrations to less than LFL between 15 and 40 seconds after the start of the discharge.

Task 2 Scenario Tests

Task 2 testing was conducted in a 3.95 x 4.81 x 2.42 m test room. Six deflagration vents were included in the test room because of the larger planned propane discharges. As in Task 1, each piece of equipment was tested with more than one “charge size”. An obstruction resembling a queen size bed was included for both the PTAC and Mini-Split tests. This same obstruction was used in a vertical orientation representing a nearby product display rack for the reach-in cooler tests.

Discharge amounts were based on current safety standards or proposals regarding A3 refrigerants. If proposals were not available for A3 refrigerants, then amounts were calculated based on equations similar to those being proposed or in use for A2L refrigerants.

PTAC testing: The unit was mounted such that the discharge location was 0.6 m above the floor in the center of the evaporator. Use of the internal fan unit was investigated as a means of dispersing the refrigerant to values less than LFL. Discharge rates were based on 49% scaling of R-32 discharge rates observed in the 9007-1 A2L PTAC tests. The scaling factor of 49% was based on the experimental mass flow rate comparison of liquid R-32 and propane at 95°F. Three ignition tests were conducted and ignition was observed in each case. The electric arcs were energized five seconds after the discharge was completed. The concentration tests showed a maximum dispersal time to less than LFL concentrations in 1.5 minutes (fan off) and 20 seconds (fan on).

Mini-Split testing: The unit was mounted such that the release height (h_0) and air delivery height (h_a) were at 1.8 m above the floor. Discharge rates were based on 49% scaling of R-32 discharge rates observed in the 9007-1 A2L PTAC tests. Two tests were conducted with the circulating fan off and both resulted in ignition. One test with the fan running before the discharge began did not result in ignition. The last test used a delayed fan start (15 seconds). In this test it was observed that approximately 10 seconds were required to establish full fan flow. There was ignition in this fan delay case. Concentration test data showed concentration levels dispersed to less than LFL within two minutes with the unit fan operating regardless of charge size. Concentration test data with the fan off showed concentrations levels dispersed to less than LFL within one minute (lowest charge) and seven minutes (highest charge).

Reach-in Cooler testing: A three-door cooler (1.87 m^3 internal volume) and a single-door cooler (0.60 m^3 internal volume) were used in this test series. The program consisted of internal leaks at a return bend in the evaporator and external leaks at a return bend in the condenser. The time of the discharge was 11 minutes and 10 seconds as specified in IEC 60335-2-89 CDV Ed 3 V3.

The internal leak test process followed a proposed "Door Opening" test from IEC/UL 60335-2-89 61C/732/CDV. The three internal release tests resulted in ignition at an arc location on the floor in front of the opened door. One test resulted in overpressure or quasi-detonation [3]. This resulted in minor damage to the test room and prevented the program from advancing to the highest discharge amounts originally desired by the AHRTI PMS committee.

The three door cooler design included a compressor/condenser unit at floor level. The release at the condenser when the fan was not operating resulted in floor concentrations above the LFL throughout the entire floor area of the room. This propane pool ignited as soon as the electric arcs were energized. This same unit with the condenser fan operating continuously mixed the discharge within the room volume such that the highest concentrations in this case were approximately 50% of LFL. The single door cooler had a top mounted compressor/condenser unit. The single door unit external release at the condenser with the fan off resulted in concentrations less than LFL and was not ignitable.

Summary of Findings

In all tests, pressure rise from ignition within the test facility was limited by the use of deflagration vents.

Task 1 Parametric Tests

- Propane releases at low elevation (0.2 m) in the presence of an obstruction resulted in a flammable mixture for all discharge rate and discharge amount cases investigated.
- Concentration test data showed releases at high elevation (1.8) without obstructions in the stream dispersed to less than LFL in less than 1 minute for all discharge rate and discharge amount cases investigated.

Task 2 Scenario Tests

- All PTAC tests resulted in ignitable mixtures in close proximity to the unit.
- PTAC concentration tests showed propane-air flammable concentrations dispersed to less than LFL in 1.5 minutes (Fan Off) and 20 seconds (Fan On).
- The design of the mini-split unit and its installation height (1.8 m) reduced discharge velocities resulting in (density driven) flows of propane-air flammable concentrations which accumulated at the floor level.
- Propane discharges from the center of the mini-split evaporator with the fan running reduced concentrations below the LFL at 6.4 seconds after the discharge was completed. The mixture did not ignite.
- The range of charge sizes used in these tests are detailed in the body of this report.

- The mini-split fan with a 15 second delayed start did not prevent ignition. It was also observed that the fan did not achieve full speed until 10 seconds after the command to start.
- Reach-in cooler external propane releases from a condenser coil located just above floor level resulted in a room-wide flammable mixture at floor level. This same reach-in cooler test with the condenser fan operating dispersed propane concentrations at all sensors to less than LFL throughout the test.
- External propane releases from a top-mounted condenser dispersed quickly. All sensors recorded propane concentrations less than LFL.
- Reach-in cooler internal propane refrigerant release tests were terminated before reaching the objective of 355 grams. One concentration test with 200 grams propane discharge resulted in overpressure causing minor damage to the test facility. Thus, tests for reach-in cooler were limited to maximum 200 grams discharge.

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1. Glossary

The following terms are used throughout this report and refer to specific information

- **Concentration Test:** Discharge tests to measure propane concentrations. The electric arc igniters are not energized in these tests.
- **Density Driven:** The flow of a propane-air mixture to a lower level due to the force of gravity with little or no momentum remaining from the location of the initial discharge.
- **Diffusion Flame:** A flame in which fuel and air mix or diffuse together at the region of combustion.
- **Igniter Test:** Discharge tests including the use of the electric arc igniters. In some igniter tests ignition of the propane-air mixture did not occur.
- **LFL:** Lower Flammability Limit, for propane in air the value is 2.1% by volume.
- **Premixed Flame:** A flame for which the fuel and oxidizer are mixed prior to combustion, as in a laboratory Bunsen burner or a gas cooking range; propagation of the flame is governed by the interaction between flow rate, transport processes, and chemical reaction
- **UFL:** Upper Flammability Limit, for propane in air the value is 9.5% by volume.

2. Background

The previous AHRTI 9007-1 [1] study focused on ignition testing of A2L refrigerants in room size environments. The study focused on ignition of refrigerants resulting from various leak rate conditions. This follow-on study looks at A3 refrigerants under similar conditions. In this study, only R-290 was tested.

A3 refrigerants are classified as having "Higher Flammability" by the AHRAE Standard 34, while A2L refrigerants are classified with "Lower Flammability." A3 refrigerants include agents such as propane, isobutane, n-butane. A3 refrigerants are typically hydrocarbons, meaning that the compounds contain hydrogen, carbon, and sometimes oxygen. Interest in deployment of this class of refrigerants comes from their zero Ozone Depletion Potential (ODP) and low Global Warming Potential (GWP), as well as their efficient energy use in certain refrigeration or air conditioning cycles.

Caution in the use of A3 refrigerants is recognized because of their higher heats of combustion (>19,000 kJ/kg), and low flammability limit, (LFL<0.1 kg/m^3). By comparison, A2L refrigerants have a lower heat of combustion (<19,000 kJ/kg), higher flammability limit (LFL>0.1 kg/m^3), and a low burning velocity (<10 cm/s).

Refrigerant	Heat of Combustion (kJ/kg)	LFL	
		kg/m^3	% by Volume
R-290	46,300	0.038	2.1
R-452B	9,450	0.307	11.9
R-32	9,400	0.304	14.4

3. Objectives

Th objectives for this investigation were as follows:

- Investigate and document the fire hazard of propane refrigerant (A3 flammability class) under whole room conditions.
- Provide test data to support future revisions of safety standards.

4. Scope

The investigation was limited to propane as the test refrigerant and used electric arc ignition sources to cause ignition of the consequent propane-air mixtures. The probability of available specific energy sources and their ability to ignite propane-air mixtures was outside the scope of this investigation.

5. Technical Plan

The initial project plan had identified 16 ignition tests and 16 concentration tests using the same propane release parameters. The originally planned ignition tests are outlined in Table 1. Decisions based on test results resulted in re-allocating one of the PTAC tests to the Reach-In cooler test series. Task 1 provides data allowing comparison of similar A2L tests from the AHRTI 9007-1 project. The Task 2 series of tests provide data for requirements or proposed requirements for 60335-2-40 and 60335-2-89 standards.

Throughout this report tests performed without use of the electric arc igniters will be referred to as “concentration” tests. Those tests where the electric arcs are energized are referred to as “igniter” tests. Not every igniter test resulted in ignition of a propane-air mixture.

Table 1 – Technical Plan

Task	Equipment	Planned / Actual Ignition Tests	Parameters
Task 1 **Parametric tests**	ISO 9705 Test Room 2.4 x 3.6 x 2.4 m	4/4	• 25% and 50% of LFL concentration when distributed in the whole room • High and Low Discharge Rates • High and Low Discharge Locations • Discharge rate scaled for comparison to 9007-1 A2L tests
Task 2 **Scenario Tests**	PTAC 3.9 x 4.9 x 2.4 m Test Room	4/3	• Charge sizes according to current or proposed UL or IEC standards • With and without air circulation from the unit • Discharge rate scaled for comparison to 9007-1 A2L tests
	Mini-Split System (Indoor unit) 3.9 x 4.9 x 2.4 m Test Room	4/4	• Charge sizes according to current or proposed UL or IEC standards • With and without air circulation from the unit including delayed start • Discharge rate scaled for comparison to 9007-1 A2L tests
	Reach-in Cooler (one and three door units) 3.9 x 4.9 x 2.4 m Test Room	4/5	• Charge sizes and discharge rate according to current or proposed UL or IEC standards • Internal and External leaks • With and without external air circulation • Discharge rate according to current or proposed UL or IEC standards.

6. Refrigerant

Propane (R-290) was selected in collaboration with the AHRTI PMS committee as the A3 refrigerant for study. For safety of operations CP-grade propane with an odorant was selected for use throughout the study. CP-grade propane has a minimum concentration of 99% propane while R-290 has a minimum concentration of 99.5% propane. The properties of propane are summarized in Table 2.

Table 2 – Properties of propane

Parameter	Value
Molecular Weight	44.1 kg/kmol
Chemical Formula	C_3H_8
Lower Flammability Limit (LFL) % by volume	2.1%
Lower Flammability Limit (LFL) kg/m³ at Standard Pressure (101.3 kPa)	0.038 kg/m³
Upper Flammability Limit (UFL) % by volume	9.5%
Laminar Burning Velocity	44 cm/s
Heat of Combustion [4]	46,300 kJ/kg
Refrigerant Concentration Limit RCL (ppm by volume)	5,300
Ozone Depletion Potential (ODP)	0
Global Warming Potential (GWP_{100})	<1 [5]
Boiling Point @101.3 kPa	-42 °C; -44 °F
Odorant Concentration (ppm by mass) (Sensitive to nose at one-fifth of LFL or less)	24 ppm minimum Ethyl Mercaptan [6]

7. Test Facility and Hazard Controls

7.1. Test Facility and Test Structure

A special test facility was constructed for the project. Figure 1 shows the plan and a photo of the facility during construction. The photo shows the framing for the test room on the left side. Two roughed-in deflagration vents are shown in the plan view of the test facility.

Internal dimensions for Task 1 test room were 2.44 m x 3.66 m x 2.43 m (W x L x H) for a total enclosed volume of 21.7 m³. The walls were 2 in. by 4 in. wood stud, 16 in. on center construction with R-15 insulation in the stud bays. The walls, floor, and ceiling of the test room were sheathed with one layer of ½ -inch gypsum wallboard (5/8-inch for ceiling) and one layer of ½-inch cement board to provide a non-combustible interior surface. The interior was painted with Sherwin Williams™ Pro Industrial™ Pre-

Catalyzed water-based Epoxy to seal the room and prevent air leakage through walls, floors, and ceiling. The four deflagration vents each had dimensions of 0.6 x 1.2 m (2 ft. x 4 ft.).

The two doors attached to the test room were exterior doors with integrated seals.

The facility was supplied with heat and air conditioning equipment to support conditioning of the test room. The test room was supplied with a smoke damper that could be opened or closed from the control room. Return air was accomplished by opening the door between the test room and equipment room.

When not in use for igniter testing, the deflagration vents were covered by insulated shutters allowing the room to be conditioned between 60°F and 80°F. Just prior to performance of an igniter test, the vents were covered with a 0.7 mil (0.018 mm) sheet of painter's plastic drop cloth material and secured in place with duct tape. The insulated shutters were then opened just prior to starting the test.

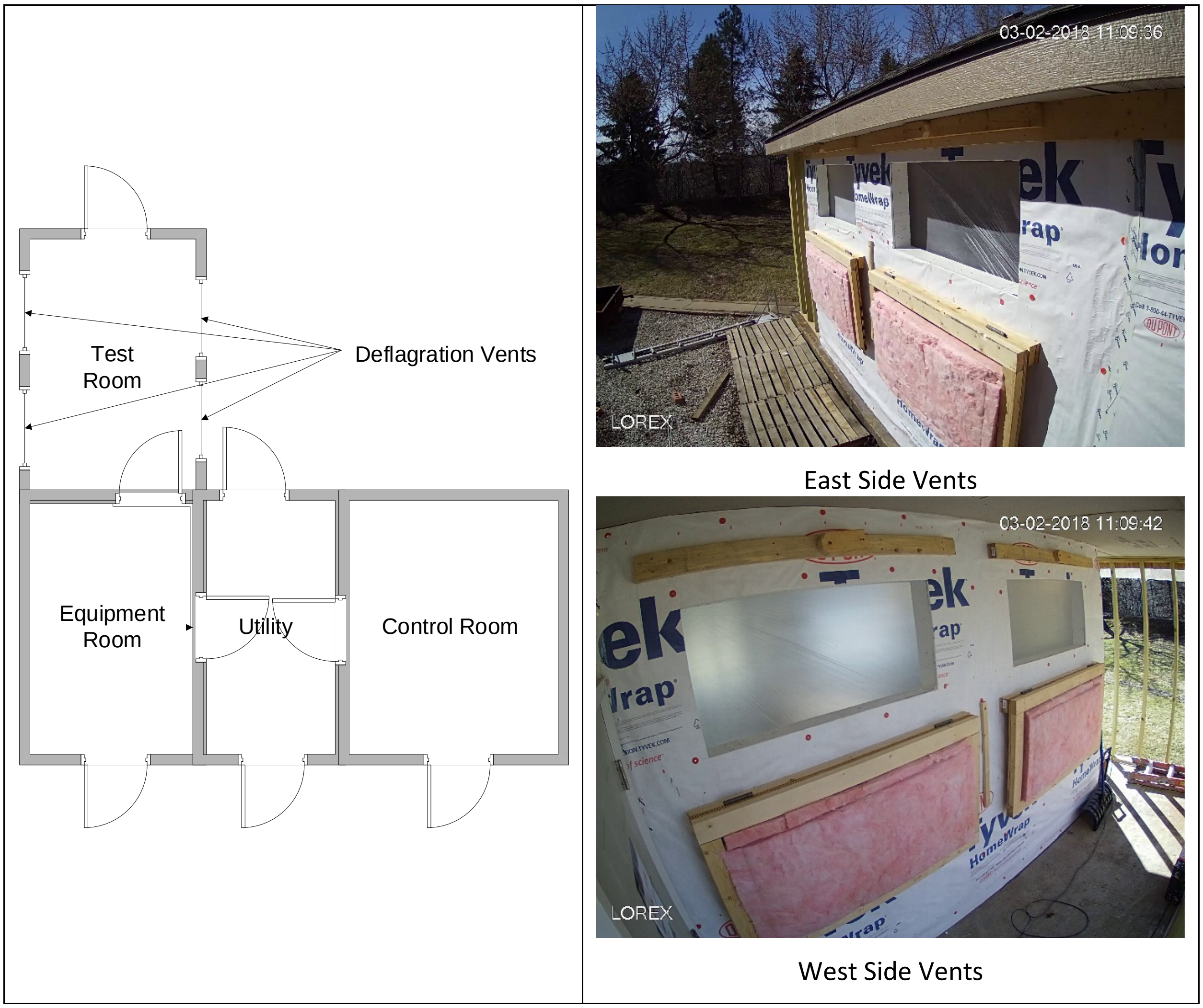


Figure 1 – Task 1 Facility Plan and Construction

The Task 2 facility was an expansion of the Task 1 facility to yield a test room with internal dimensions of 3.95 x 4.81 x 2.42 m (W x L x H) for a total volume of 46.0 m³. The floor space for the Task 2 room (used to calculate charge sizes) was 19.0 m². Two additional deflagration vents with dimensions 0.6 x 0.9 m (2 ft. x 3 ft.) were added as shown in Figure 2.

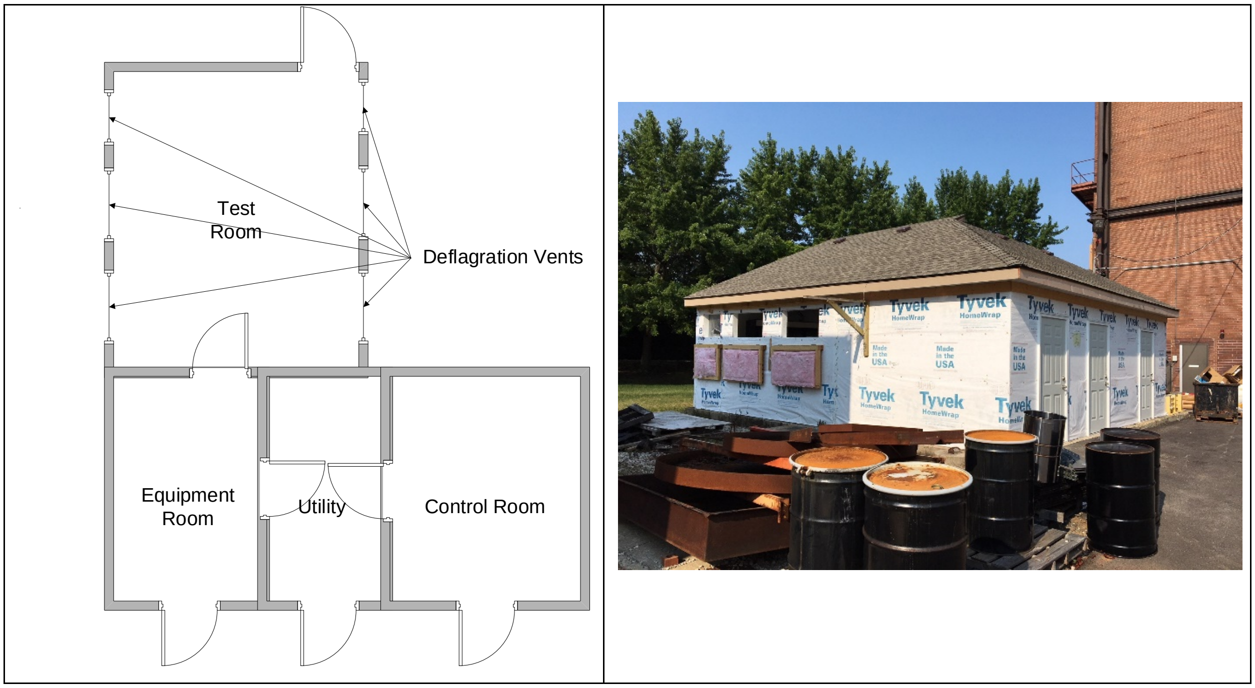


Figure 2 – Task 2 Facility Plan and Construction

7.2. Hazard Controls

The conduct of this test program involved hazards to test personnel, test facilities and the environment. Potential hazards to personnel and the test facility included non-flammable and flammable gases, fire, suffocation, toxic gases, electric shock, frostbite, and mechanical hazards. Hazards were addressed by:

- Elimination.
- Engineering controls.
- Administrative controls.
- Personal protective equipment.

7.2.1. Hazard Elimination

Potential hazards in the workspace were assessed as they were introduced into the laboratory workspace. When possible, hazards were eliminated from the workspace entirely. For example, unused or no longer to be used compressed gas cylinders were removed from the facility and stored in a nearby tank storage facility. Hazards that could not be eliminated immediately were periodically reassessed to determine if changes in the test program enabled the hazards to be eliminated. Hazards that could not be eliminated were addressed through engineering controls, administrative controls or personal protective equipment.

7.2.2. Engineering Controls

When propane is combusted it produces heat, water, and carbon dioxide. In the case of incomplete burning soot and carbon monoxide are also produced. The test facility was constructed such that heat and gases were exhausted from the test room without the risk of personnel exposure.

To prevent over-pressurization, the test facility included deflagration vents, sized by calculations from NFPA 68: Standard on Explosion Protection by Deflagration Venting. Additional testing was conducted prior to design of the facility to determine the minimum deflagration vent area needed for the actual discharge amounts planned for the facility.

Some tests included simulating refrigerant leakage from equipment that included combustible materials. A ceiling mounted sprinkler was installed in the test room that enabled remote extinguishment for any sustained ignition event. Ignition of propane mixtures within the room were expected to last no more than 7 seconds.

All necessary actions required to initiate and provide input to tests were designed such that each action could be conducted from outside the test room.

7.2.3. Administrative Controls

Standard operating procedures (SOPs) were developed in order to provide laboratory staff with guidance for safe test setup and conduct. SOPs consisted of assigning pre-test, test and post-test roles to every member of the project team. Pre-test safety actions were monitored via a checklist reviewed by the lead technical engineer.

Prior to initiating a test, all staff evacuated the test room. Actions needed to initiate and administer a test were conducted remotely from the control room.

Before any staff was permitted entry into the test room, the test room was ventilated with portable fans through open doors and any deployed deflagration vents. Additionally concentration sensors within the test room were monitored to insure that all propane and combustion products had been evacuated.

Electrical equipment requiring hands-on work was de-energized within the circuit breaker for the given equipment; the equipment was switched off, and unplugged. All electrical cabling was verified de-energized with a digital multi-meter.

Hazards typically associated with handling refrigerants by tradesmen were handled only by staff with appropriate training and authorization.

7.2.4. Personal Protective Equipment

UL's standing safety requirement for personnel entering the test facility includes hard hat, safety shoes, and safety glasses.

Additional protective equipment included:

- Long sleeve shirts and long pants.
- Refrigerant operations were conducted by personnel trained and authorized to do so.

7.2.5. Equipment Considerations

It was determined that some amount of propane remains in the discharge tube or collects in the equipment under test. This propane can continue to burn well after the concentrations within the test room air have ceased combustion which generally lasted about 2 seconds. If it was determined that continued flaming posed a potential for damage to instrumentation within the test room, a nitrogen purge was attached to the discharge equipment and any remaining propane in the discharge tube or equipment was purged.

7.2.6. Approach to Highest Discharge Amounts

Propane has the potential to cause severe overpressure either due to large deflagrations or possibly detonations. In order to stay within the design of the built-in deflagration vents, a cautious, step-wise approach was taken toward the discharge amounts specified by the AHRTI project monitoring committee.

For example, the approach to the 400 gram release in the ISO 9705 test room (2.4 x 3.6 x 2.4 m-high) began with a 50 gram discharge igniter test. The testing proceeded to increase the charge amount by 50 gram increments. Behavior of the deflagration vents were monitored for adequate venting behavior before moving on to the next increment.

Using this method resulted in terminating one series of tests short of the AHRTI PMS goal due to an overpressure event that cause minor, repairable damage to the test room.

8. Equipment, Measurements, and Data Acquisition

Deployment of instrumentation and equipment varied in Task 1 and Task 2. For Task 2 instrumentation varied with each scenario (PTAC, mini-split, and reach-in cooler). Details are available in Appendix H Test Instrumentation and Equipment

8.1. Equipment

The equipment groups included (i) refrigerant discharge control system; (ii) mass flow control system, and (ii) electric arc ignition sources.

8.1.1. Refrigerant Discharge Control System

Figure 3 shows the refrigerant release system used in the Task 1 tests. The system consisted of a pressurizer tank and a release tank. The pressurizer tank assisted with maintaining the pressure in the release tank to enable liquid release to the test room at a constant rate. Prior to release, the line between the pressurizer and release tank, and release tank and mass flow meter were evacuated to a vacuum of less than 1 mmHg. Just prior to starting a release the cross over valves between the pressurizer tank and release tank were opened to allow fluid communication between pressurizer and release tanks. The emergency stop valve was opened to allow liquid to fill the lines between the release tank and the refrigerant solenoid valve. At the start of a release the refrigerant solenoid valve was opened and the mass flow control system throttled the flow rate to the test requirements. At the completion of the discharge, the control system closed the refrigerant solenoid.

Both refrigerant release tanks were submerged in water baths to establish initial temperatures as required. The temperature of the pressurizer bath was set such that 20-30 °F of sub cooling was established in the release tank liquid once the two tanks were cross connected.

Manual valve operations after completion of the discharge were used to vent the mass flow control lines and prevent high pressures from expanding liquid propane. In some cases, it was necessary to purge the discharge line with nitrogen into the test room to extinguish fire at the exit of the discharge tube.

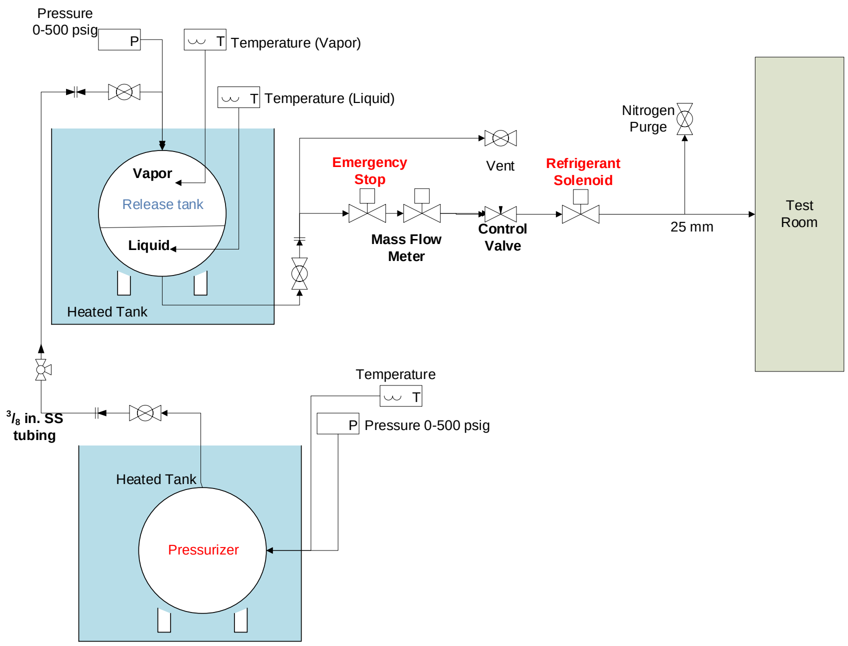


Figure 3 – Refrigerant Release System for Task 1

The release system was similar for Task 2 operations with the exception that the 25 mm discharge tube was replaced with a ¼ inch O.D. copper tube for placement in the test equipment (PTAC and mini-split). The reach-in cooler tests further narrow the ¼-inch tube down to a capillary tube for positioning in either the evaporator or condenser coil as called for in the test specifications. Figure 4 shows the Task 2 release system.

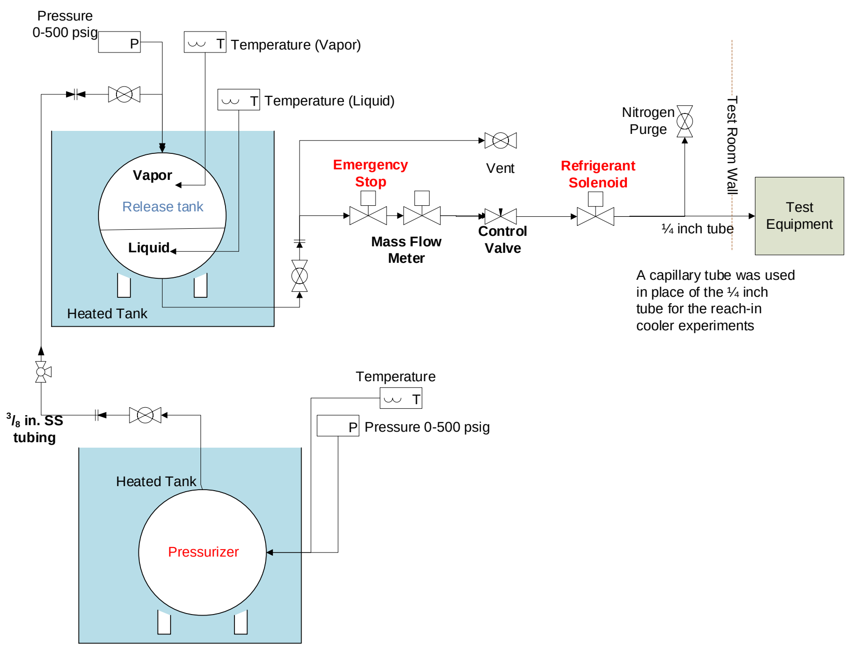


Figure 4 – Refrigerant Release System for Task 2

Figure 5 shows the release and pressurizer tanks as constructed for this project.

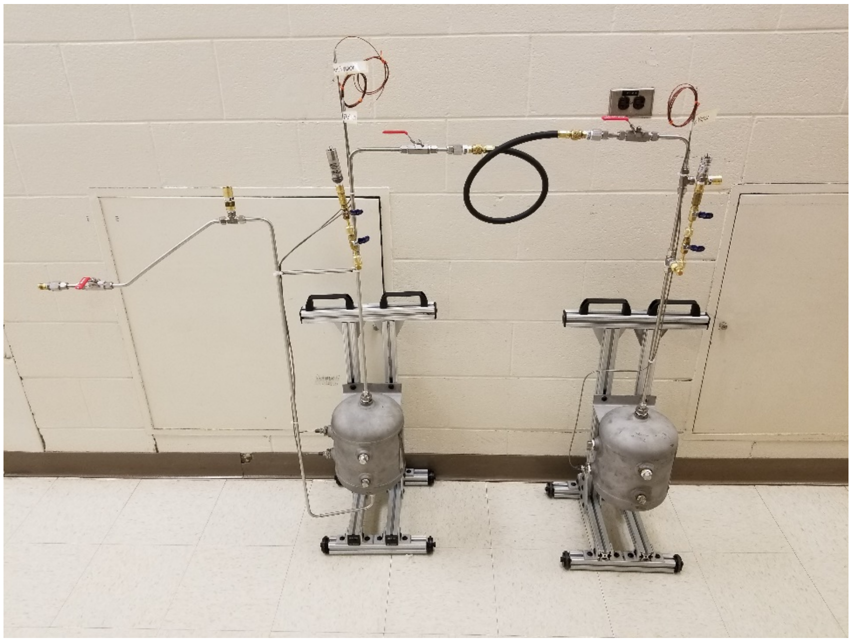


Figure 5 – Release Tank (left) and Pressurizer Tank (right)

8.1.2. Mass Flow Control System (6.8 to 40 g/s or 25 to 144 kg/hr)

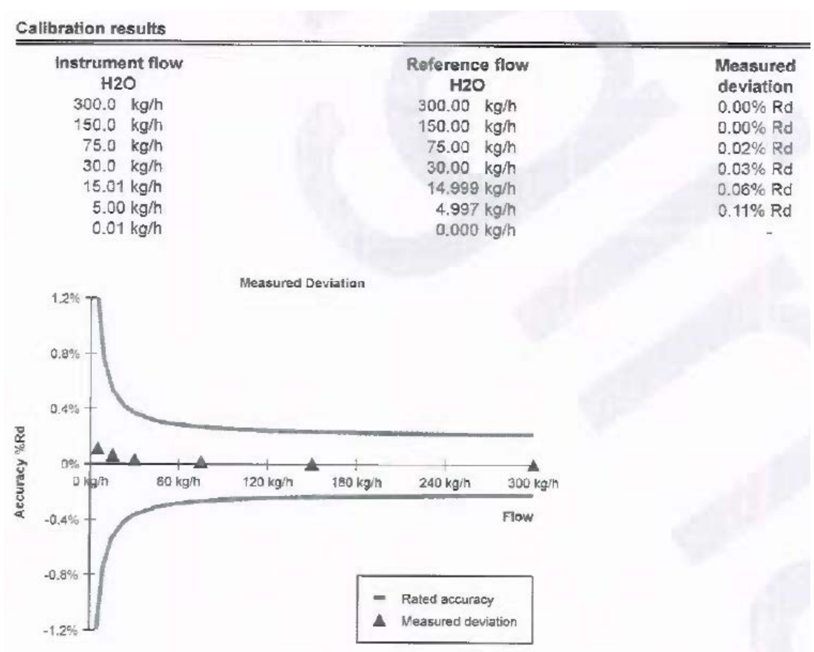
The mass flow control system was comprised of Coriolis mass flow meter, programmable logic controller (PLC) and a motor operated metering valve. Additional components included two solenoids, one for an emergency stop and the other for stopping the discharge at the end of the metered release (See Appendix H Test Instrumentation and Equipment).

A 4-20 mA signal was generated by the mass flow meter and fed into the PLC and the data acquisition system on a current loop using high precision resistors to insure high fidelity of the signal in both systems.

The mass flow meter as delivered for this project was calibrated by the manufacturer from 0 to 300 kg/hr (83.3 g/s) as shown in Figure 7. In order to improve resolution at the data acquisition system the full scale output signal was set to 150 kg/hr. This setting was made in software and did not affect the calibration. The mass flow meter is shown in Figure 6.

Figure 6 – Mass Flow Meter

The needed flow rates were determined based on the relative liquid mass flow rates of R-32 and propane (See 11.1.1 Comparison of R-32 and Propane Release Rates). These rates were determined to be 6.8 g/s and 40 g/s (24.6 kg/hr. and 144 kg/hr., respectively). The manufacturer's calibration certificate shows a specification of ±0.4% of reading at the lowest flow rate of 25 kg/hr.



Calibration results

Instrument flow H2O	Reference flow H2O	Measured deviation
300.0 kg/h	300.00 kg/h	0.00% Rd
150.0 kg/h	150.00 kg/h	0.00% Rd
75.0 kg/h	75.00 kg/h	0.02% Rd
30.0 kg/h	30.00 kg/h	0.03% Rd
15.01 kg/h	14.999 kg/h	0.06% Rd
5.00 kg/h	4.997 kg/h	0.11% Rd
0.01 kg/h	0.000 kg/h	-

Figure 7 – Coriolis Mass Flow Meter Calibration

The manufacturer did not report the accuracy of the mass totalizer function, but initial verification tests of the integrated system flowing a total of 1,000 grams showed errors between -2% and +0.5% (-20 and +10 grams).

8.1.3. Mass Flow Control System (0.2 to 0.6 g/s or 0.76 to 2.16 kg/hr)

The reach-in cooler tests required a much lower flow rate than other tests in the project. This required adjustment of the output range of the mass flow meter 7.2 kg/hr (2 g/s) and a separate calibration (see Appendix F Mass Flow Control Validation).

The test set-up for verification of the mass flow meter and controller is shown in Figure 8 according to the manufacturers guidance for field calibration. Due to time constraints there was no opportunity to return the meter to the manufacturer for full calibration in this low range. The accuracy of the flow rate was found to be ±4% of reading at the lowest flow rates used in the reach-in cooler testing. At the highest flow rates the accuracy was found to be ±1% of reading.

Total Mass flow was calculated in software following the test. The totalizer within the meter was not used because it depended on factory calibration. The accuracy of the total mass calculation was found to be ±5% of reading at the lowest total mass releases used in the reach-in cooler testing. At the highest total mass release the accuracy was found to be ±2% of reading.

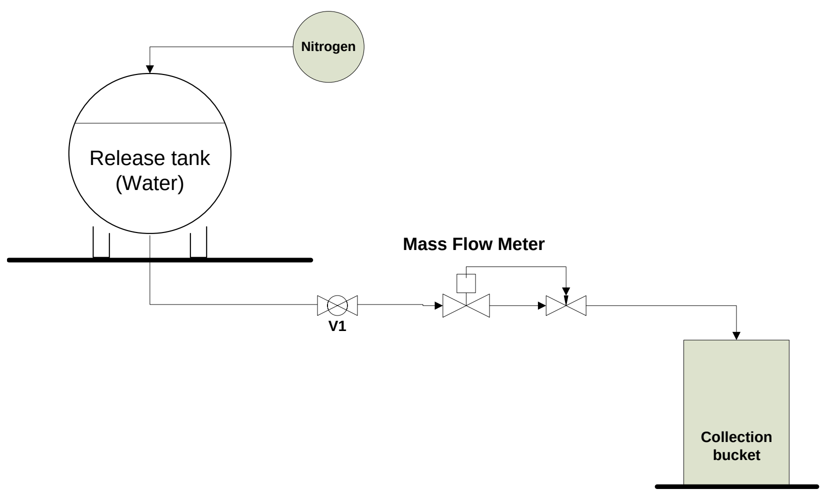


Figure 8 – Test Set up for Response Time and Validation of Mass Flow Meter and Controller

8.1.4. Electric Arc Ignition Source

The electric arc ignition source was identical to that used in the 9007-2 A2L project. That information is repeated here. Location of the electric arcs varied with task 1 and 2 activities. The mounting locations are documented in the associated sections.

A step-up gas tube transformer was used to create an electric arc as an ignition source. The leads of the transformer were connected to a pair of tungsten rods mounted such as to leave a ¼ inch air gap. Photographs of this equipment are included in Figure 9. Note that the transformer secondary ratings are based on open-circuit voltage and short-circuit amperage.

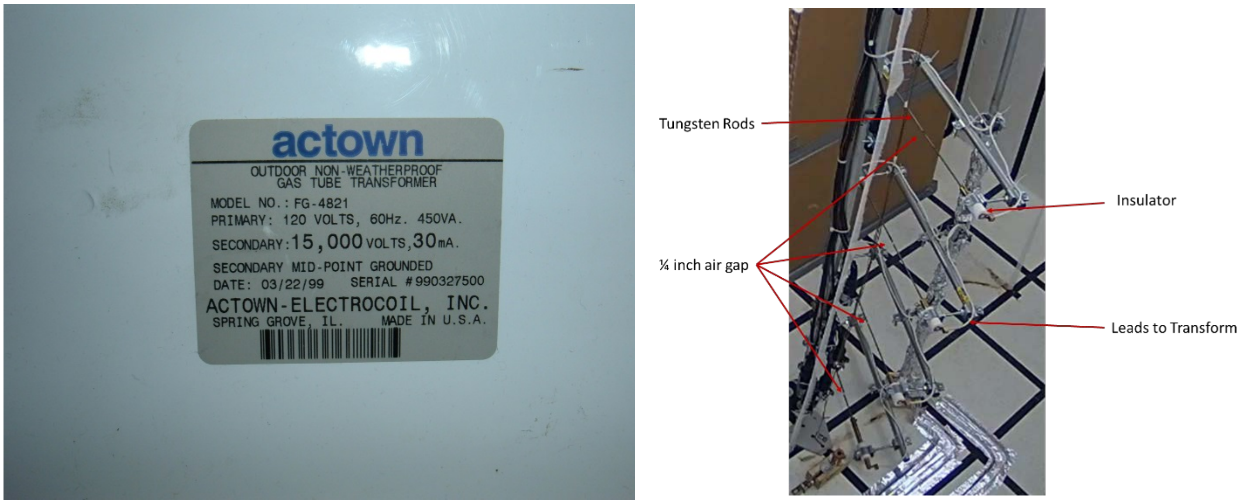


Figure 9 – Gas tube transformer and arc gap

Table 3 shows the measured rms voltage and amperage developed by each electric arc/transformer pair. The rms power of the electric arc was 17.6 watts (joules/sec). The energy of the electric arc in one-half 60 Hz cycle (8,333 μs) was 0.147 joules (147 mJ). This ignition energy is nearly 300 times the commonly accepted minimum ignition energy of propane/air mixtures at 0.46 mJ. This energy per half cycle cannot be directly compared to Minimum Ignition Energy (MIE) tests which use a single capacitive discharge with a much shorter duration (0.01 to 0.1 μs).

Table 3 – Electric arc Input Power and resulting output

Input P_{RMS}	Output per Electrode		
	V_{RMS}	I_{RMS}	P_{RMS}
watt	**Volts**	**milliAmpere (mA)**	**watt**
75.0	1590	11.06	17.6

Figure 10 shows a typical voltage and current trace of two 60 Hz cycles of an electric arc such as used in these tests.

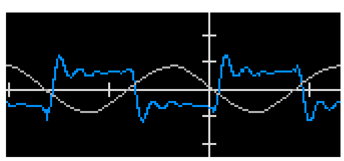


Figure 10 – Trace of current (smooth sine wave) and voltage in an electric arc

When used in testing, the electric arc transformer was continuously energized for several minutes.

9. Data Acquisition System

The data acquisition system was a National Instruments system supporting up to 128 thermocouple channels and 64 voltage inputs. The data acquisition rate was selectable up to 1000 Hz. The rates chosen for this project included 1 Hz (room leakage tests), 10 Hz, and 50 Hz. The 50 Hz rate was selected later in the program after it was determined that the room pressure rise from ignition events could not be adequately recorded at the 10 Hz rate.

9.1. Measurements

In the tests, temperature, propane concentration and room pressure were measured.

9.1.1. Temperature

The test room temperature was monitored using 0.035 in. (0.89 mm) open bead Type K thermocouples. The thermocouple response time was approximately 3.0 seconds. Eight thermocouples were assembled into vertical arrays to measure the temperature profile at one floor location. Each array was created with thermocouples at 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) above the floor. The number and location of arrays varied with Task 1 and Task 2 scenarios.

Additional single thermocouples were placed at floor locations where liquid propane pools were expected to form.

9.1.2. Propane Concentration

Propane concentration was measured using an oxygen sensor (Apogee SO-220 electrochemical sensor) as compared to hydrocarbon sensors used in A2L project [1]. The oxygen sensors are lower cost and have a faster response time as compared to the hydrocarbon sensors reported in AHRTI 9007-1 [1] project. The output of the Apogee SO-220 sensor is dependent on the absolute partial pressure of oxygen at the measurement membrane. The sensor is equipped with a heater to maintain constant temperature to prevent moisture condensation at the diffusion membrane. An important condition for providing reliable measurements with this sensor was that the barometric pressure, cell temperature and humidity at the sensor are similar to initial test conditions. To achieve this, the sensors were calibrated with different mixtures of propane concentrations in air with conditions similar to that anticipated in the test room as described in Appendix G.

The calibration with 100% propane concentration the sensor output yielded a voltage of 0.2 mV ±0.1 mV (per specifications); and at 0% propane, the sensor output was range of 12 to 13 mV (in agreement with manufacturer's specifications).

It is assumed that propane concentration at the sensor displaces all atmospheric gases in proportion to their initial concentrations. For example, if the ambient concentration is 20.95% by volume, and local propane concentration is x, then the local oxygen concentration has changed to $(1 - x) * \ 20.95\%$ This relationship provides a means to infer propane concentration by solving for x.

The details of the calibration, and correlating equation are presented in Appendix G. The manufacturer's specification for accuracy of the this measurement are ±6% of reading at 2% concentrations and ±1% at 10% concentrations. The resulting linear equation is shown in Equation 1.

$$x = \left(\frac{S_{init} - S}{S_{init} - S_{zero}}\right) \times 100\% \qquad \text{Eqn. 1}$$

Where:

x	Is the propane concentration (% by volume)
S	Is the sensor output (mV)
S_{zero}	Is the sensor output at 0% oxygen (based on Nitrogen) (mV)
S_{init}	Is the sensor output at 20.95% oxygen (mV)

The manufacturer of this sensor also provides a temperature correction. The effect in all tests was small with the exception of tests where the sensor was rapidly cooled by an impacting mist of propane liquid. The final conversion equation for propane concentration including temperature correction is shown in Equation 2.

$$x = \left(\frac{S_{init} - S}{S_{init} - S_{zero}}\right) \times 100\% - \sum_{i=0}^{3} \frac{C_i T^i}{0.2095} \qquad \text{Eqn. 2}$$

Where:

C_i	Constants provided by Apogee Instruments for the SO-200 series sensor
T^i	Measured temperature (°C) raised to an integer power
0.2095	Ambient Oxygen volume fraction

The constants are listed in Figure 11.

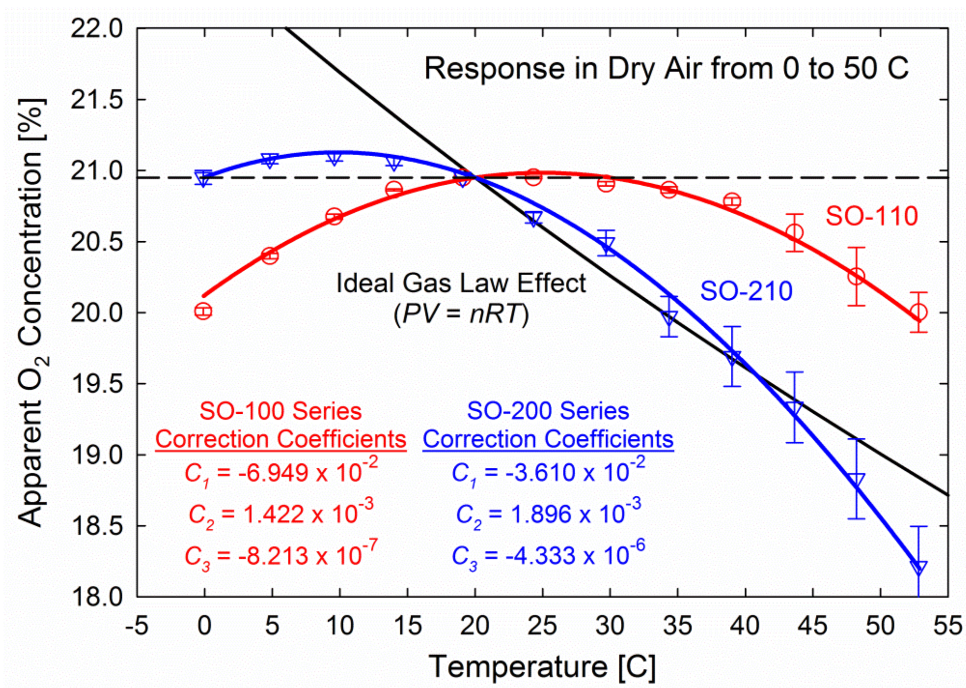


Figure 11 – Temperature Correction Constants (Apogee Instruments: SO-100-200-manual)

The response time from the manufacture is 14 seconds to respond to 90% of a step increase in the measured concentration. This corresponds to a time constant (τ) of 6.08 seconds. A deconvolution method was used to obtain instantaneous concentration.

In differential form and delta form the deconvolution calculation is shown in Equation 3.

$$D(t) = C(t) + \tau \frac{dC(t)}{dt} \qquad \text{Eqn. 3}$$

Where:

$D(t)$	Is the deconvoluted propane concentration at time t
$C(t)$	Is the concentration reported by the sensor at time t
τ	Is the time constant for sensor response (6.08 seconds)
$\frac{dC(t)}{dt}$	Is the rate of change of concentration at time t

The formula for determining the derivative from discrete data is shown in Figure 12.

$$f'(x_0) \approx \frac{-f_2 + 8f_1 - 8f_{-1} + f_{-2}}{12h}$$

Figure 12 – Fourth Order Central Difference [7]

Figure 13 is an example of an Excel spreadsheet applying the deconvolution method to a hypothetical sensor response to a concentration that changes from 0% to 100% in one second. Cell D8 has been highlighted to show the calculation of the rate of change, $\frac{dC(t)}{dt}$. In this case the *h* in Figure 12 is one second so it is not shown in the cell formula.

	A	B	C	D	E	F
1	Time (s)	Actual Concentration (%)	Sensor response (%)	f' (%/s)	tau * f' (%)	Deconvoluted (%)
2	0	0%	0%	0.0%		
3	1	0%	0%	0.0%		
4	2	0%	0%	7.7%	38.4%	38%
5	3	100%	15%	15.3%	76.4%	91%
6	4	100%	28%	11.7%	58.7%	86%
7	5	100%	39%	10.0%	49.9%	88%
8	6	100%	48%	8.5%	42.4%	90%
9	7	100%	56%	7.2%	36.1%	92%
10	8	100%	62%	=(-C12+8*C11-8*C9+C8)/12		93%
11	9	100%	68%	5.2%	26.0%	94%
12	10	100%	73%	4.4%	22.1%	95%
13	11	100%	77%	3.8%	18.8%	96%
14	12	100%	80%	3.2%	16.0%	96%
15	13	100%	83%	2.7%	13.6%	97%
16	14	100%	86%	2.3%	11.6%	97%
17	15	100%	88%	2.0%	9.8%	98%
18	16	100%	90%	1.7%	8.4%	98%
19	17	100%	91%	1.4%	7.1%	98%
20	18	100%	93%	1.2%	6.0%	99%
21	19	100%	94%	1.0%	5.1%	99%
22	20	100%	95%	0.9%	4.4%	99%

Figure 13 – Example Calculation of Deconvolution

Figure 14 is a graphical example of this same data in Figure 13, but extended with a one second drop in concentration from 100% to 0%. The resulting deconvoluted curve is shown to be much closer to the actual concentration than the uncorrected sensor signal

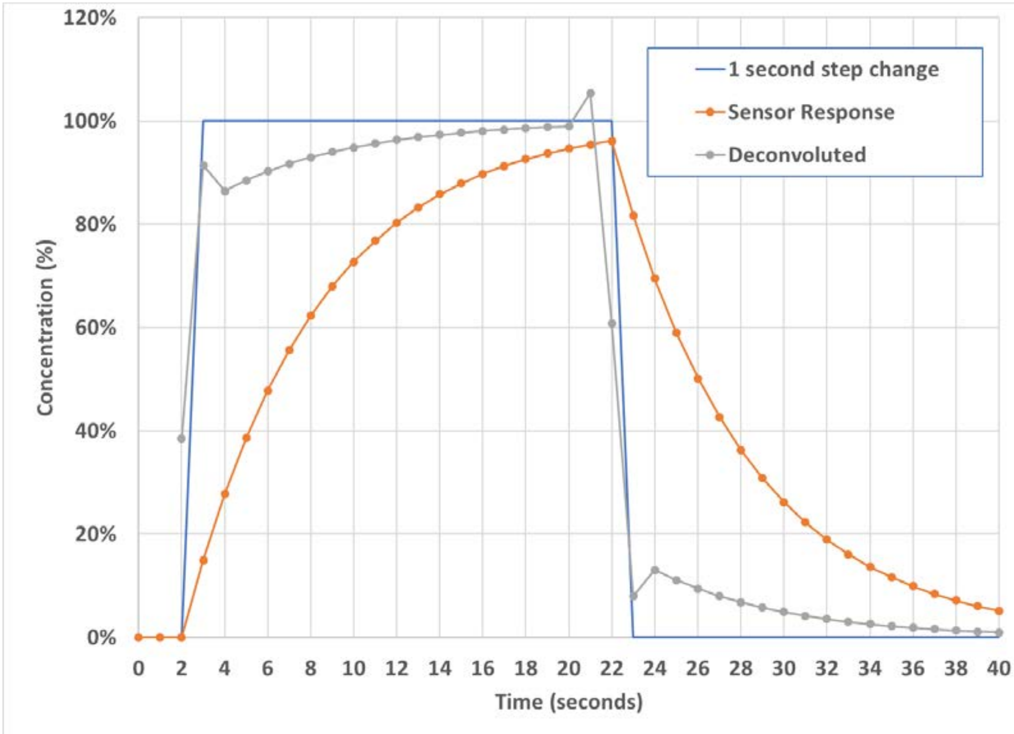


Figure 14 – Example of Deconvolution

Figure 15 shows the effect of deconvolution on one of the datasets from a reach-in cooler test. The red-orange line is the calculated concentration without deconvolution applied. The blue deconvoluted line rises to its peak approximately 10 seconds before the series without deconvolution. Deconvolution is using the measured rate of change and the exponential response function of the sensor to boost the measured signal to be closer to the actual concentration.

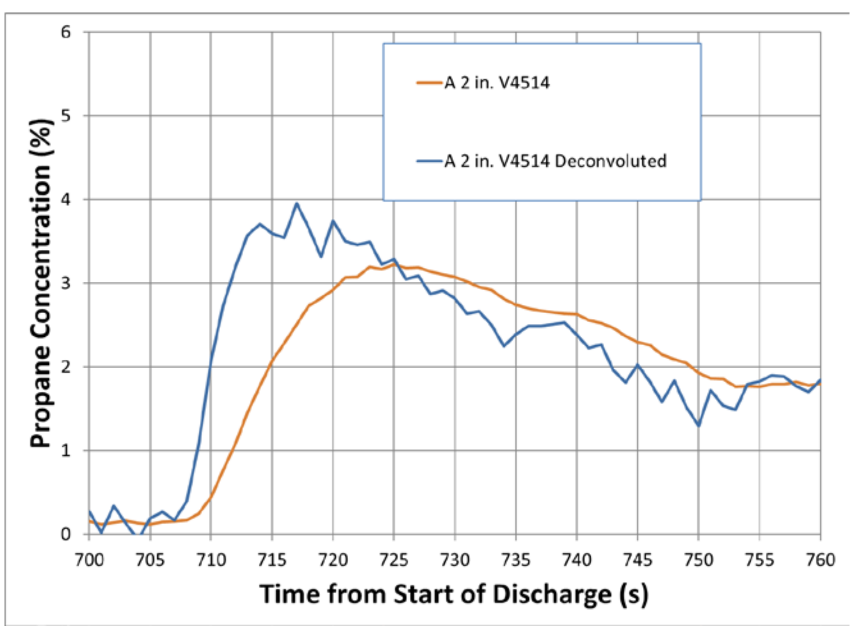


Figure 15 – Effect of Deconvolution on measured concentration

9.1.3. Video and Digital Documentation

A video recording system was used for all igniter tests. The system was capable of supporting 16 IP cameras. The number of cameras used varied in each scenario. Two 4K cameras were available for high resolution videos. One infrared camera was also connected to this same system.

Two high-speed cameras, Casio model EX-F1, were also used to capture ignition events. The camera was operated at 300 frames per second (fps) with a resolution of 512 × 384 pixels.

9.1.4. Heat Flux

Heat flux was measured in the Task 1 test series using a 0-50 kW/m^2 heat flux gauge. For reference the threshold for second degree burns is based on the heat flux and the time of exposure. The following graph describes this effect based on an SFPE paper from 2000 [8].

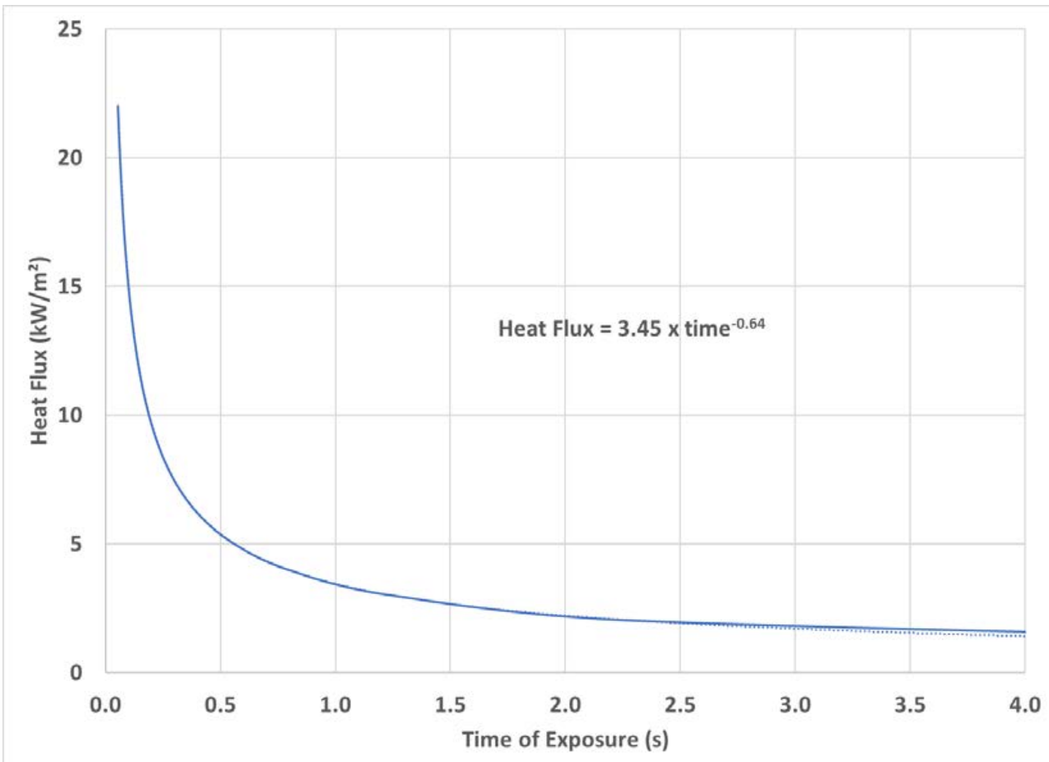


Figure 16 – Exposure time and Heat Flux to cause 2nd degree burns

10. Characterization of Test Room Leakage

The degree of tightness of the Task 1 test room was determined by discharging 1.6 kg of carbon dioxide into the test room. Carbon dioxide and propane have nearly identical molar masses (~44 kg/kmol). This discharge was equivalent to 4% concentration when fully mixed in the test room. The discharge was made through the 25 mm tube using the mass flow control system at the rate of 10 g/s. The discharge was in liquid form from a siphon tube equipped carbon dioxide tank.

During the discharge, there was some formation carbon dioxide ice (dry ice) which quickly evaporated. Figure 17 shows the measured concentration for 2 hours after the release while the room remained undisturbed. The initial release and formation of dry ice resulted in peak values at location B2 and heights between 2 inches and 12 inches above the floor. At 10 minutes (600 seconds) all the dry ice had evaporated and a slow decay in concentration began due to leakage. An exponential decay curve fit to this data gives a time constant of 3900 seconds or a half-life of 2700 seconds. For reference, the time constant for the 9007-1 A2L project for the room leakage test was 2500 seconds or a half-life of 1700 seconds.

It is concluded that leakage out of the room is very slow and takes much longer than the duration of any of the ignition tests performed, so room leakage is acceptable for the purposes of this test program.

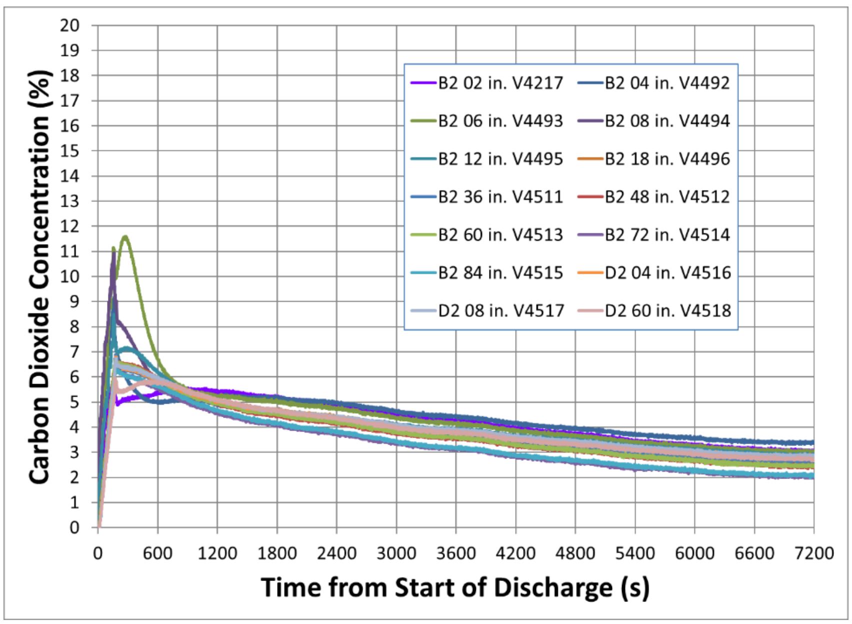


Figure 17 – Leakage of Carbon Dioxide from the Test Room

11. Task 1 - Parametric Tests

Task 1 testing was performed in 2.4 x 3.6 x 2.4 meter (W × D × H) facility as specified in ISO 9705 [2]. The room was modified with deflagration vents and access doors for the purpose of the test program.

The following three factors were selected for variation in the investigation:

- Release Height (0.2 and 1.8 m)
- Discharge Quantity (25% and 50% of LFL when mixed in the entire room volume)
- Release Rate (Low and High).

Final discharge rates were based on the finding (See Section 11.1.1) that the mass flow rate of liquid propane is 49% of the R-32 liquid mass flow rate at the same saturation temperature and orifice size. These values were selected so that comparisons are possible between the A2L and A3 Task 1 tests in both 9007 programs.

The tests resulted in consistent ignition when propane was discharged at the 0.2 m height, regardless of discharge rate, while ignition at the 1.8 m height was dependent on precise placement of the electric arc at similarly high elevations in the test room. The electric arcs were placed at 0.025m, 0.3m, 0.6m, 0.9m (1 inch, 1ft., 2ft., and 3ft.) above the floor. For the tests with discharges at the 1.8 m height, the 0.9m arc was moved to a height of 1.8m. The concentration tests at the 1.8 m height showed dispersal of concentrations to less than LFL between 15 and 40 seconds after the start of the discharge. For all igniter tests, the electric arcs were energized within 6 seconds of completion of the discharge.

11.1. Specifications of Charge Size and Refrigerant Release Rate

The three factors investigated were as follows:

- Refrigerant Concentration: 25% and 50% of LFL when evenly mixed within the test room
- Refrigerant Release Rate: 6.8 g/s and 40 g/s based on scaling the leak rates found in the A2L project by a factor of 0.49. See section 11.1.1 for the determination of this factor.
- Refrigerant Release Height: 0.2 m and 1.8 m based on similar heights used in the A2L project.

A full factorial design of experiment requires 8 tests (2×2×2) to include the full variability of these factors, but resource constraints led to the selection of a sparse matrix involving 4 tests as shown in Table 4. The release quantities of propane were based on the LFL of 0.038 kg/m³ (sea level), the Task 1 room volume, and adjustment for elevation of the UL Northbrook facilities.

Table 4 – Test Matrix for Task 1 A3 study

Room Average Concentration	Release Height		Leak Rate		Release Quantity
	(-)	(m)	(-)	(g/s)	(g)
50% LFL	Low	0.2	Low	6.8	400
25% LFL	High	1.8	Low	6.8	200

50% LFL	High	1.8	High	40	400
50% LFL	Low	0.2	High	40	400

11.1.1. Comparison of R-32 and Propane Release Rates

Since R-32 and R-290 have different thermodynamic properties (density, viscosity, saturation pressures) it follows that under the same operating conditions an identical leak size would result in different mass flow rates. A series of tests were conducted to determine the ratio of R-290 mass flow to R-32 mass flow through an identical orifice (0.037 inches) and at the same saturation temperature, 95°F (35°C). This factor (0.49) would then be used to scale the discharge rates from the A2L project that used R-32 for a comparable R-290 discharge rate.

Figure 18 shows the equipment setup for comparing the discharge rates under identical conditions. The equipment consisted of two 50 lb. refrigerant tanks, each filled with either R-290 or R-32. The liquid valve was connected to a line containing a pressure transmitter, mass flow meter, a manual valve, the orifice, thermocouples, and the exhaust system. One thermocouple measured the bath temperature and the other measure the tank surface temperature.

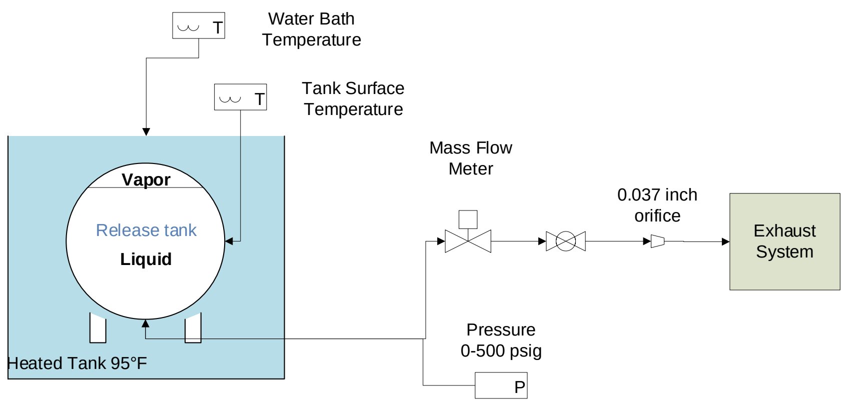


Figure 18 – Equipment Setup for Comparing R-32 and R-290 Discharge Rates.

A series of 10 tests (5 for each refrigerant) were conducted according to the following procedure:

- The tanks were filled (7.4 kg R-32; 3.8 kg R-290)
- A tank was placed in the water bath (controlled at 97°F) and connected to the discharge lines.
- Tank temperature and pressure monitored until stable at 95°F or slightly increasing
- Data recording started at 1 Hz sampling rate
- The manual discharge valve was opened and then closed after 40 seconds.
- Data recording was stopped

Figure 19 shows the data recorded from these tests. The data show some initial instability in flow rate followed by a repeatable flow rate.

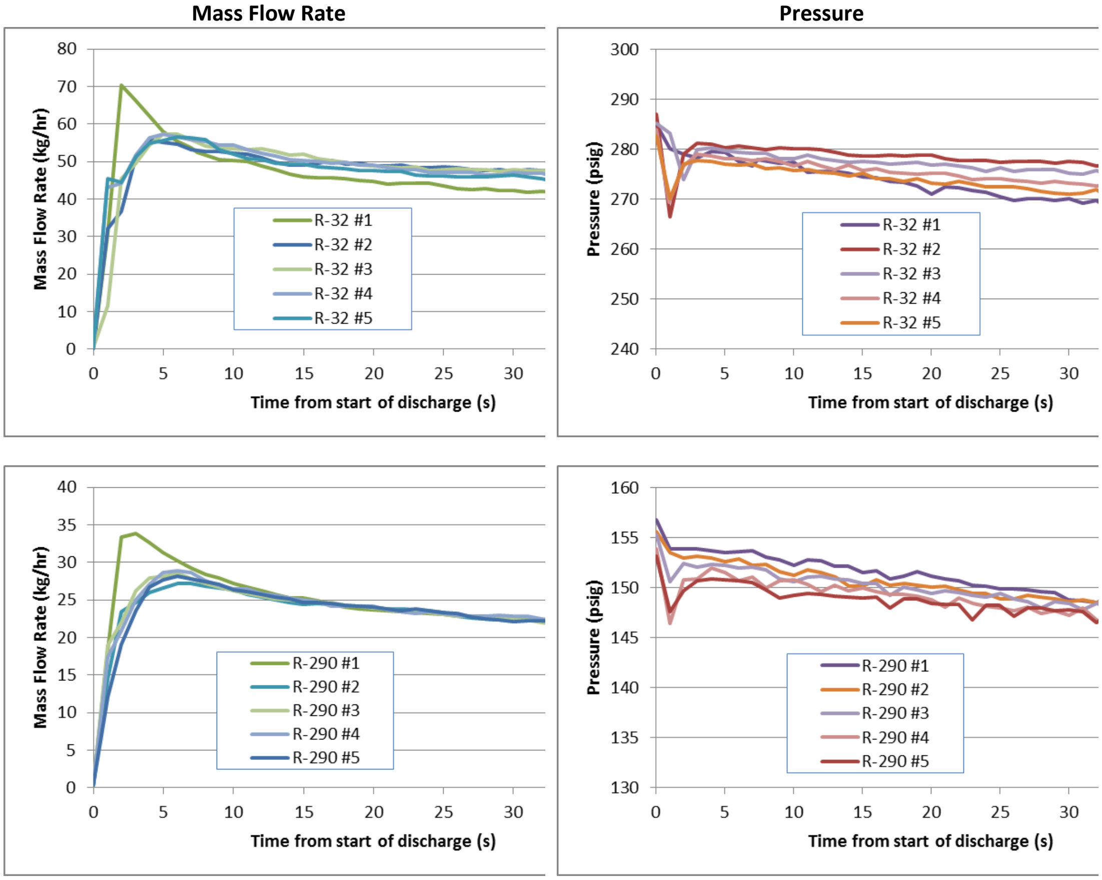


Figure 19 – Compare flow rate and pressure, R-32 vs. R-290

Figure 20 shows a second-by-second comparison to the average mass flow rates. The overall average of these ratios is rounded to 0.49. This value was used to establish propane discharge rates based on the R-32 rates measured in the A2L project.

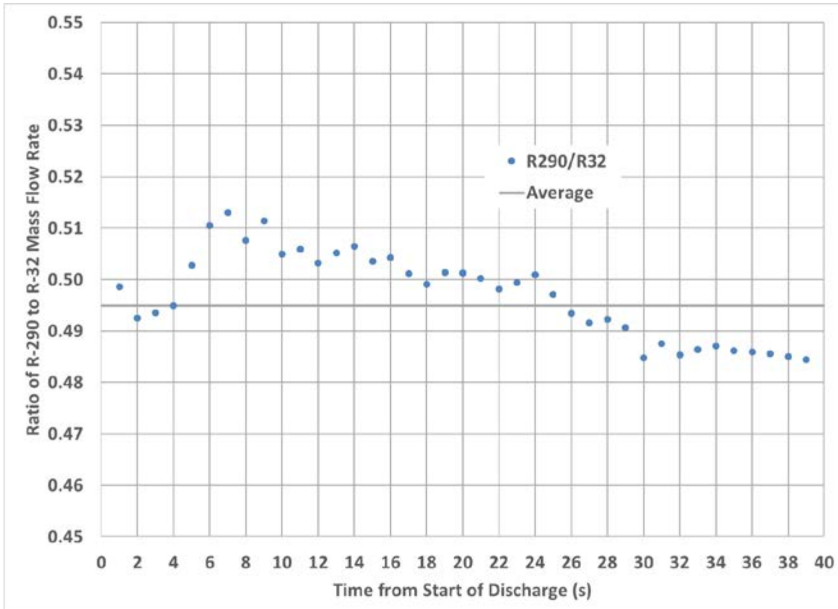


Figure 20 – Second-by-second Ratios of Mass Flow

11.2. Parametric Series Test Plan

The test series outlined in Table 4 posed a safety concern because of the potential for a large overpressure event that would put personnel and facilities at risk of injury or damage. Management of this deflagration hazard involved the use of a step-wise or titration approach of increasing discharge amounts to explore the limits of discharge quantities that might lead to damaging overpressure events. To accomplish this, propane was discharged starting from 50 grams and increasing by 50 grams. In each series, the first test was a concentration test to document propane concentrations. This was followed by an igniter test. The test series was to be terminated before overpressures became too large for the test facility.

11.3. Instrumentation

Figure 21 shows the room layout for Task 1 tests. There were four deflagration vents, each measuring 0.6m x 1.2m (2 ft. x 4 ft.). Two vents were on each of the long walls and equally spaced. The bottom of each vent was 1.5m (5 ft.) above the floor. The final room dimensions were 2.44 m x 3.66 m x 2.43 m (8 ft. x 12 ft. x 8 ft.) for a total volume of 21.7 m^3 (768 ft^3).

The obstruction was constructed from cardboard boxes and measured 0.9m x 1.8m x 0.9m (3 ft. x 6 ft. x 3 ft.); and was placed in the center of the room.

The 25 mm discharge tube location varied with the specifications of each test and was located at either 0.2m or 1.8m (8 inches, or 6 ft.) above the floor on the room centerline. The end of the discharge tube was flush with the wall.

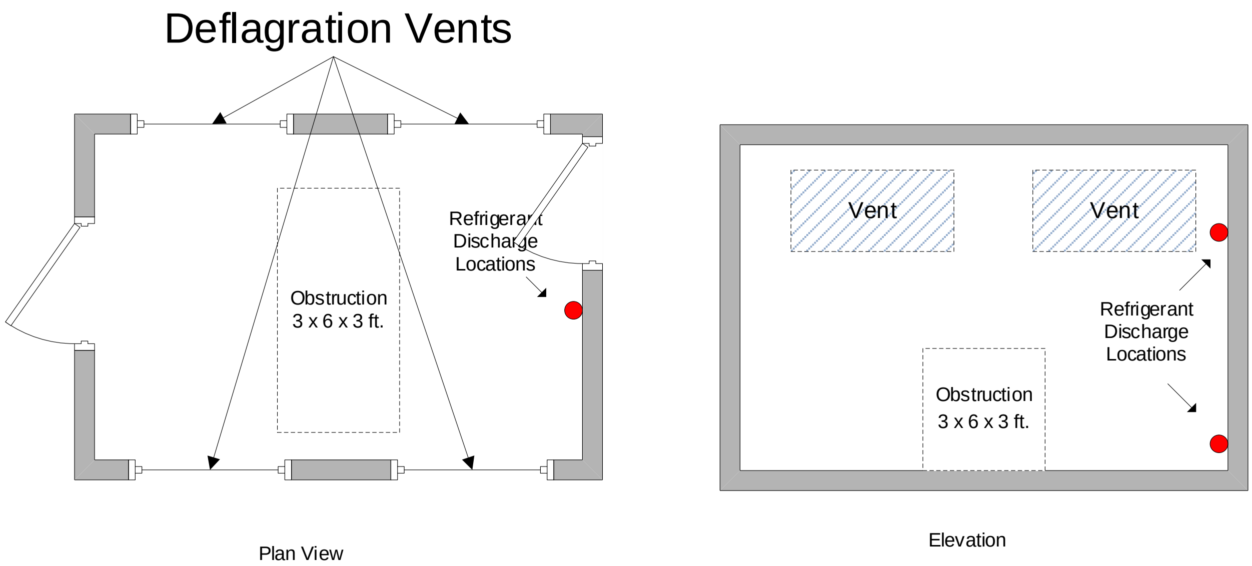


Figure 21 – Task 1 Room Deflagration Vents, Obstruction, and Discharge Locations

Figure 22 shows the positioning of instrumentation for Task 1. The locations were labeled using a grid system. Locations A and B were 0.45m and 0.9 m (1.5 ft. and 3 ft.) from the front wall. Locations E and D were similarly placed with respect to the back wall. Locations 1 and 3 were 0.45 m (1.5 ft.) from the side walls, while location 2 was on the room centerline. Cheesecloth strips were hung at every grid location with the exception of A2 which is directly in front of the discharge tube. Refrigerant sensors were located at locations B2 and D2 (10 sensors at B2 and 3 at D2). The electric arcs were at location B2 at 0.025m, 0.3m, 0.6m, 0.9m (1 inch, 1ft., 2ft., and 3ft.) above the floor. The heat flux gauge was at floor level at location B2. Actual equipment locations were within 15 cm (6 inches) of the specified grid location, but refrigerant sensors were placed directly over the grid location.

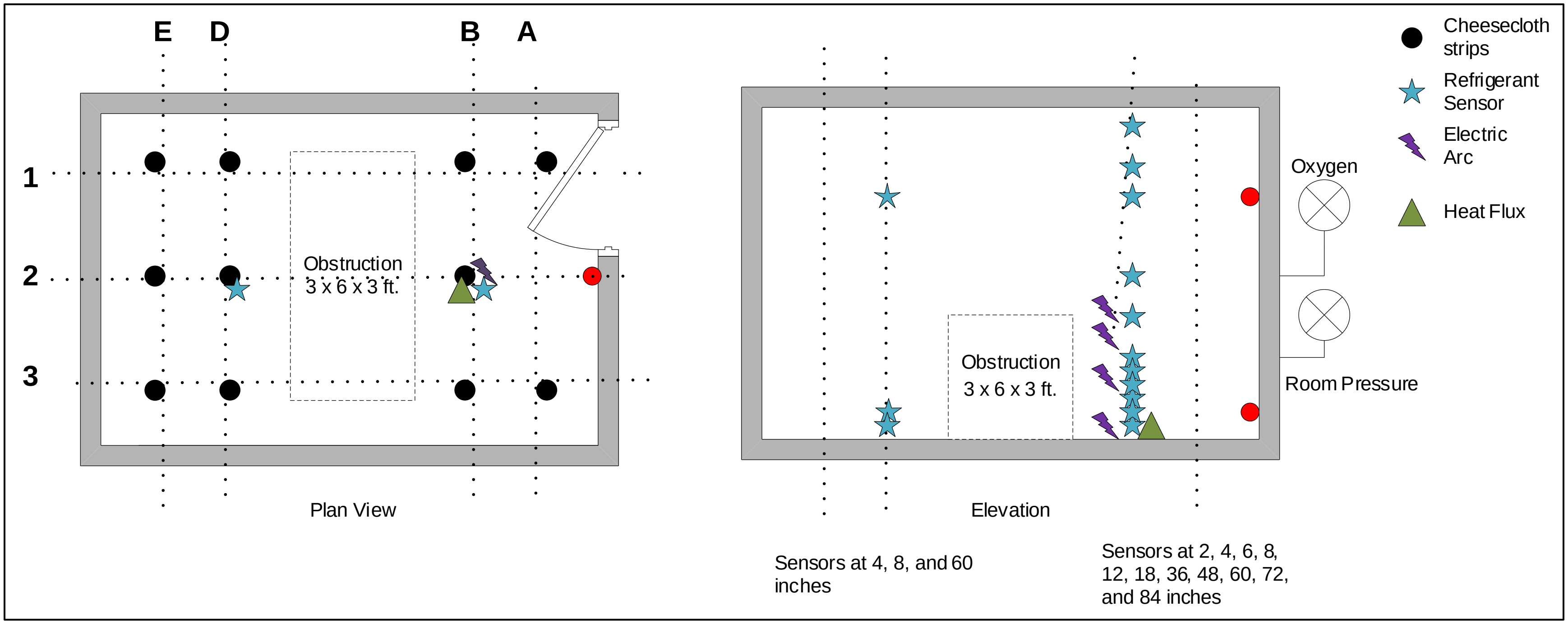


Figure 22 – Task 1 Instrumentation Locations

Figure 23 shows the arrangement of thermocouples. Six trees were at locations A1, A3, B2, D2, E1, and E3. A cluster of four thermocouples were placed in a diamond pattern on the floor directly in front of the discharge tube to capture indications of liquid pools of propane. An additional thermocouple was placed in the exit of the discharge tube.

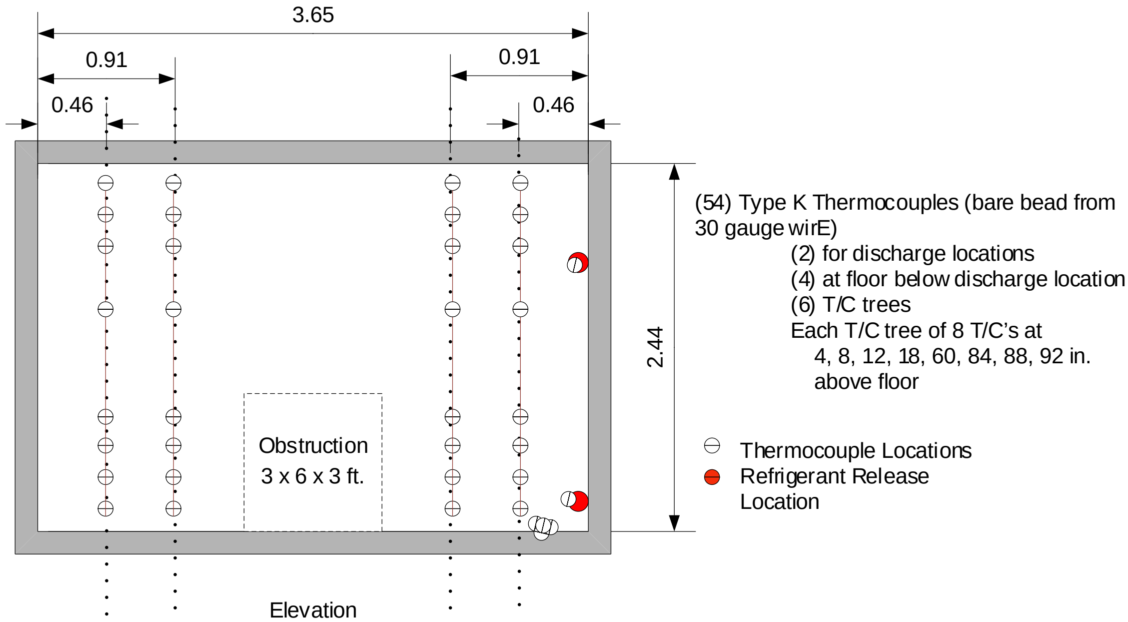


Figure 23 – Task 1 Thermocouple Locations

11.4. Test Procedure

The detailed test procedure is contained in Appendix I Test Procedure and a checklist was developed to ensure appropriate test conditions and safety measures were in place prior to testing.

The following list summarizes the checklist items covered prior to conducting a test:

- The facility is free of any explosive or asphyxiating concentrations and initially at normal atmospheric conditions (20.95% oxygen)
- Fire suppression is ready for operation if needed.
- Oxygen sampling system is in operation
- Test room ambient conditions are in the range of 60-80°F.
- Test information recorded and displayed for camera view
- Cameras and video recording system are prepared
- Data recording operational and all instruments functioning
- Test room HVAC isolated and deflagration vents prepared.
- Release system prepared including charge level, temperatures, pressures and valve operations
- Safety briefing completed and grounds are free of unnecessary personnel

11.5. Parametric Test Results

This section summarizes the test results for Task 1. Greater detail is provided for each test in Appendix B Parametric Test Data and Summary.

11.5.1. Concentration Tests

The concentration testing results are shown in Appendix B Parametric Test Data and Summary. The summary in Table 5 shows the tests at the 0.2 m height listed first followed by the tests at the 1.8 m height and sorted by the planned discharge mass. In most cases the measured discharge rate was close to the designed value of either 6.8 g/s or 40 g/s. The one exception is test CP_04 where instability in the mass flow control resulted in an overall average of 1 g/s.

The propane concentrations shown are deconvoluted values. With the exception of the 50 gram tests, both locations B and D showed concentrations greater than the LFL for propane gas. Many of the tests reported maximum concentrations greater than the UFL of 9.5% at location B.

The column, “Minimum Temperature (Pooling) comes from the four thermocouples place at floor level in front of the discharge tube. Pooling of liquid propane was observed at planned discharges of 300 grams and higher, but only when the discharge tube was at the 0.2 m height.

The last column, “Time sensors < LFL”, reports the time in seconds for the duration of a flammable layer. In all but one of the 0.2 m height discharge tests, a flammable layer endured past the end of data recording

Table 5 – Concentration Tests Summary

		Planned Discharge		Measured Discharge			Maximum at Location B		Maximum at Location D			
Test Number	Discharge Location (m)	Mass (g)	Rate (g/s)	Mass (g)	Rate (g/s)	Minimum Temperature (Pooling) (°F)	Conc. (%)	Height (in.)	Conc. (%)	Height (in.)	Time sensors <LFL (s)	Test Duration (s) [2]
CP_01	0.2	50	6.8	35	6	65	9.9	2.0	1.6	4.0	235.1	
CP_05	0.2	100	6.8	92	8	69	10.9	2.0	6.0	4.0	[1]	132.9
CP_07	0.2	150	6.8	129	9	67	10.9	6.0	2.4	4.0		301.5
CP_09	0.2	200	6.8	193	8	68	10.7	6.0	3.0	4.0		134.4
CP_11	0.2	250	6.8	240	7	62	11.0	2.0	4.0	4.0		165.9
CP_13	0.2	300	6.8	292	7	-48	13.3	2.0	5.1	4.0		158.4
CP_16	0.2	350	6.8	342	6	-72	12.5	2.0	5.7	4.0		179.9
CP_18	0.2	400	6.8	397	7	-68	13.3	2.0	8.1	4.0		196.7
CP_24	0.2	400	40	391	40	-68	14.4	2.0	7.4	4.0		300.1
CP_20	1.8	200	6.8	199	7	66	6.7	72.0	1.6	4.0	36.4	--
CP_22	1.8	400	40	401	44	70	9.8	72.0	4.2	60.0	18.1	--

Notes:

[1] No data means that some concentration sensors remained above the LFL throughout the duration of data recording.

[2] The duration of data recording for those tests that had some concentration sensors above the LFL at the end of data recording

Figure 24 presents the propane concentration data at location B2, 2-inch level for the discharge at the 0.2 m height. The time axis for each series is set such that zero time is the end of the propane release. Thirty seconds of data before the end of the discharge has also been plotted.

The data shows the formation of a floor-level concentration that remains for a considerable period of time after the discharge had been completed. Each data series is plotted through the end of data recording. In general, the final values increase with increasing size of the mass release.

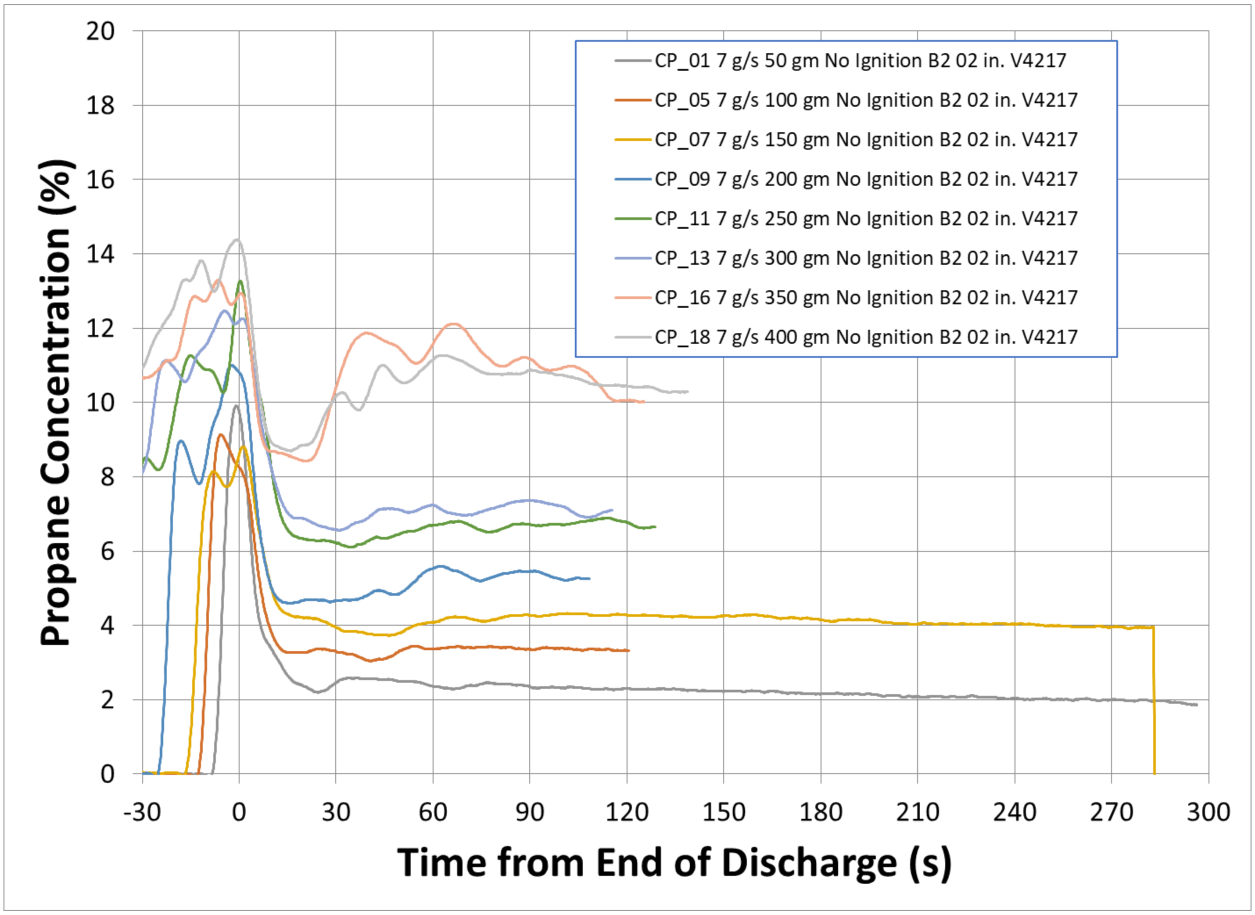


Figure 24 – Concentration Tests: Location B2 at 2-inch level; 0.2 m Discharge Height

Figure 25 shows data similar to Figure 24 at location D2 (from the opposite side of the obstruction) at the 4-inch level. Again, time zero on the graph represents end of discharge for the tests.. The rise in concentration in the time before the end of the discharge is much slower due to transport time around the obstruction. The final concentrations are lower due to the difference in height of the sensor (4 inches vs. 2 inches in Figure 24).

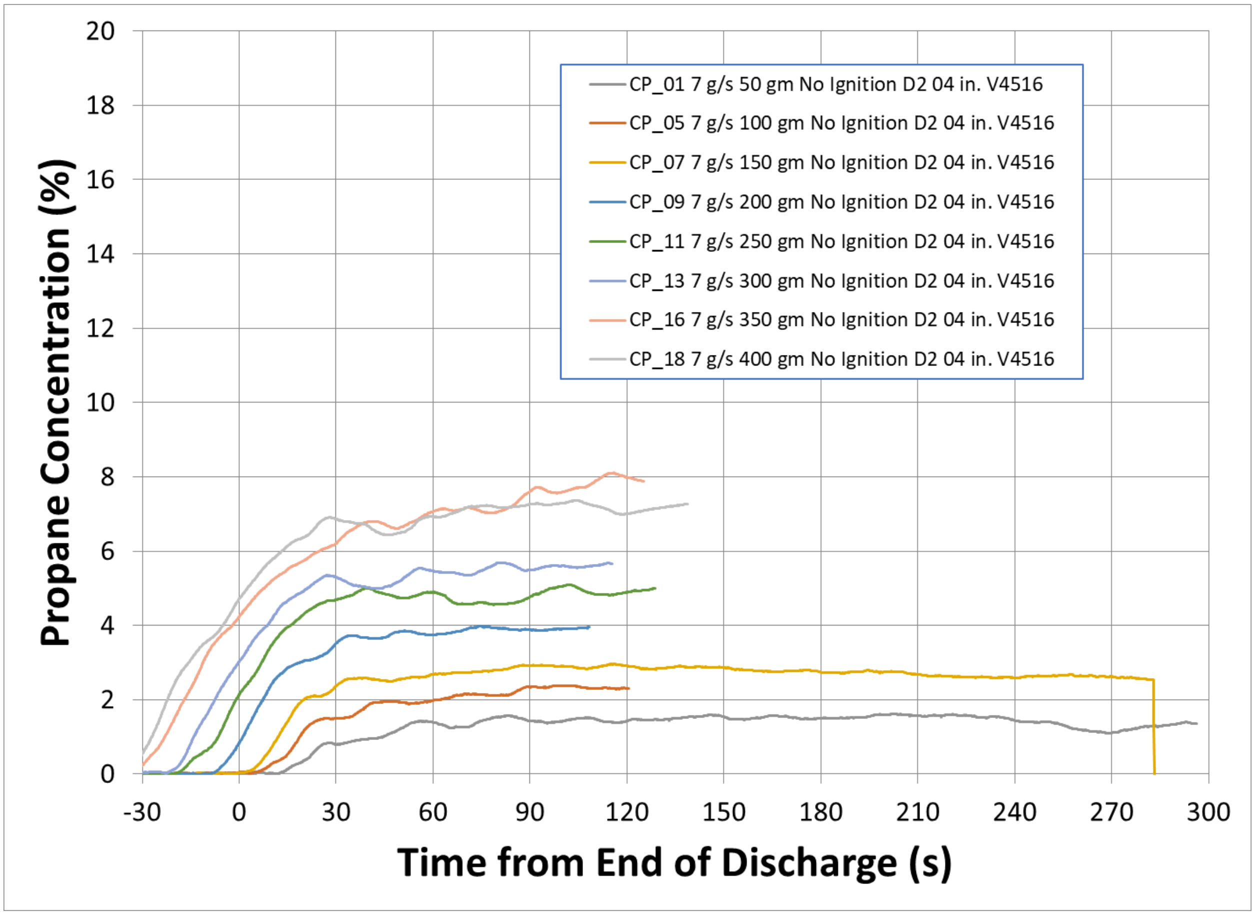


Figure 25 - Concentration Tests: Location D2 at 4-inch level; 0.2 m Discharge Height

Figure 26 compares concentrations at locations B2 2-inch level, and D2 4-inch level. Both tests (CP_18 and CP_24) released 400 g, but at two different rates. The data show much higher concentrations at the floor level for the 7 g/s discharge with significant differences between the B2 and D2 locations. The 40 g/s test (CP_24) show the effect of much greater turbulence and near equalization of concentrations at both locations (front and back of the obstruction).

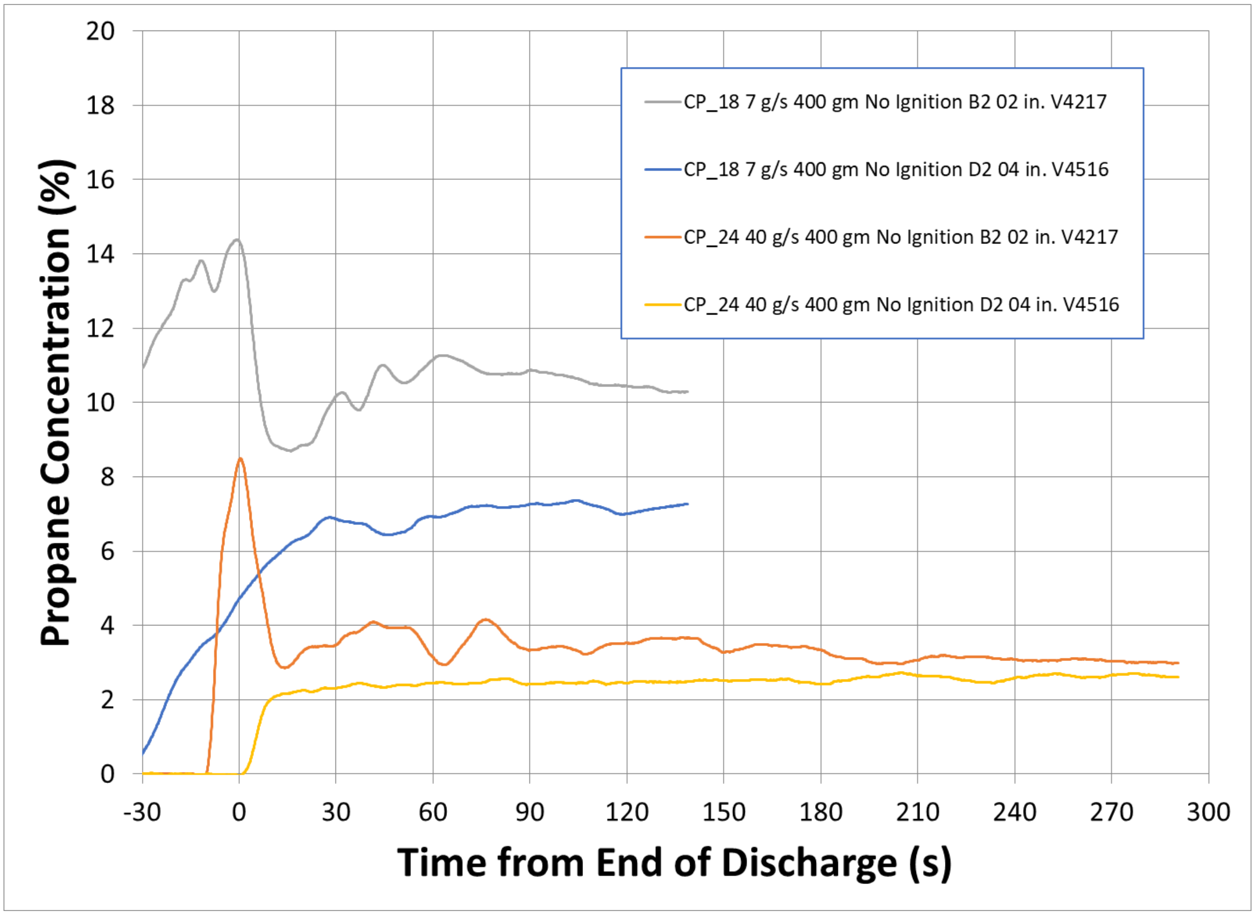


Figure 26 – Compare Concentrations from 400 g releases at 7 g/s vs. 40 g/s at 0.2 m Discharge Height

Figure 27 compares resulting concentrations from the two concentration tests at the 1.8 m (72 inches) height. Test CP_20 released 200 g at 7 g/s and CP_22 released 400 g at 40 g/s. The data show a short period of 5 or 8 seconds (CP_22 and CP_20, respectively) where concentration is above the LFL at either the 60 or 72 inch heights. This data was used to inform placement of the electric arc at location B2 72-inch level for the igniter test.

The data at location B2 60 inches shows marked difference due to the unimpeded velocity of the discharge. At 7 g/s this location showed a concentration of 3.6% at time zero, while at 40 g/s and double the discharge mass the concentration was 0.9% indicating that the higher momentum jet from 72-inches was not being sensed 12-inches below the discharge location.

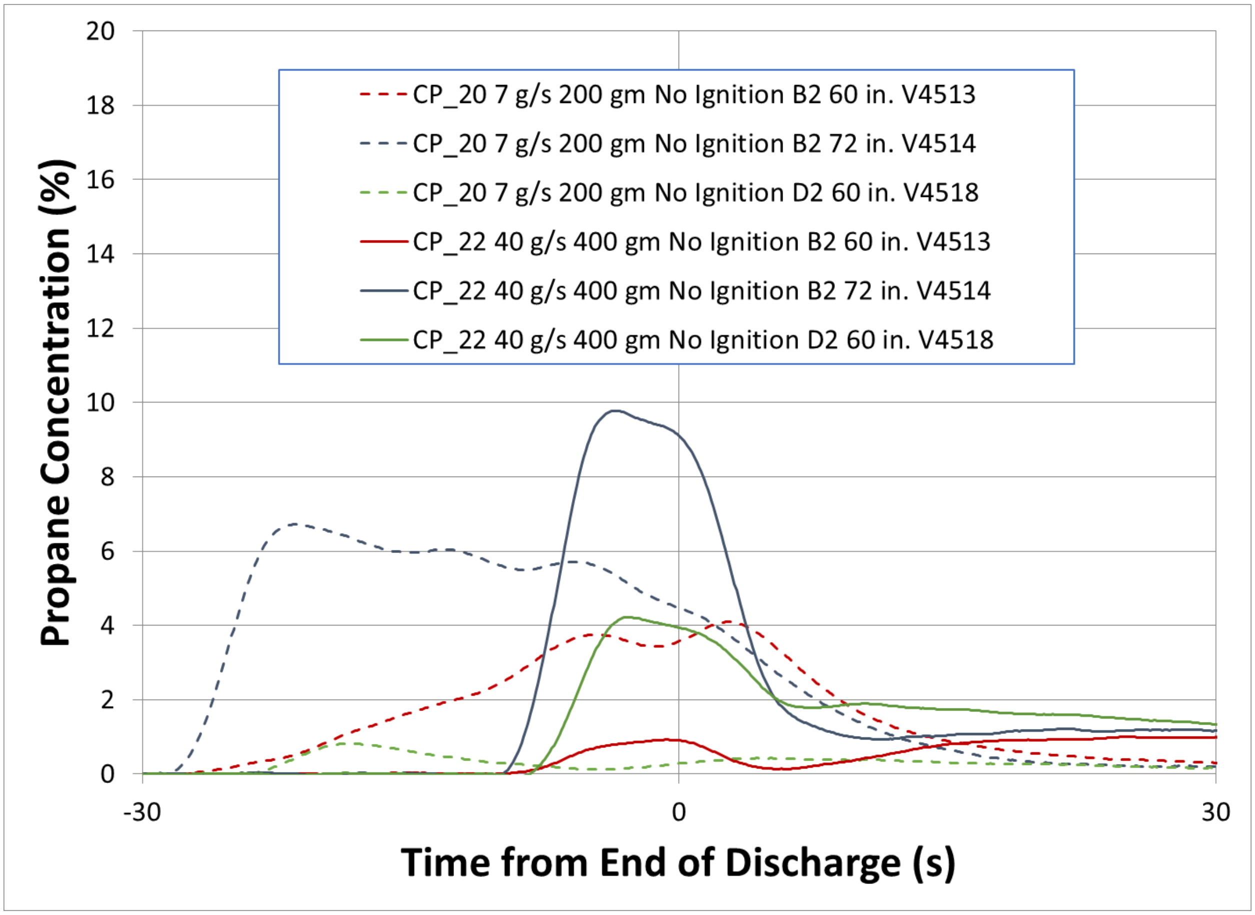


Figure 27 – Concentrations from 1.8 m height discharges

11.5.2. Igniter Tests

The tests with electric arc ignition sources are summarized in Table 6. The tests at the 0.2 m height are separated from the tests at the 1.8 m height and sorted by the planned discharge mass. The propane concentrations shown are deconvoluted values. Ignition caused the measurement of concentration by oxygen sensors to become invalid. As a result the maximum concentrations recorded are from two seconds prior to energizing the electric arcs.

All of the concentrations at location B with the exception of the 50 gram tests report values above the UFL. Depending on the other test parameters, the height of this highest concentration varied between 2, 6, and 72 inches.

The last column, "Vents Burst/Melted", serves as an indicator of the pressure developed from ignition or the temperatures of gases at the deflagration vents. The 200 gram test at 7 g/s and the 400 gram test at 40 g/s resulted in all four deflagration vents bursting at ignition time. The concentration test data shows that 200 g discharge resulted in the largest volume of concentrations between LFL and UFL.

The column, "Minimum Temperature (Pooling) comes from the four thermocouples place at floor level in front of the discharge tube. Pooling of liquid propane was observed at planned discharges of 300 grams and higher, but only when the discharge was made at the 0.2 m height.

Table 6 – Igniter test Summary

		Planned Discharge		Measured Discharge		Maximum Temperature					Maximum at Location B		Maximum at Location D		
Test Number	Discharge Location (m)	Mass (g)	Rate (g/s)	Mass (g)	Rate (g/s)	(°F)	Location	Maximum Ceiling Temperature (°F)	Minimum Temperature (Pooling) (°F)	Peak Heat Flux (kW/m²)	Conc. (%)	Height (in.)	Conc. (%)	Height (in.)	Vents Burst / Melted
CP_02	0.2	50	7	49	7	79	A1_92	79	66	0	8.9	6.0	0.1	4.0	1/0
CP_03	0.2	50	7	38	7	809	A1_84	237	65	15	8.7	6.0	0.1	4.0	2/0
CP_06	0.2	100	7	84	6	826	A1_08	510	68	73	10.2	6.0	0.1	4.0	2/1
CP_15	0.2	100	7	96	7	725	B2_12	679	71	67	9.6	6.0	0.1	4.0	3/1
CP_08	0.2	150	7	141	7	799	A1_12	757	68	89	10.8	2.0	0.1	4.0	3/1
CP_10	0.2	200	7	187	7	1081	B2_18	1043	69	107	11.4	2.0	0.5	4.0	4/0
CP_12	0.2	250	7	241	7	1055	A1_12	613	66	77	11.6	2.0	1.6	4.0	3/1
CP_14	0.2	300	7	294	7	998	E3_18	783	-59	74	13.3	2.0	2.4	4.0	3/1
CP_17	0.2	350	7	353	7	1232	B2_18	1066	-57	69	13.1	2.0	3.1	4.0	3/1
CP_19	0.2	400	7	397	7	1092	A1_92	1092	-63	64	15.6	2.0	4.6	4.0	2/2
CP_25	0.2	400	40	402	41	892	E3_04	853	-61	84	12.0	6.0	0.2	4.0	4/0
CP_21	1.8	200	7	196	7	530	D2_92	530	66	2	7.6	72.0	1.1	4.0	2/0
CP_23	1.8	400	40	403	43	335	B2_92	335	61	1	11.1	72.0	2.5	60.0	0/0
CP_26	1.8	400	40	400	44	628	B2_84	614	59	2	10.1	72.0	3.1	60.0	3/1

Temperatures are color coded according to the following legend:

Range
< 0°F
0 – 105 °F
105 – 400 °F
400°F and higher

Details of each test are included in Appendix B Parametric Test Data and Summary.

12. Task 2 Scenario Tests

Equipment for use in concentration and igniter testing in scenario based tests was provided by AHRTI. A description of the equipment, refrigerants, and scenarios is shown in Table 7. The table also shows the number of valid tests conducted and a short summary of the results. See the following sections for a complete description of each scenario and test results. Detailed results for each test conducted are included in appendices B, C, D, and E.

Table 7 – Whole Room Scale Scenarios and Summary

<table>
<tr><th>Scenario</th><th>Equipment</th><th>Number of igniter tests</th><th>Number of Concentration tests</th><th>Result</th></tr>
<tr><td>Motel Room</td><td>PTAC Unit</td><td>4</td><td>13</td><td>One igniter test was invalid and repeated.
All ignitions test resulted in ignition of the propane/air mixture</td></tr>
<tr><td>Residential</td><td>Mini-split indoor unit</td><td>5</td><td>8</td><td>One igniter test was invalid and repeated.</td></tr>
<tr><td>Commercial</td><td>Single Door Reach-in cooler</td><td>5</td><td>11</td><td rowspan="2">See discussion section for details. Many ignition steps were step-wise approaches to the maximum values requested by AHRTI</td></tr>
<tr><td>Commercial</td><td>Three Door Reach-in cooler</td><td>11</td><td>10</td></tr>
</table>

The test room was expanded to give greater floor space and deflagration venting as shown in Figure 28. The interior dimensions of the test room were 3.95m x 4.81m x 2.42m (13 ft. x 15 ft. 9 in. x 7 ft. 11 in.). The enclosed volume was 46.0 m^3 (1620 ft^3). The floor area was 19.0 m^2 (205 ft^2). Equipment and instrumentation layouts are discussed in each of the following sections.

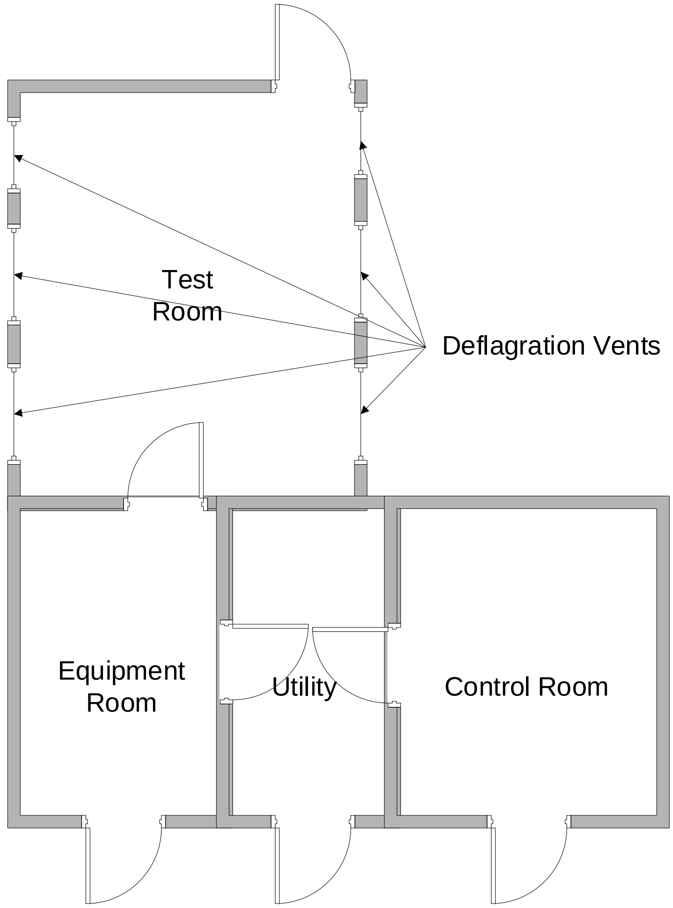


Figure 28 – Task 2 Facility and Larger Test Room

12.1. Test Procedure

The same checklist procedure used in Task 1 was followed for all Task 2 tests as follows:

- The facility is free of any explosive or asphyxiating concentrations and initially at normal atmospheric conditions (20.95% oxygen)
- Fire suppression is ready for operation if needed.
- Oxygen sampling system is in operation
- Test room ambient conditions are in the range of 60-80°F.
- Test information recorded and displayed for camera view
- Cameras and video recording system are prepared
- Data recording operational and all instruments functioning
- Test room HVAC isolated and deflagration vents prepared.
- Release system prepared including charge level, temperatures, pressures and valve operations
- Safety briefing completed and grounds are free of unnecessary personnel.

An additional step was included in the PTAC and mini-split tests to delay energizing the electric arcs until 5 seconds after the completion of the discharge.

A more detailed procedure for the reach-in cooler test is described in that section of the report.

12.2. PTAC Tests

The motel room scenario involved the use of a Package Terminal Air Conditioner (PTAC) in a motel room layout. The test setup for the motel room is shown in Figure 29 and Figure 30. This arrangement is directly comparable to the PTAC series of tests in the A2L project (9007-1). An object representing a bed was located in the test area.

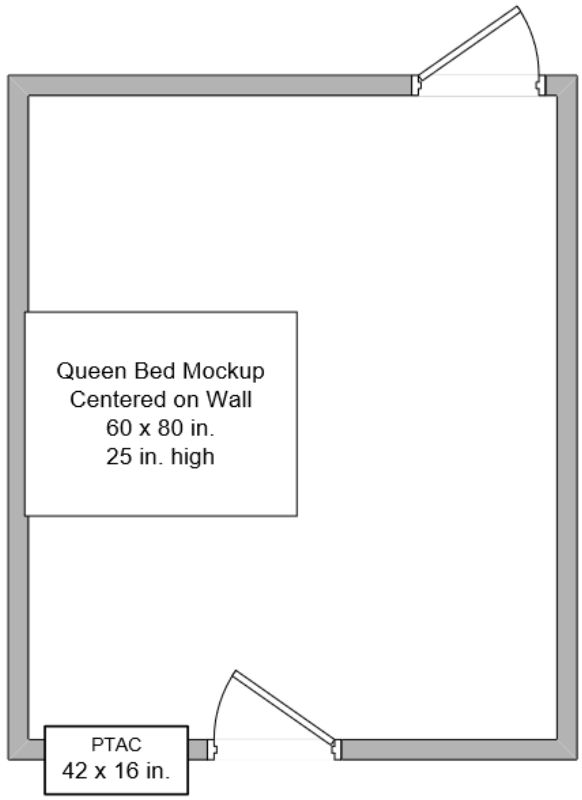


Figure 29 – PTAC room layout showing mounting location

Figure 30 – PTAC shown in location prior to a test

The PTAC was mounted such that the base of the unit was 0.4 m (16 inches) above the floor at the minimum distance from the side wall. For the first three tests (concentration tests), the discharge tube was placed at a return bend on the evaporator coil as shown in Figure 31.

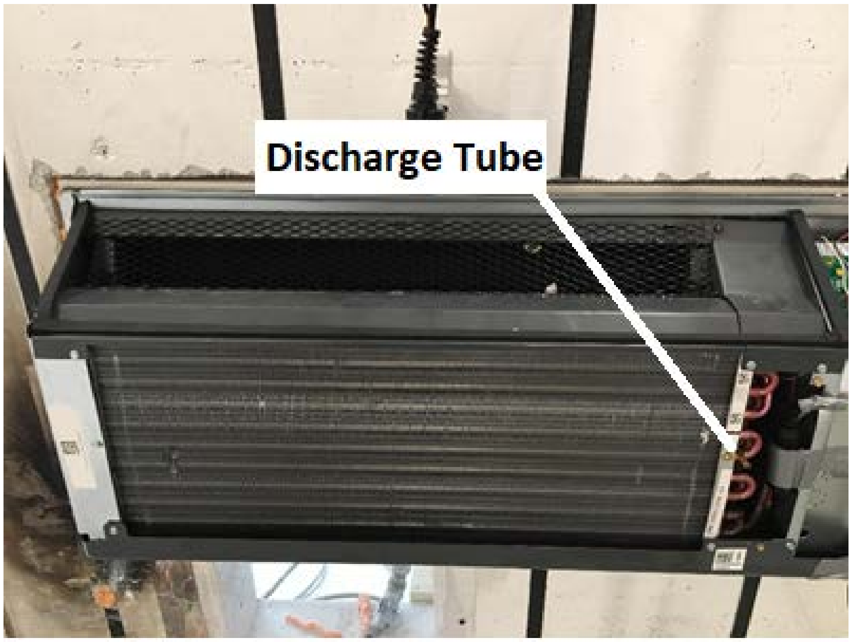


Figure 31 – PTAC discharge tube location for tests PTAC_01 through PTAC_03

For the remaining tests, an 8 mm (¼ inch) O.D. copper tube was placed in the center of the evaporator coil at 0.6 (24 inches) above the floor. The tube was angled directly out from the face of the evaporator towards the grill as shown in Figure 32.

Figure 32 – ¼ inch discharge tube in the center of the PTAC evaporator coil

When used, the unit fan was operated on low speed. The fan volume flow rate was determined to be 5.7 m^3/min (200 CFM). The measurements were made with a calibrated vane anemometer at several locations across the exhaust outlet and integrated with area to determine volume flow rate.

12.2.1. Specifications of Charge Size and Release Rate

A total of four tests were planned for the PTAC testing using electric arc ignition sources. In order to optimize the planned tests, a flow chart was developed to guide test parameters used on subsequent tests. The plan included using the unit fan to disperse leaked refrigerant in the test room as a mitigation method. The test series started with an initial planned discharge quantity of 217g and with the circulation fan in OFF position. The discharge quantity and circulating fan operation were changed in subsequent tests based upon test results as shown in Figure 33.

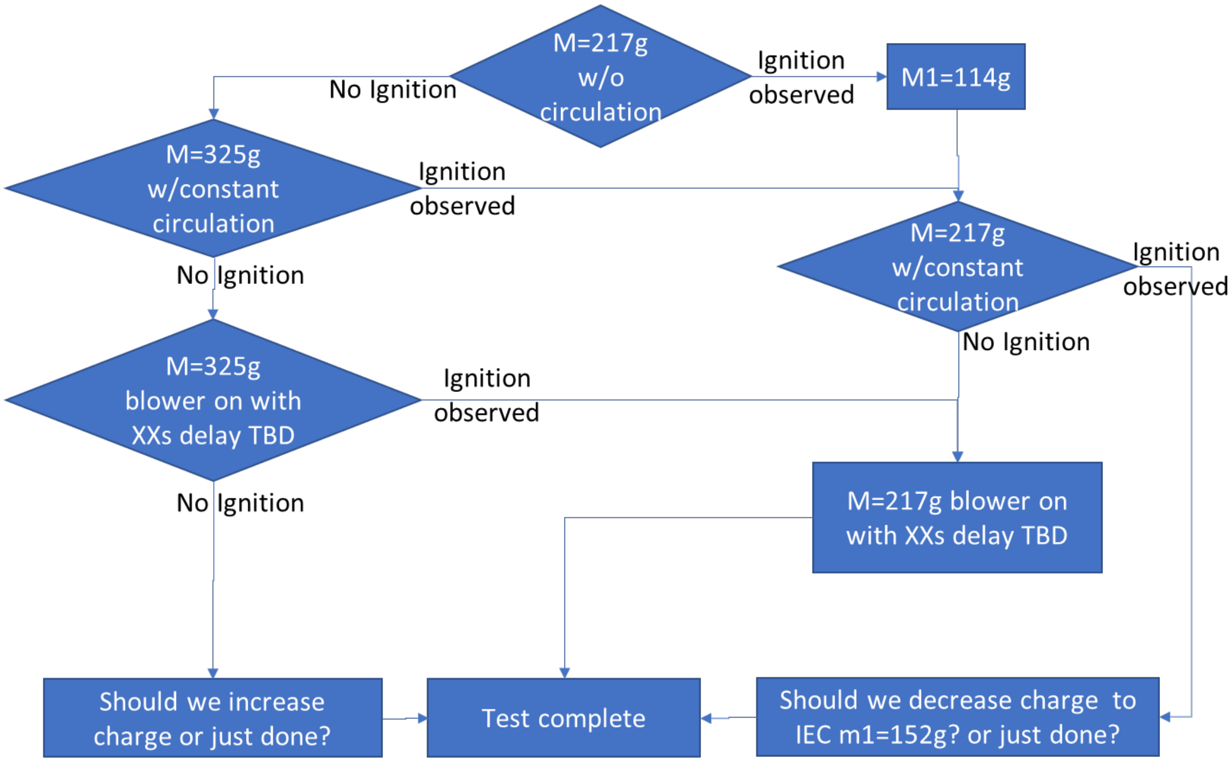


Figure 33 – PTAC Test Plan

The discharge quantity shown in the plan had their bases in either existing or proposed limits for A3 refrigerants. In the absence of recommended limits for A3 refrigerants, the formulas for A2L refrigerants were used on the assumption that limits for A3's would follow the same form.

Table 8 and the notes below the table contain the determination of the charge limits used in this test series.

Table 8 – PTAC Charge Limit Determination

Charge Limit	A3 (R290)	A2Ls	Mitigation Requirement
m_1 per UL 60335 2-40 Nov 2017	$3 \times LFL$ (114g)	$6 \times LFL$ (R-32: 1.81kg, R-452B: 1.85kg)	No mitigation required
m_1 per IEC 60335 2-40 Edition 6	$4 \times LFL$ (152g)		

m_{max} per UL 60335 2-40 Nov 2017	217g (notes 1,3)	$0.5 \times LFL \times h_a \times A$	Air circulation
m_{max} per IEC 60335 2-40 Edition 6	325g (notes 2, 3, 4)	$0.75 \times LFL \times h_a \times A$	Air circulation

Notes:

1. Nov. 2017 draft of UL 60335-2-40: $m_{max} = 0.5 \cdot LFL \cdot h_a \cdot A = 217g$
2. IEC 60335-2-40 Edition 6: $m_{max} = 0.75 \cdot LFL \cdot h_a \cdot A = 325g$
3. Using A2L equations for A3. A3 equations in development.
4. 325g not tested because 217g ignited with air circulation

The discharge rate was specified at 21.4 g/s based on the scaling factor of 0.49 from similar PTAC tests in the A2L project.

12.2.2. Instrumentation

Instrumentation for the PTAC series is documented in Table 9 and shown as a plan view in Figure 34.

Table 9 – PTAC Instrumentation Locations

Location Label Distances from the left-hand wall (x) and PTAC wall (y)	**Instrumentation**
A 0.4m , 0.48m (16 in. , 18 in.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3, 0.6, 1.2 m (1, 12, 24, 48 inches) Electric arcs at 0.025 and 0.15 m (1 and 6 inches) Cheesecloth strip
B 2.1m , 1.2m (7 ft. , 4 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3, 0.6 m (1, 12, 24 inches) Electric arcs at 0.025 and 0.15 m (1 and 6 inches) Cheesecloth strip
C 2.9m , 2.4m (9.5 ft. , 8 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3 m (1, 12 inches) Cheesecloth strip
D 2.1m , 3.6m (7 ft. , 11.7 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3 m (1, 12 inches) Cheesecloth strip

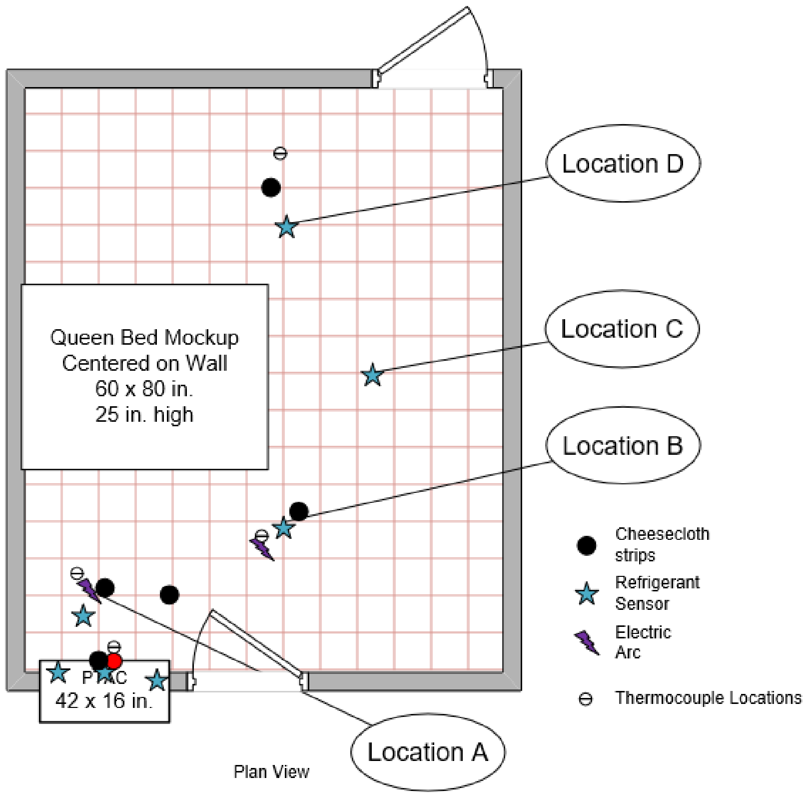


Figure 34 – PTAC instrumentation plan

Three additional concentration sensors were placed within the PTAC unit. Two were placed behind the grill and one was placed 0.1 m (4 inches) above the center of the PTAC air outlet.

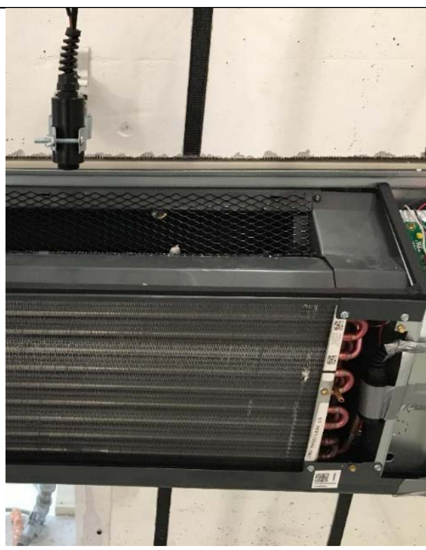
 One sensor is above the air outlet. The other sensor is taped in place in the cavity near the evaporator return bend. (Right side when viewed from front)	 The third sensor is taped to the inside of the grill. (Left side when viewed from the front).

Figure 35 – Additional sensors at the PTAC unit

12.2.3. PTAC Test Results

A total of 13 concentration tests were conducted prior to igniter testing to assess the potential hazards that may occur during igniter testing. A total of four igniter tests were conducted, but one was repeated due to a procedure violation.

12.2.3.1. *Concentration Tests*

A total of thirteen concentration tests were conducted with the test parameters outlined in the igniter test plan in Figure 33. The test parameters for the tests are shown in Table 10.

The first three tests were conducted with the discharge tube at a return bend in the evaporator coil. After these tests, a decision was then made to move the discharge tube to the center of the evaporator coil. This move was made because when fully assembled the PTAC's front grill created an enclosure around evaporator return bend. The plan was to simulate a rupture of an evaporator tube that begins discharging propane directly toward the front grill and into the test room.

The table documents the maximum propane concentration (deconvoluted) at five seconds after completion of the discharge. All tests reported a concentration above the LFL for propane. These maximum concentrations occurred at the 25 mm (1-inch) level at location A after the change of the discharge tube location.

Table 10 – PTAC Concentration test summary

Test Code	Fan State	Planned Discharge (g)	Planned Discharge Rate (g/s)	Discharge Location	Measured Mass (g)	Measured Rate (g/s)	Maximum Deconvoluted Concentration at 5 seconds after discharge completion	
							Location	(%)
PTAC_01	Off	325	21.4	Return Bend	322	19.9	B 01 in.	5.4
PTAC_02	Off	217	21.4	Return Bend	213	20.3	B 01 in.	5.8
PTAC_03	Off	114	21.4	Return Bend	110	20.0	A 01 in.	3.5
PTAC_04	Off	325	21.4	Center	321	21.9	A 01 in.	5.7
PTAC_05	On	325	21.4	Center	322	20.1	A 01 in.	4.3
PTAC_06	On	217	21.4	Center	207	19.0	A 01 in.	3.9
PTAC_07	On	114	21.4	Center	110	19.2	A 01 in.	3.0
PTAC_08	Off	217	21.4	Center	212	18.4	A 01 in.	3.8
PTAC_09	Off	114	21.4	Center	111	20.8	A 01 in.	4.4
PTAC_10	On	325	21.4	Center	322	24.8	A 01 in.	4.3
PTAC_11[a]	On (+7s)	325	21.4	Center	323	21.4	A 01 in.	5.3
PTAC_12[a]	On (+7s)	217	21.4	Center	213	21.1	A 01 in.	4.7
PTAC_13[a]	On (+7s)	114	21.4	Center	111	20.5	A 01 in.	3.5

Note: (a) Circulating fan was started 7 seconds after end of discharge

The maximum propane concentration data from the 217 g concentration tests are presented in Figure 36. The data shows that the fan running continuously resulted in lower concentrations compared to the fan delay of 7 seconds. The 7 second delay was to simulate a mitigating action. All tests showed a maximum concentration above the LFL.

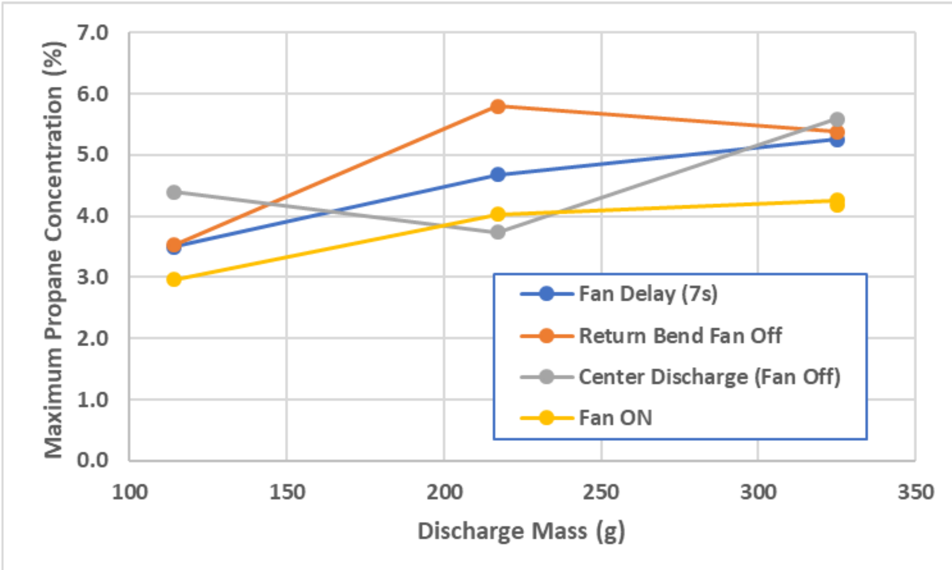


Figure 36 – PTAC, 217g tests: Maximum Concentrations at 5 seconds after completion of discharge

Figure 37 shows the concentrations measured at locations on the PTAC from the PTAC_09 test. The sensors at the left and right locations (see Figure 25) showed levels above 25% of LFL(2.1% X 25% = 0.5 volume %) within 3.5 to 5.5 seconds. The sensor above the PTAC showed a maximum of 1% concentration.

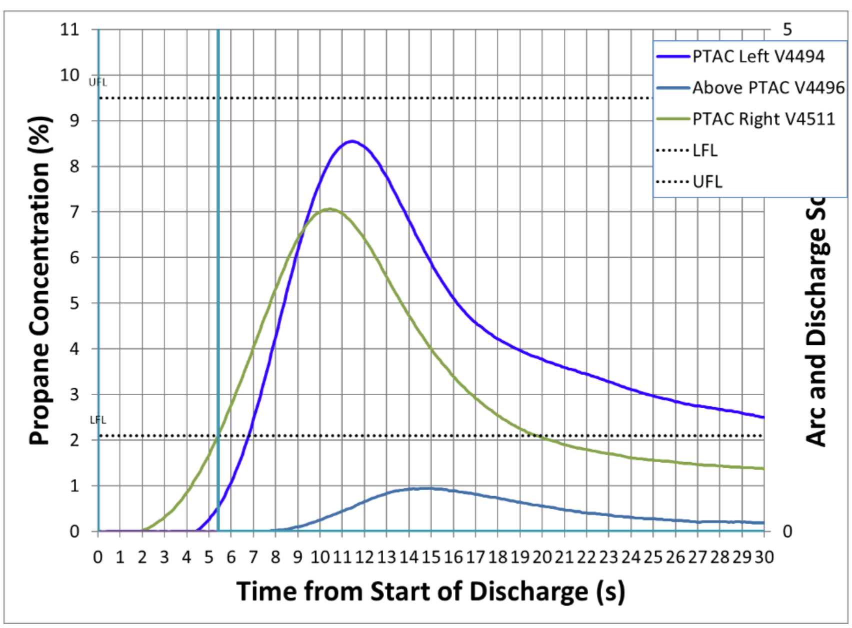


Figure 37 – PTAC_09 sensor at the PTAC (114 g; No Fan)

The next three figures examine Location A at the 25 mm height (1 inch) at each of the three different discharge quantities. Figure 38 shows propane concentration for 114 g discharge quantity. In test PTAC_03, the concentration fell below the LFL after more than 30s. This is likely to be related to location of the discharge tube at a return bend on the evaporator which was semi-enclosed once the PTAC grill was installed. In the other tests shown in the figure, the discharge tube located in the center of the evaporator coil. This resulted in faster drop in the propane concentration.

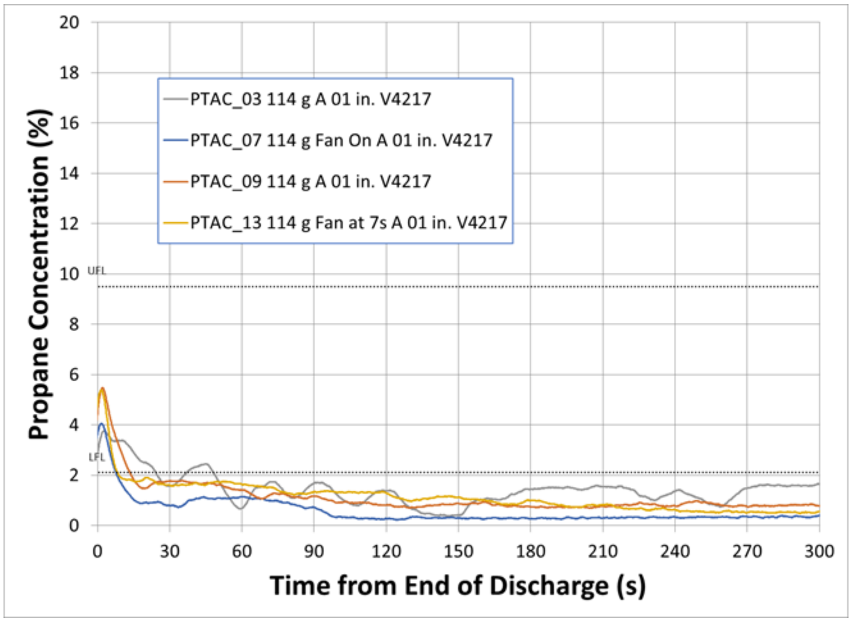


Figure 38 – PTAC tests: 114 g, Location A 25 mm (1-inch) height

The results from 217 g discharge are presented in Figure 39. The location of the discharge tube influenced the rate of reduction of propane concentration in the room for PTAC_02 test. With the fan operating, concentrations dropped to less than LFL in about 40 seconds. Without the fan, concentrations dropped to less than LFL in 50 seconds. With a delay in operation of the fan, concentrations did not drop below LFL until 80 seconds. The delayed fan operation resulted in evaporating and transporting any liquid propane remaining in the PTAC frame resulting in higher concentrations at the floor level.

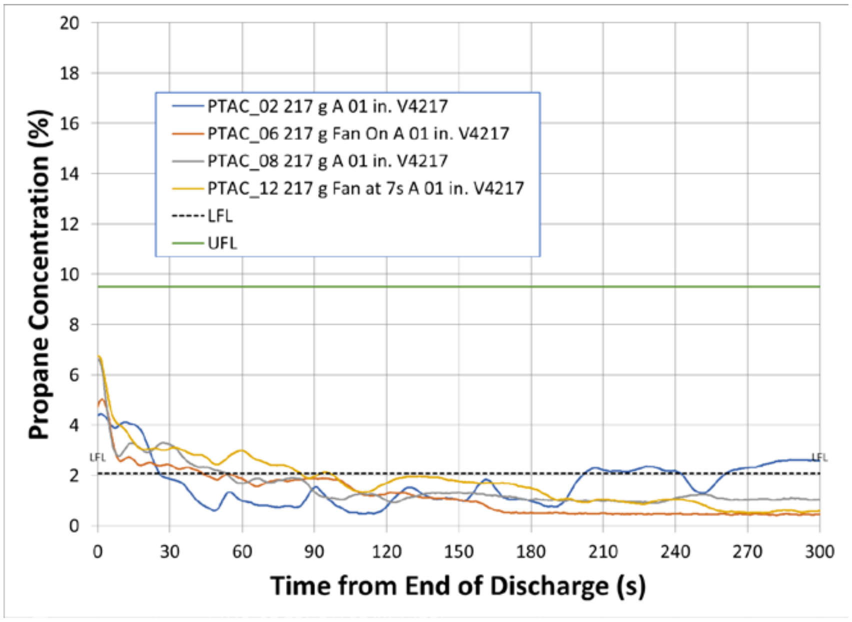


Figure 39 - PTAC tests: 217 g, Location A 25 mm (1-inch) height

The results from 325 g discharge are presented in Figure 40. The shortest time for propane concentrations to drop below LFL was 70 seconds without the fan running. With the fan running, or on a delayed start the concentrations did not drop below LFL until 90 to 100 seconds. The fan action caused trapped propane in the unit to be moved into the test room at higher concentrations. In contrast, with the fan not operating, propane concentrated in the unit is distributed at a slower rate.

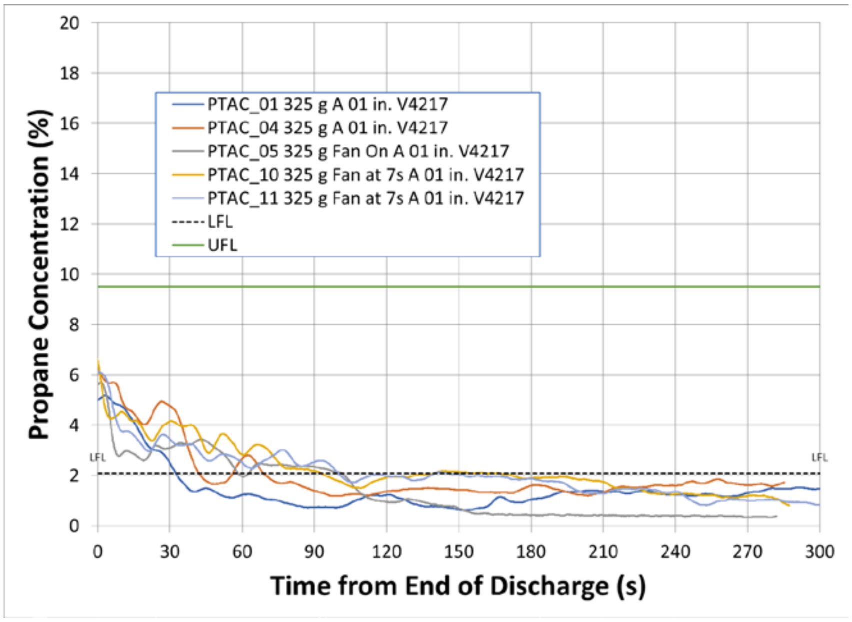


Figure 40 - PTAC tests: 325 g, Location A 25 mm (1-inch) height

In all of these tests at 325g total discharge, liquid propane was seen forming on the face of the PTAC grill and dropping to the floor. The action of the unit fan speeds the vaporization of liquid propane, increasing local gaseous concentrations. The PTAC unit fan pulls room air in over the evaporator coil and exhausts it from the top mounted grill directing the flow upward and into the room.

12.2.3.2. *Igniter Tests*

The PTAC igniter tests are summarized in Table 11. Three igniter tests were performed following the plan outlined in Figure 33.

In PTAC_15 test, the electric arcs were energized 1 s instead of planned 5 s after completion of the discharge. The yellow highlight in the table indicates the time of 0.9 seconds as compared to the desired value of 5 seconds. This test was repeated as PTAC_16. Since all three planned tests resulted in ignition, the PTAC series was terminated and the 4th test was reserved for use later in the reach-in cooler series.

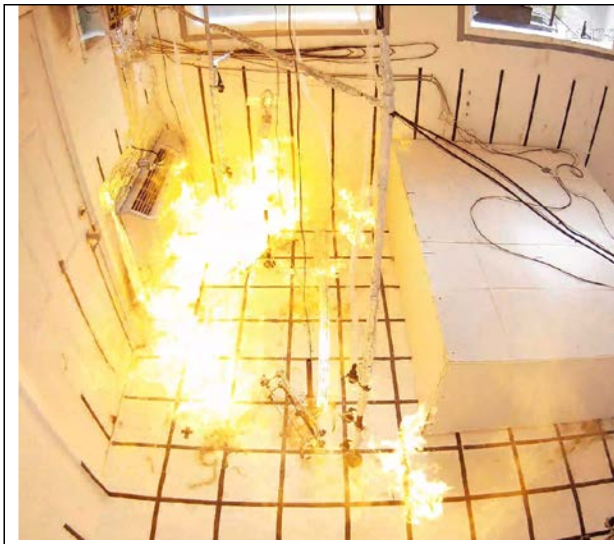
While PTAC_15 was incorrect in its procedure, the largest number of deflagration vents were burst in this test due to the higher concentrations existing immediately after completion of the discharge.

Table 11 – PTAC Igniter tests

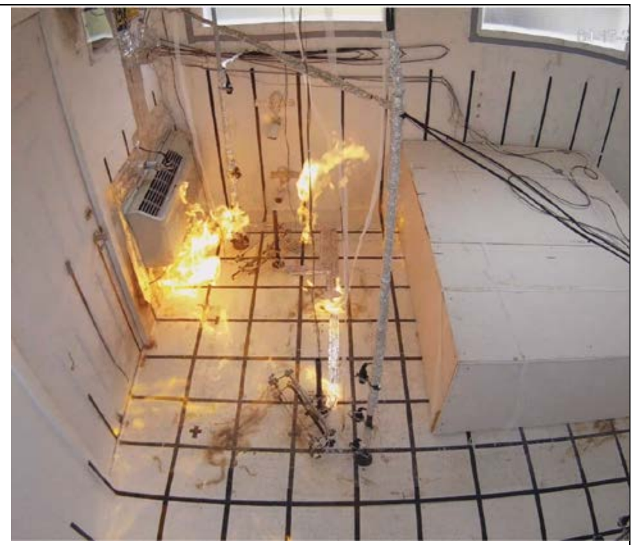
Test Code	Fan State	Planned Discharge (g)	Planned Discharge Rate (g/s)	Measured Mass (g)	Measured Rate (g/s)	Max Temp (°F)	Max Temp Location	Max Ceiling Temp (°F)	Number of Vents Burst /Melted	Arc Delay Time (s)
PTAC_14	Off	217	21.4	214	18.3	866	C-08	420	3/3	4.3
PTAC_15	Off	114	21.4	111	20.9	993	C-08	531	4/1	0.9
PTAC_16	Off	114	21.4	110	20.4	699	C-08	210	2/1	5.7
PTAC_17	On	217	21.4	215	20.4	722	B-60	243	3/1	5.7

Details of each test are included in Appendix C PTAC Test Data and Summary.

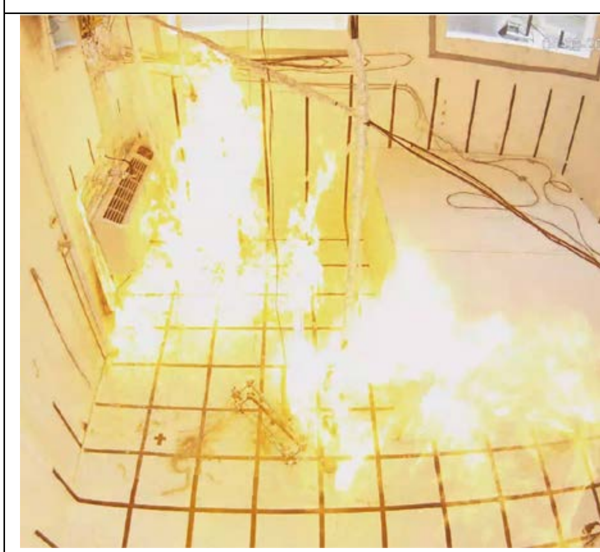
Estimates for the maximum flame size were made from the videos and are shown in Figure 41. The photos demonstrate the effect of timing the electric arcs. PTAC_15 was an invalid test and the comparison to PTAC_16 shows the effect of early ignition before the propane was able to mix and diffuse. PTAC_15 is considered an invalid test because its igniter timing was too short compared to the test plan, but still contains informative data about ignition timing. Comparison of PTAC_14 (Fan off) and PTAC_17 (Fan ON) both with 217 g discharges shows a small effect from the action of the fan in reducing the size of the flames. PTAC_17 (Fan on) resulted in bursting three deflagration vents compared to two bursts in the PTAC_14 test (Fan off).



PTAC_15: 114 g, early ignition



PTAC_16: 114 g, ignition per procedure



PTAC_14: 217g, Fan Off

PTAC_17: 217 g, Fan ON

Figure 41 – PTAC Estimated maximum flame sizes

Pooling of liquid propane on the floor of the test room was evident in the high speed videos. Figure 42 shows one video frame from PTAC_17 test. Frames prior to ignition show liquid drops falling and splashing into the pool at floor level. These flames persisted for 15 s after the flammable mixture of gases in the room volume had been consumed.

Figure 42 - PTAC_17 (217 g; Fan On). Flames attached to a pool of liquid propane

12.3. Mini-Split Tests

The motel room scenario involved the use of a mini-split indoor unit in a motel room layout. The test setup for the motel room is shown in Figure 43 and Figure 44. An object representing a bed was located in the test area.

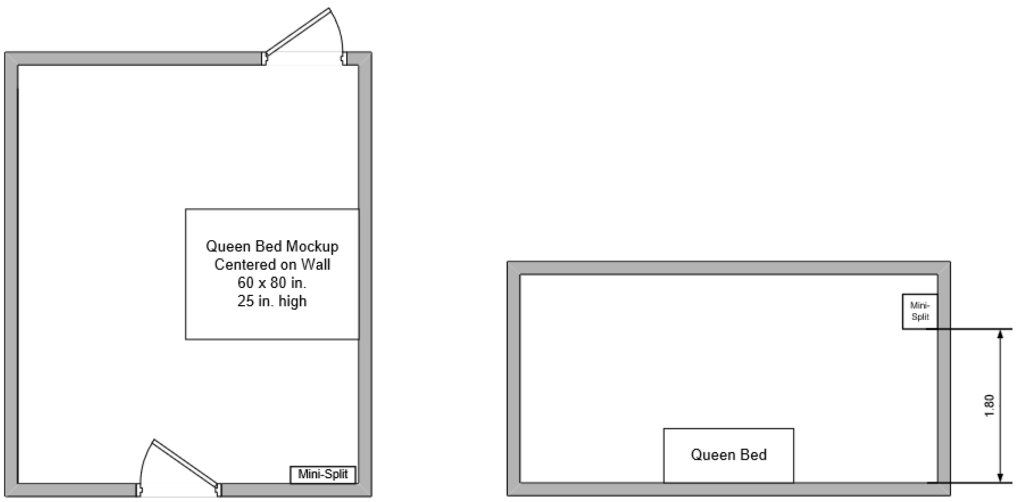


Figure 43 – Mini-split room layout showing mounting location

Figure 44 – Mini-split shown in location prior to a test. Red arrows showing the air flow path

The mini-split was mounted such that the base of the unit was 1.8 m (71 inches) above the floor at the minimum distance from the side wall. A small piece of cheesecloth was attached to the front panel to give visual indicate of fan flow. The ¼ inch discharge tube was placed in the center of the evaporator coil as shown in Figure 45.

Figure 45 – Mini-split discharge tube location

The tube was angled directly out from the face of the evaporator towards the front panel as shown in Figure 45. The condensate pan drain was plugged during these tests.

When used, the fan was operated on one of two speeds. Attempts to measure volume flow rate using a vane anemometer resulted in large variations centered around the manufacturer's specifications. The lower flow rating used was 468 CFM (13.0 m^3/min) and the higher was 505 CFM (14.3 m^3/min).

The unit directs the outlet air by means of two motorized flaps at the bottom of the unit. When the unit fan is off, these bottom flaps are closed.

12.3.1. Specifications of Charge Size and Release Rate

A series of four igniter tests were planned with the mini-split unit. In order to optimize the planned tests, a flow chart was developed to guide test parameters used on subsequent tests. The flow chart is shown in Figure 46. The plan included using the unit fan to disperse leaked refrigerant in the test room as a mitigation method. The test series started with an initial planned discharge quantity of 329g and with the circulation fan in OFF position.

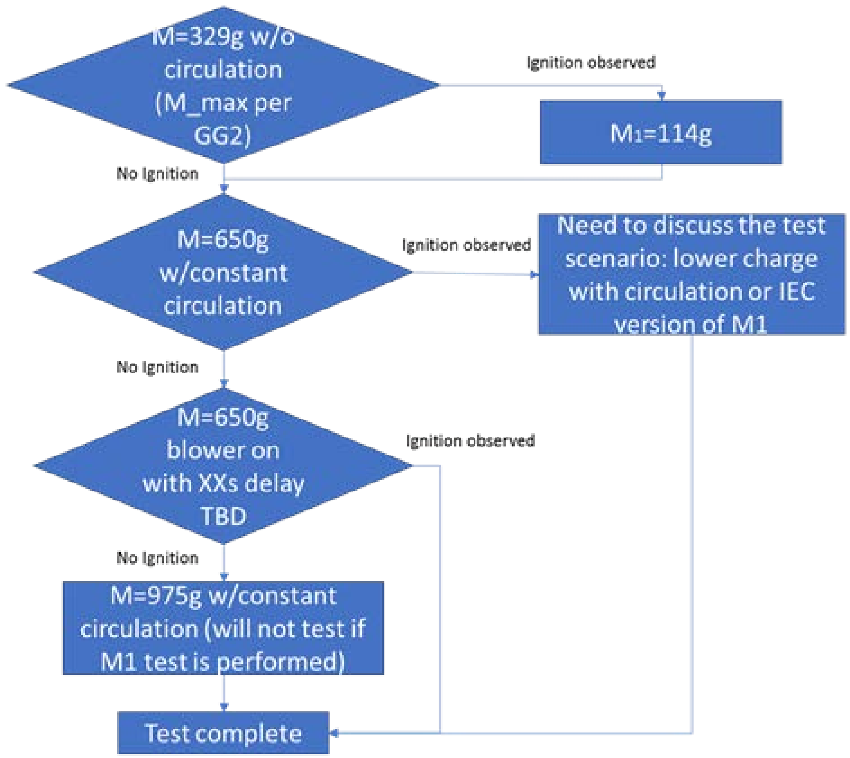


Figure 46 – Mini-split Test Plan

The charge sizes shown in the plan had their bases in either existing or proposed limits for A3 refrigerants. In the absence of recommended limits for A3 refrigerants, the formulas for A2L refrigerants were used on the assumption that limits for A3's would follow the same form.

Table 12 and the notes below the table contain the determination of the charge limits used in this test series.

Table 12 – Mini-split Planned Charge Determination

Planned Charge	Rationale	Tested charge	Concentration when mixed completely in room (Volume %)
114g	Feb. 2017 draft of UL 60335-2-40 $m_1 = 3 \cdot LFL$	115g	0.1
329g	Without fan circulation per GG2: $m_{max} = 2.5 \cdot LFL^{\left(\frac{5}{4}\right)} \cdot A^{0.5} \cdot h_0$	327g	0.4
650g	With fan circulation from UL 2-40 (Nov 2017) for A2L: $m_{max} = 0.5 \cdot LFL \cdot h_a \cdot A$ $h_a = 180\ cm;\ A = 19\ m^2$ (0.5 is UL safety factor)	647g	0.8
975g	With fan circulation is from IEC 2-40 for A2L: $m_{max} = 0.75 \cdot LFL \cdot h_a \cdot A$ $h_a = 180\ cm;\ A = 19\ m^2$ (0.75 is IEC safety factor)	(not tested)	1.2

The term h_0 refers to the release height and the term h_a refers to the air delivery height. For the case of the mini-split these parameters were equal to 1.8 m (71 in.). The A2L equations were used for higher charges based on the assumption that A3 equations would have a similar form.

The mini-split discharge rate was specified at 21.4 g/s which is the same as the PTAC A3 testing for similar equipment size and tube size.

12.3.2. Instrumentation

Instrumentation for the mini-split series is documented in Table 13 and shown as a plan view in Figure 34.

Table 13 – Mini-split Instrumentation Locations

Location Label Distances from the left-hand wall (x) and mini-split wall (y)	Instrumentation
A 3.4m , 0.6m (11 ft., 2 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3, 0.6, 1.2, 1.5, 2.1 m (1, 12, 24, 48, 60, 84 inches) Electric arcs at 0.025 and 0.15 m (1 and 6 inches) Cheesecloth strip
B 1.8m , 0.9m (6 ft. , 3 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3, 0.6, 1.2 m (1, 12, 24, 48 inches) Electric arcs at 0.025 and 0.15 m (1 and 6 inches) Cheesecloth strip
C 1.2m , 2.4m (4 ft. , 8 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3 m (1, 12 inches) Cheesecloth strip
D 1.8m , 3.6m (6 ft. , 11.7 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensors at 0.025, 0.3 m (1, 12 inches) Cheesecloth strip

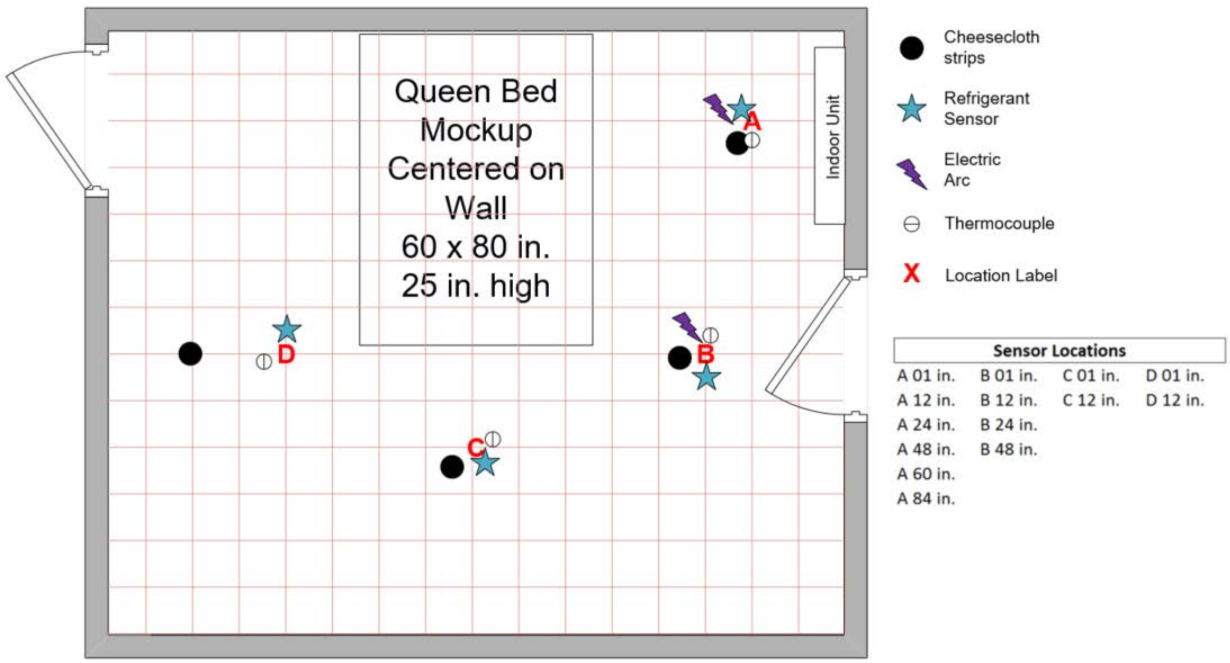


Figure 47 – Mini split instrumentation plan

12.3.3. Mini-Split Test Results

12.3.3.1. *Concentration Tests*

A total of seven concentration tests were conducted that included the test parameters outlined in the igniter test plan in Figure 46. The test parameters used in the concentration tests are presented in Table 14.

The table records the maximum propane concentration (deconvoluted) at five seconds after completion of the discharge. All tests reported a concentration above the LFL for propane. Two of these tests were repeated (MS_02 and MS_04) because the measured discharge rate was significantly lower than planned. These tests were repeated in MS_06 and MS_12 with flow rates much closer to planned values. The column for chart location refers to the position of this test on the test plan shown in Figure 46.

Two tests were run with 5 second delays for starting the fan. It was later determined that the delay should be 15 seconds in order to simulate a mitigation action upon sensing a refrigerant leak.

Table 14 – Mini-split Concentration test summary

Test Code	Fan State	Fan Flow (CFM)	Planned Discharge and Rate		Measured Mass and Rate		Maximum Deconvoluted Concentration at 5 seconds after discharge completion	
			(g)	(g/s)	(g)	(g/s)	Location	(%)
MS_01	Off	0	329	21.4	325	22.9	A 01 in. V4217	8.5
MS_02	Off	0	114	21.4	111	17.4 [a]	A 01 in. V4217	3.8
MS_03	On	468	650	21.4	649	19.8	A 12 in. V4492	2.8
MS_04	Delay 5 s	468	650	21.4	646	13.2 [b]	A 12 in. V4492	2.3
MS_05	On	505	975	21.4	975	21.5	A 12 in. V4492	2.9
MS_06	Off	0	114	21.4	113	21.8	A 01 in. V4217	3.2
MS_07	Delay 5 s	468	650	21.4	649	23.7	B 01 in. V4515	2.4
MS_12	Delay 15s	468	650	21.4	648	21.9	B 12 in. V4513	4.1

Notes:

[a] Discharge rate too low, repeated in MS_06

[b] Discharge rate too low, repeated in MS_07

Figure 48 plots the concentrations at location B, 1-inch height across all of the concentration tests. Location B is 1.2 m (5 ft.) away from the center of the mini-split. This location was selected for this graph because it showed higher concentrations than at location A, directly under the mini-split. The plot for MS_01 (329 g and no fan operation) shows concentration stabilizing above the LFL for propane at the end of 5 minutes after the end of the discharge. The 114 g discharge (MS_06, no fan) drops below the LFL after 40 seconds. Of the two cases with the fan on continuously, (650 g and 975 g), concentrations are less than LFL within 10 seconds after the completion of the discharge.

In the test with fan delay (MS_12, 650 g), it took approximately 45 s for concentration to fall below LFL for propane. This observation indicates a build-up of a high concentration of propane from the discharge, inside of the wall unit, which is then exhausted as the fan comes up to speed. Test observations showed a time period of 10 seconds for the fan to come up to speed.

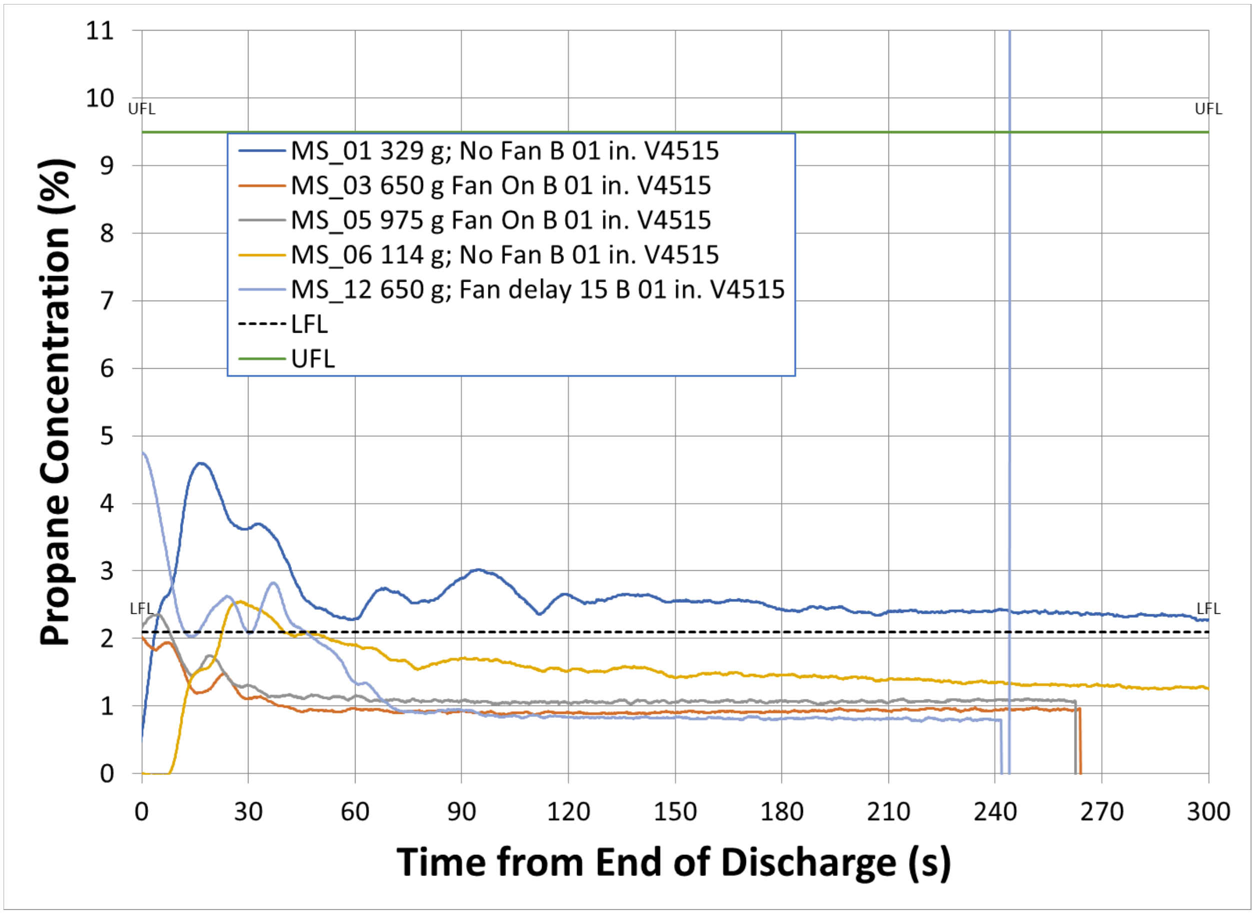


Figure 48 – Mini-split concentration test concentrations at Location B, 1 inch height

Figure 49 shows the concentrations from MS_05 (975 g; Fan ON at 505 CFM) at all locations. The data show the action of the fan resulted in mixing the final concentrations to values close to the predicted well-mixed value of 1.2%.

The two sensors showing a different final concentrations were at location A 12-inch and 24-inch level. These two sensors were located in the exhaust stream of the mini-split which pulls air from the ceiling level and directs it downward. This indicates that the room was not yet fully mixed at the end of data recording.

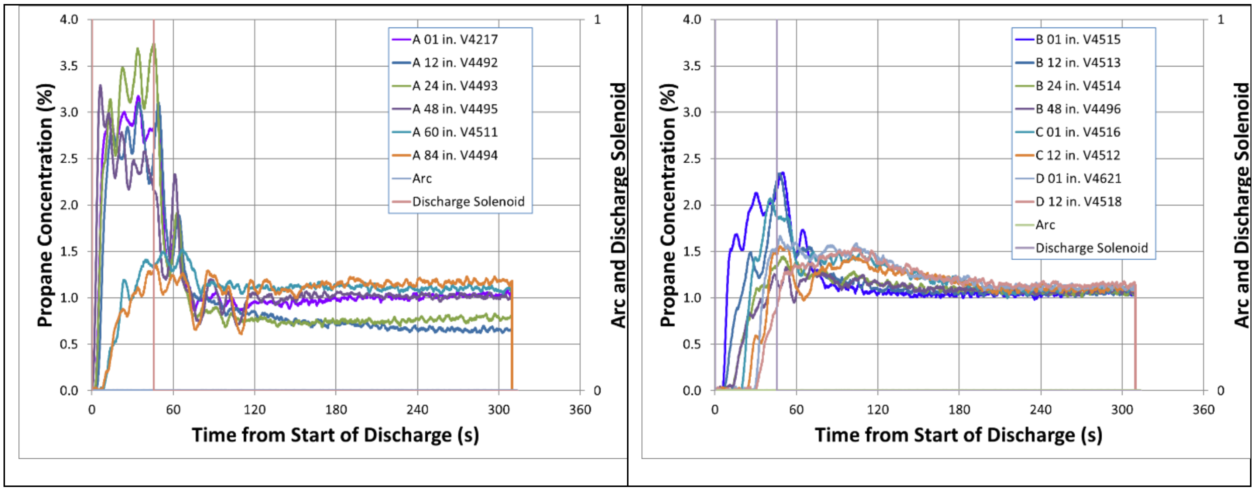


Figure 49 – MS_05 Concentrations (975 g, Fan ON)

Figure 50 presents a selection of concentrations at the 1-inch and 12-inch levels for test MS_01 (329 g, No Fan). The location A sensors shows a drop from 10% to LFL (2.1%) in 20 seconds. During that drop the sensors at location B (1- and 12- inch) show an increase. During this initial 40 seconds, the location B 1-inch sensor shows an increase above the location A sensor.

At the end of the test, the two 1-inch level sensors have stabilized to a value just above the LFL while the 12-inch sensor reports about ½ of that final value. This data shows that a relatively stable layer of a flammable mixture has been established. Locations A and B have been shown for clarity of the plot, but locations C and D show stabilization at the same levels.

The mini-split enclosure functioned to dampen the jet of propane from the discharge tube resulting in a non-turbulent, density driven drop to the floor level and the formation of a flammable layer. There was no visible sign of drops of liquid propane falling from the unit. Additionally, the igniter test, MS_11 (329 g, no fan) high speed camera did not show liquid drops. Instead the high-speed camera captured distortion similar to heat waves due to changes in the propane-air mixture index of refraction. This distortion indicated the presence of a high concentration of gaseous propane falling out of the unit.

These final concentrations are above the well-mixed concentration of 0.4%, confirming the existence of a stratified layer at floor level.

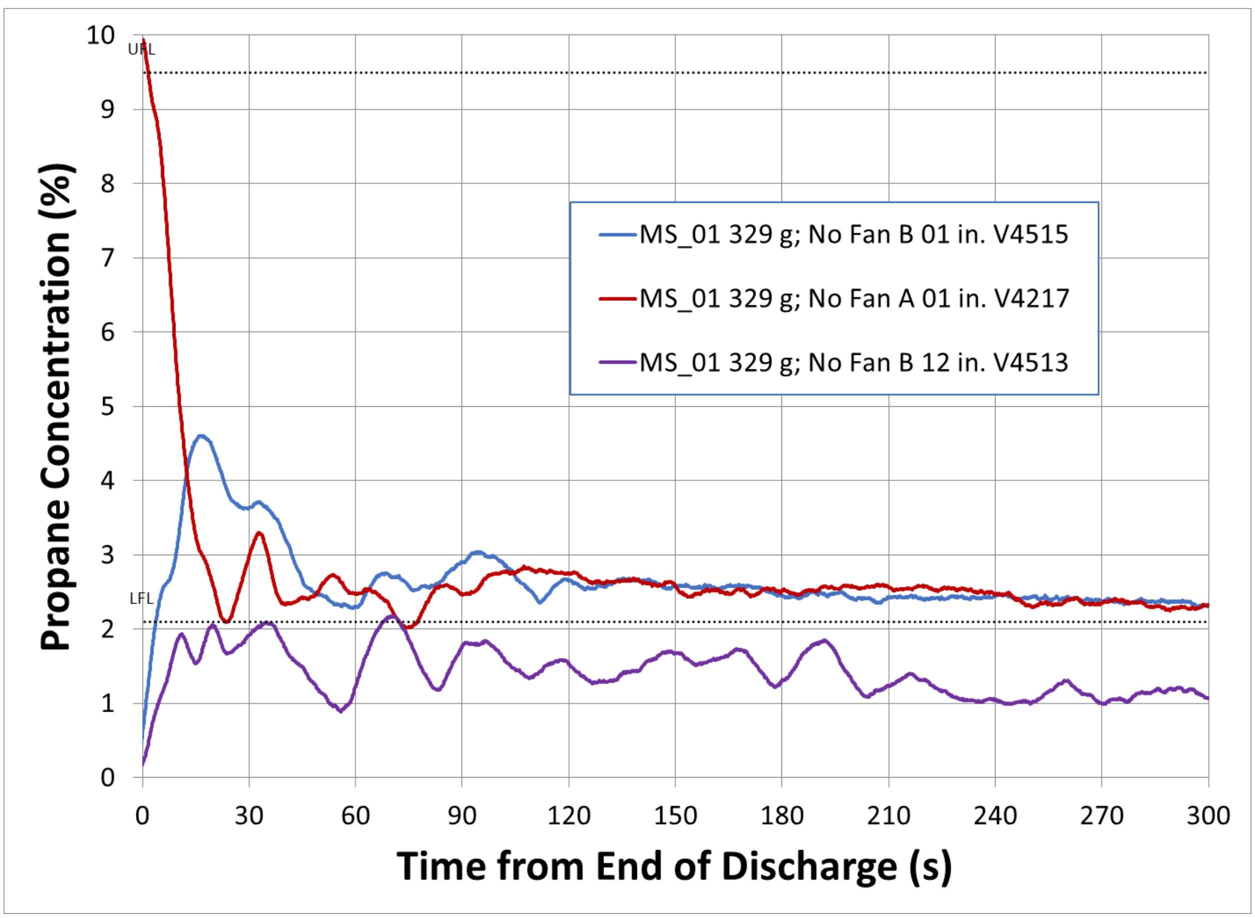


Figure 50 – MS_01 (329 g; No Fan) Locations A (1&12 inch) and B (1 inch) heights

12.3.3.2. *Igniter tests*

The mini-split igniter tests are summarized in Table 15. Three igniter tests were performed following the plan outlined in Figure 33.

There were no ignitions in tests where the fan was running continuously before the start of the discharge. Concentration test MS_09 (329 g) was not part of the test plan, but was performed to insure safety before proceeding to concentration test MS_10 (650 g).

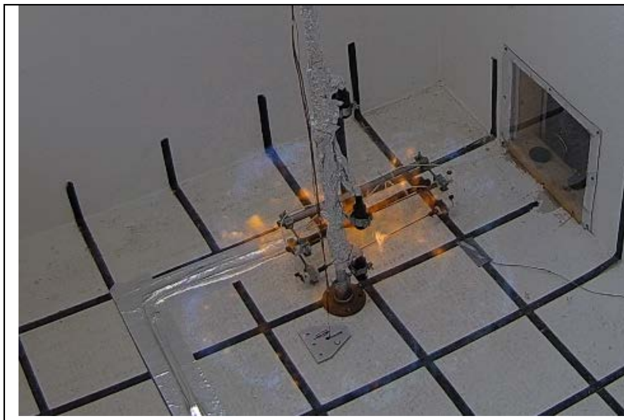
The other three tests all resulted in ignition. The severity depended on the charge level and the state of the fan. In all igniter tests, the highest temperatures were recorded close to floor level indicating flames were low in height. Temperatures at the ceiling level were due to buoyant transport and not direct flame impingement.

Table 15 – Mini-split Igniter tests

			Planned Discharge and Rate		Measured Discharge and Rate					
Test Code	**Fan State**	**Fan Flow (CFM)**	**(g)**	**(g/s)**	**(g)**	**(g/s)**	**Max Temp (°F)**	**Max Temp Location**	**Max Ceiling Temp (°F)**	**Number of Vents Burst /Melted**
MS_08	Off	0	114	21.4	115	23.4	758	A-04	328	2/1
MS_09	On	468	329	21.4	327	21.2	No Ignition Occurred			
MS_10	On	468	650	21.4	649	19.3				
MS_11	Off	0	329	21.4	327	24.8	1005	A-18	600	5/1
MS_13	Delay 15 s	468	650	21.4	647	21.6	700	D-08	534	4/2

Figure 51 includes video frames at the moment of ignition. The photos show the difference in concentrations near the electric arcs. All three show the blue colored flame front of a pre-mixed propane/air mixture. Ignition in test MS_08 (114 g) occurred only at the location A electric arc. Ignitions occurred simultaneously in test MS_11 (329 g) at locations A and B.

The initial ignition event in MS_13 (650 g; Fan delay) was visible only in the infrared camera. Ignition occurred at location B only. The frame shown is approximately 0.5 seconds after ignition. This data shows that the fan had begun to sweep away flammable concentrations at location A. A higher fan flow rate, earlier activation, or faster spin-up time are indicated to prevent ignition at this charge level.



MS_08: 114 g; Fan Off;

Ignition at Location A

MS_11: 329 g; Fan Off;

Ignition at Locations A and B

MS_13: 650 g; Fan Delay Start by 15 s

Ignition at Location B

Figure 51 – Mini-split Ignitions

Estimates for the maximum flame size were made from the videos and are shown in Figure 52. The flames in MS_08 (114 g) were localized to the area near location A. The largest flames occurred in MS_11 (329 g). The sweeping action of the delayed fan start is clearly shown in the MS_13 test (650 g) with the flames localized to the East side of the test room.

MS_08: 114 g; Fan Off

MS_11: 329 g; Fan Off;

MS_13: 650 g; Fan Delay Start by 15 s

Figure 52 – Mini-Split Estimated Maximum Flame Size

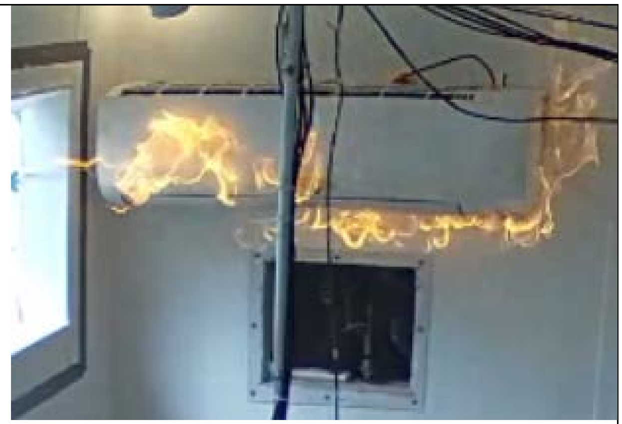
Figure 53 shows ignition of a small pool of liquid propane during the MS_13 test (650 g). The pool was ignited by a falling ember of burning cheesecloth. The high speed videos show drops of liquid propane falling to the floor during this test.

Figure 53 – MS_13 (650 g; Fan On with delay): Liquid propane pool ignition

Figure 54 shows flames continuing in the mini-split unit after flames in the rest of the room had extinguished. The fan was off and the bottom flaps were closed in tests MS_08 and MS_11 showing that the enclosure retained some concentration of propane. The MS_13 test (650 g; Fan delay) shows flames being blown down into the room.

The unit filters were replaced following test MS_08 due to melting and flaming. The unit was completely replaced with a new unit after MS_11 because of combustion of internal components of the unit. In all three tests, flames were suppressed with water spray after the appearance of gray or dark smoke indicating combustion of plastic components.

MS_08: 114 g; Fan Off



MS_11: 329 g; Fan Off

MS_13: 650 g; Fan Delay Start by 15 s

Figure 54 – Mini-Split Flames from retained propane

Figure 55 shows the effect of changing index of refraction during the propane discharge (MS_11; 329 g and no fan). The left-hand image is the difference in two video frames taken 1 second apart before the discharge had begun. The right-hand image is the difference in two video frames also separated by one second after the discharge had begun. The increase in red on the right-hand image is due to the refraction of light from the difference in index of refraction of the gases between the camera and the floor. This effect is similar to the “heat waves” seen coming off a hot car in the heat of summer. These still images are used to demonstrate that the camera “sees” apparent motion of the unmoving objects in the camera view. This effect is more easily seen in the high speed video of this test. There was no evidence of a drip of liquid propane or of a pool forming on the floor.

The comparison was made using an internet website: https://online-image-comparison.com/

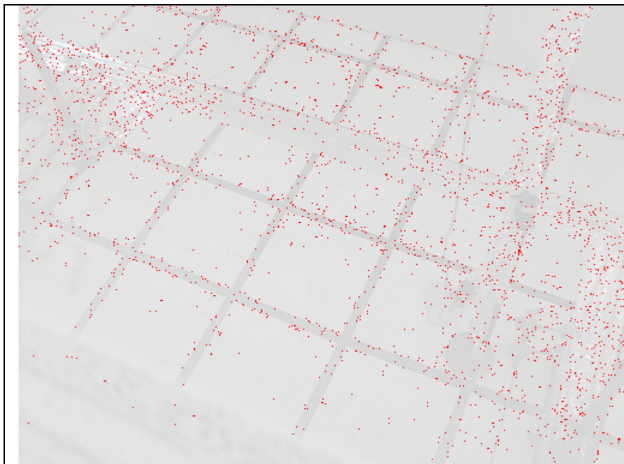
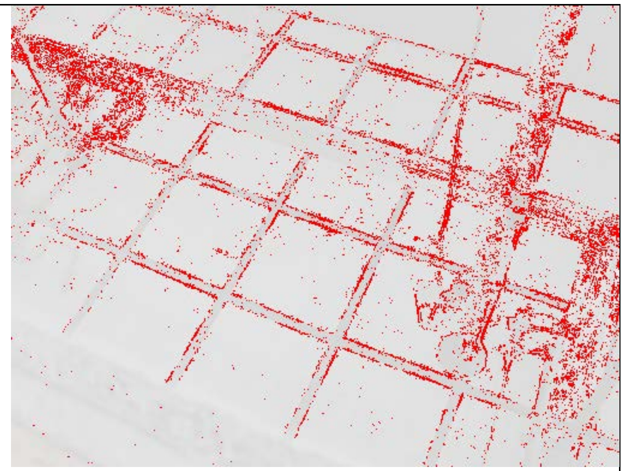
	
Differences without propane vapor in the view.	Differences with propane vapor in the view.

Figure 55 – MS_11 Comparison of video frames separated by one second

12.4. Reach-In Cooler Tests

The reach-in cooler test used both single door and three door units. An important difference is the location of the compressor and condenser where leaks external to the unit will be created. The three-door cooler has a bottom mounted compressor and condenser on the far left side when looking at the cooler from the front. The single-door cooler has a top mounted compressor and condenser. These differences impacted how refrigerant dispersed in the test room.

Figure 56 shows the room layout with the three door cooler in place. The single door refrigerator was also placed in the room during these tests because of the logistics of loading this equipment (size and weight). The display mockup was used to simulate a display case in a convenience store. The side of the mockup away from the three door cooler was open to minimize displaced volume in the test room.

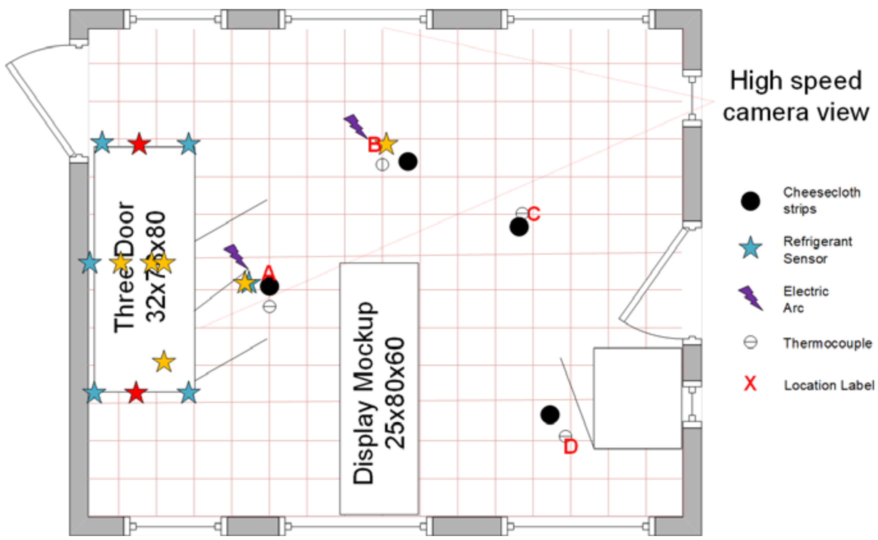


Figure 56 – Three door cooler test layout

The single door refrigerator testing used a similar layout as shown in Figure 57. The display mockup was removed and the three door cooler was used to represent a display case. The doors of the three door cooler we locked open to minimize displaced volume in the test room.

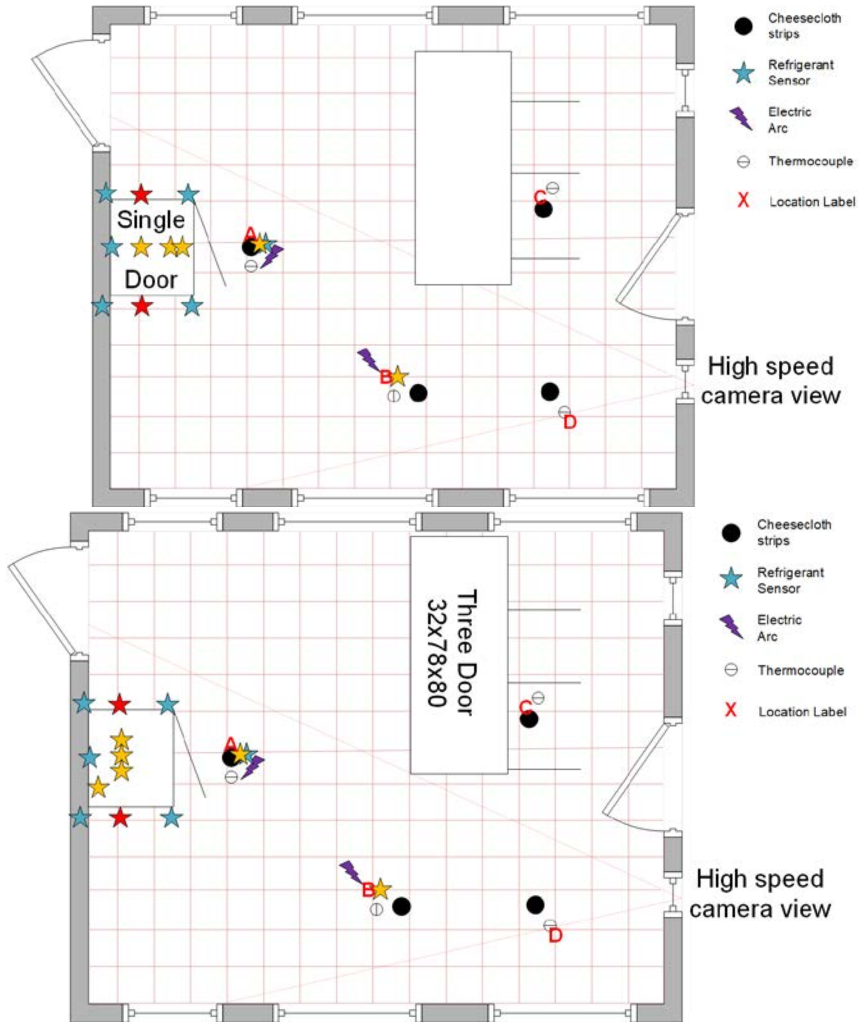


Figure 57 – Single door refrigerator test layout

12.4.1. Specifications of Charge Size and Release Rate

A series of four igniter tests were planned for the reach-in cooler series. A fifth test was added to the series after only three tests were completed in the PTAC series. The tests were a mix of internal releases (evaporator coil) with closed doors and external releases at the condenser coil. The external releases included tests with the condenser fan either off or on. In order to take best advantage of these tests, a plan was created before testing began in order to guide and select the tests based on results.

A sixth test was added to the series when it was determined to be unsafe to continue toward the 355 g internal release in the three door cooler. Figure 58 shows the test plan including single and three door coolers.

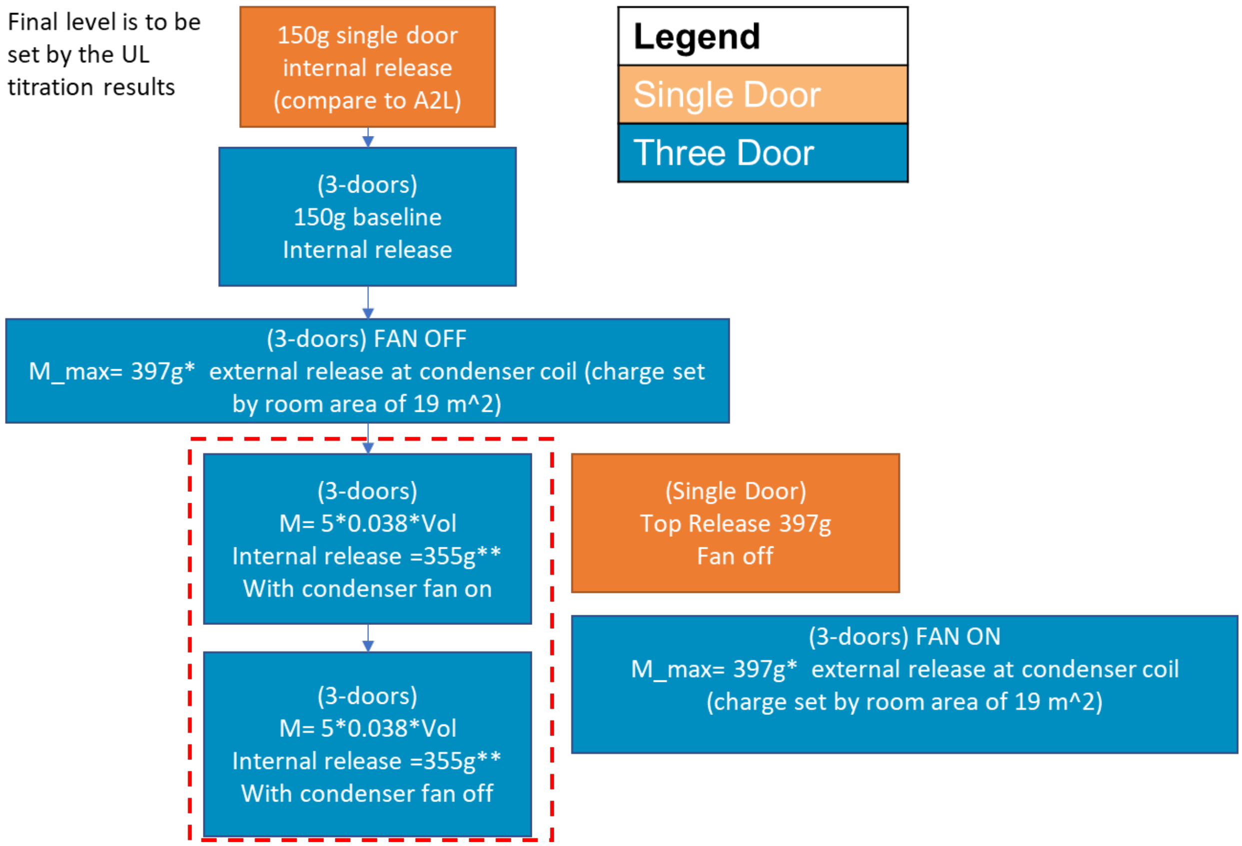


Figure 58 – Reach-in Cooler Test Series

The charge sizes shown in the plan had their bases in either existing or proposed limits for A3 refrigerants. Table 16 contains the determination of the charge limits used in this test series.

Table 16 – Reach-in Cooler Charge Limit Determination

Planned Charge	Rationale	Tested charge	Parameters	Well Mixed Concentration (Volume %)
150g Internal	Limit in current standard IEC 60335 2-89	154g		0.2
397g External	Per 61C/732/CDV: External Release Minimum Room Area $A_{min} = \frac{M\ (kg)}{2.2\ (m) \cdot 0.25 \cdot LFL}$	400g	A = 19 m²	0.5
355g Internal	Per 61C/732/CDV: threshold to avoid “door opening” test (Annex CC) $m\ =\ 5 \cdot LFL\ \cdot Vol_{internal}$	200g Near Detonation	Internal Volume 3-Door: 1.87 m³	0.4
494g	IEC Committee Draft for Vote (CDV) Flammable Refrigerants $m = 13 \times LFL = 494$, but less than 1.2 kg	Not Tested	LFL = 0.038 kg/m³	0.6
From IEC 60335-2-89 61C/732/CDV Ed 3 V3 Release Rate for R-290 = 11 min 10 seconds				

The flow rates derived from Table 16 ranged from 0.224 g/s to 0.588 g/s (0.8 kg/hr. to 2.1 kg/hr.)which is below the smallest calibration point of the mass flow meter (5 kg/hr.) shown in Figure 7. A separate field calibration was performed at UL using a precision balance and stopwatch. These results are documented in Appendix F Mass Flow Control Validation. The estimated uncertainty is ±3% of reading discharge rate and ±5%(full scale) for Total Mass at the lowest flow rates (0.224 g/s).

The discharge tube was also changed from ¼ inch O.D. tubing to a capillary tube such that the leak flow would be primarily liquid propane. Figure 59 shows a video frame of a capillary tube with a propane mist leaving the end of the tube.

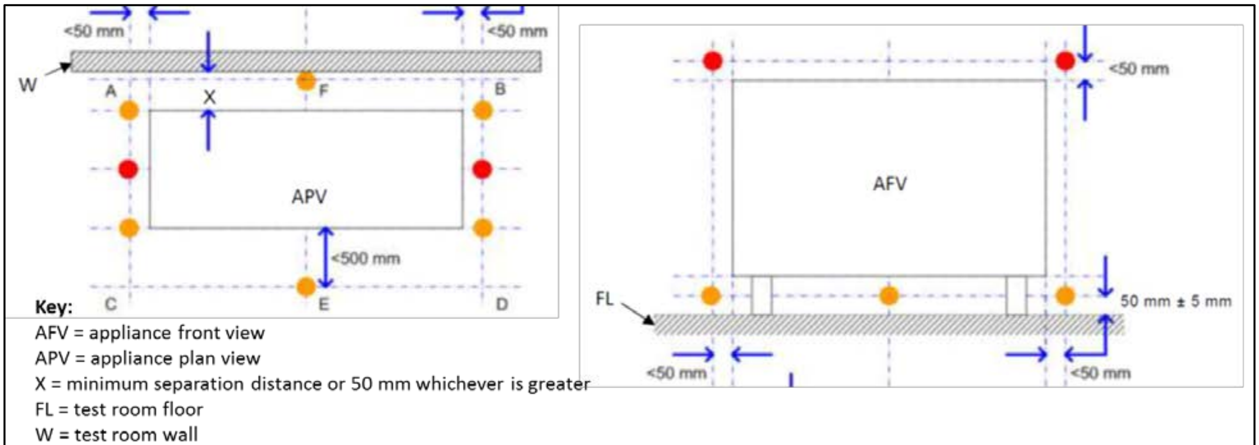
Figure 59 – Capillary Tube showing liquid mist at the exit

Figure 60 shows a capillary tube as installed on a return bend of the three door cooler evaporator. Similar installations were made on a condenser coil return bend for the external leak tests. The same method was used on the single door refrigerator evaporator and condensers as required for either internal or external leaks.

Figure 60 – Capillary tube as installed on the three door cooler evaporator

12.4.2. Test Procedure

External release tests followed the same procedures as other Task 2 tests and are described in section 11.4 Test Procedure. Internal release tests followed a different procedure as shown in Figure 61.



If the refrigerant charge per refrigerating circuit [kg] is greater than 5 x LFL [kg/m³] x refrigerated volume [m³]), the test shall include a critical leak location inside the refrigerated space.

The door or drawer shall be fully opened, at a uniform rate in a time of between 3 s ± 0,5 s, after 30 s ± 5 s of the end of the leak and shall remain open for the duration of the test.
For hinged doors, opening to an angle of 60°.

Figure 61 – Reach-in Cooler Instrumentation and Procedure per IEC/UL 60335-2-89 61C/732/CDV

Figure 62 shows the three door cooler installation. A pole was installed to stop the center door opening at a 60° angle. A wire was used to remotely open the door from the equipment room. Visible in this figure are the three sensors suspended inside the cooler. Location A is immediately in front of the center door. Location B is visible in the foreground. Some of the external sensors can also be seen attached to the exterior of the cooler.

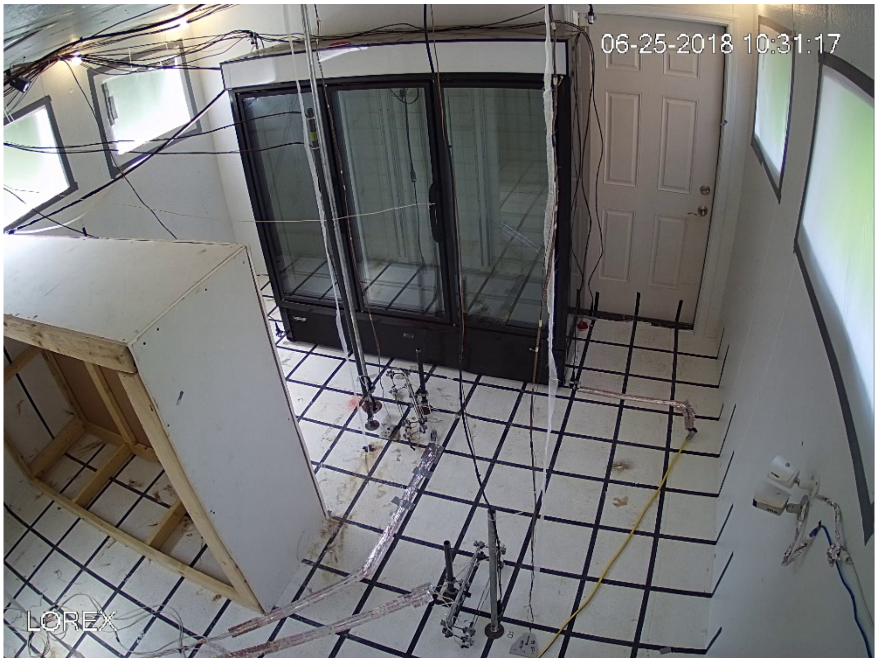


Figure 62 – Three door cooler installation

Figure 63 shows the installation for the single door refrigerator.

Figure 63 – Single door refrigerator installation

12.4.3. Instrumentation

A total of eight propane sensors were placed according to the CDV shown in Figure 61. Six additional propane sensors were deployed as shown in Table 17 and the plan view in Figure 56.

Table 17 – Reach-in cooler Instrumentation Locations

Location Label **Distances from the left-hand wall (x) and entry door (y)**	**Instrumentation**
Internal to cooler	Three concentration sensors: • 0.1 m (4 in.) • 0.75 m (30 in.) • Three door 1.3 m (51 in.) • Single door 1.4 m (54 in.)
External to cooler	A single concentration sensor: • Three door: 25 mm (1 in.) above condensate pan (bottom of unit • Single door: Cabinet Vent (top of unit)
A 2.0m , 3.4m (6.5 ft., 11 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Concentration sensor at 0.2 m (8 in.). (In addition to the CDV specified sensor at 50 mm (2 in.) Electric arcs at 0.025 and 0.15 m (1 and 6 inches) Cheesecloth strip
B 3.0m , 2.4m (10 ft. , 8 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Propane sensor at 50 m (2 in.) Electric arcs at 0.025 and 0.15 m (1 and 6 inches) Cheesecloth strip
C 2.4m , 1.2m (8 ft. , 4 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Cheesecloth strip
D 0.6m , 0.9m (2 ft. , 3 ft.)	Thermocouples elevations: 0.1, 0.2, 0.3, 0.5, 1.5, 2.1, 2.2, 2.2 m (4, 8, 12, 18, 60, 84, 88, 92 inches) Cheesecloth strip

The instrumentation was the same for the single door refrigerator tests with the exception of the locations B, C, and D as follows:

- Location B: 0.9 m, 2.4 m (3 ft., 8 ft.)
- Location C: 2.4 m, 1.2 m (8 ft., 4 ft.)
- Location D: 0.6m, 0.9 m (2 ft., 3 ft.)

12.4.4. Reach-In Refrigerator Test Results

12.4.4.1. *Concentration Tests*

A total of 10 three door cooler concentration tests were conducted that included the test parameters outlined in the igniter test plan in Figure 58. The test parameters used in each test are shown in Table 18. One test (RI_19) was an exterior release at a return bend in the condenser coil. The other 9 tests were internal releases. Door gaskets were replaced after some of the intervening igniter tests which damaged the gaskets. As a result, some of the concentration tests were repeated to verify the sealing of the unit with the doors closed.

The table records the maximum propane concentration (deconvoluted) at 30 seconds after completion of the discharge and just after opening the door.

Table 18 – Three door cooler concentration test summary

		Planned Discharge, Rate, and Duration			Measured Mass, Rate, and Duration				
Test Code	**Condenser Fan State**	**(g)**	**(g/s)**	**(MM:SS)**	**(g)**	**(g/s)**	**(MM:SS)**	**Discharge Location**	**Maximum Deconvoluted Concentration (%)**
RI_01	Off	150	0.224	11:10	159	0.235	11:16	Evap. Return	3.6
RI_02	Off	355	0.530	11:10	357	0.531	11:12	Evap. Return	8.9
RI_03	On	355	0.530	11:10	347	0.530	10:55	Evap. Return	7.0
RI_04	Off	71	0.224	05:17	71	0.229	05:12	Evap. Return	2.0
RI_07	Off	114	0.224	08:29	116	0.227	08:30	Evap. Return	2.7
RI_13	Off	355	0.530	11:10	347	0.528	10:59	Evap. Return	9.7
RI_14	Off	150	0.224	11:10	154	0.234	11:00	Evap. Return	4.0
RI_16	Off	150	0.224	11:10	150	0.225	11:09	Evap. Return	3.3
RI_17	Off	200	0.299	11:10	204	0.229	14:52	Evap. Return	5.1
RI_19	Off	397	0.593	11:10	403	0.598	11:15	Cond. Return	8.6

Table 19 shows the parameters of the single door refrigerator concentration tests. Nine of the tests were internal release tests and two were external releases. The test plan (Figure 58) called for two tests with the single door, but concern about overpressure events resulted in a careful approach to the 150 g charge in 25 g increments. All charges above 50 g resulted in measured concentrations above the LFL. At 150 g the concentration was above the UFL of 9.5%.

Because of intervening igniter tests and potential damage to the door gaskets, three additional single door tests were conducted to verify sealing of the door gaskets matched the baseline data (RI_24, RI_25, and RI_26).

Table 19 – Single door refrigerator concentration test summary

		Planned Discharge Mass, Rate, and Duration			Measured Discharge Mass, Rate, and Duration				Maximum Deconvoluted Concentration
Test Code	**Condenser Fan State**	**(g)**	**(g/s)**	**(MM:SS)**	**(g)**	**(g/s)**	**(MM:SS)**	**Discharge Location**	**(%)**
RI_21	NA	25	0.224	01:52	24	0.214	01:52	Evap. Return	0.7
RI_22	NA	50	0.224	03:43	47	0.211	03:42	Evap. Return	2.8
RI_23	NA	75	0.224	05:35	76	0.228	05:34	Evap. Return	5.5
RI_24	NA	100	0.224	07:27	103	0.233	07:25	Evap. Return	7.3
RI_25	NA	125	0.224	09:18	124	0.224	09:12	Evap. Return	8.7
RI_26	NA	150	0.224	11:10	154	0.229	11:09	Evap. Return	10.9
RI_31	NA	100	0.224	07:27	103	0.231	07:25	Evap. Return	7.6
RI_33	NA	125	0.224	09:18	130	0.233	09:17	Evap. Return	9.1
RI_35	NA	150	0.224	11:10	153	0.229	11:09	Evap. Return	10.7
RI_27	Off	397	0.593	11:10	379	0.583	10:50	Cond. Return	1.9
RI_28	On	397	0.593	11:10	394	0.590	11:09	Cond. Return	1.2

12.4.4.2. *Concentration Tests - Internal Leaks*

Figure 64 plots the data from the four 150 g discharges for the sensor placed inside the three door cooler at 4 inches above the cooler floor. This data was used to verify the operation of the door gaskets following replacement after fire damage. The RI_01 data in black color shows the initial increase of concentration. Door gasket repairs were made before tests RI_14 and RI_17. These two series showed higher concentrations than the baseline test demonstrating a successful gasket repair.

Test RI_16 was performed after the igniter test (RI_15) to verify the gasket seal. The data showed concentrations less than the baseline test (RI_01) so the door gaskets were replaced. Test RI_17 verified the repair by nearly overlapping the data following the first gasket repair (RI_14). RI_17 total discharge was 200 g, but this was released at the same rate as the 150 g tests so that the buildup rate could be compared.

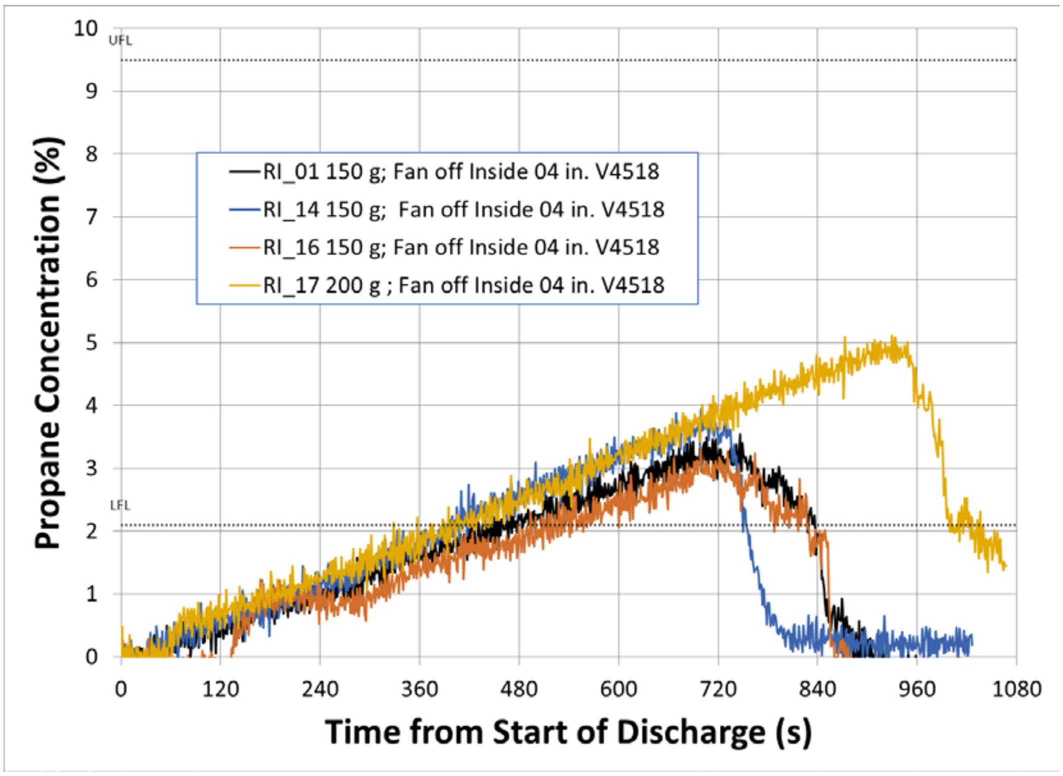


Figure 64 – Three Door Cooler 150 Internal Release Tests (no igniters)

Figure 65 plots the same concentration buildup inside the three door cooler at the 4 inch level with a higher charge level of 355 g. Tests RI_02 and RI_03 were conducted before any igniter tests. The difference between these two is the fan state. Internal circulating fans were operating in test RI_03 and not operating in test RI_02.

Test RI_13 was conducted after repairs to the door gasket. Concentrations built up to higher levels than the baseline tests (RI_02 and RI_03) indicating less leakage through the door gaskets.

There were no corresponding igniter tests matching the 355 g release because of the unsafe conditions observed in the case of the 200 g ignition.

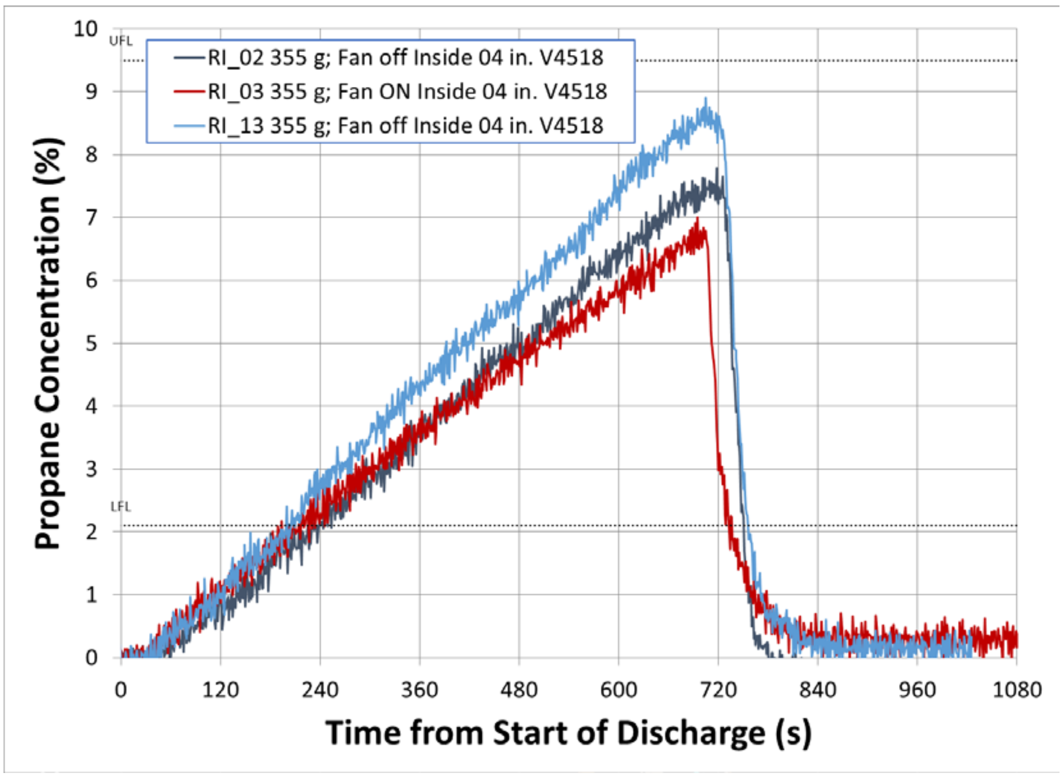


Figure 65 – Three door cooler 355 Internal Release Tests (no igniters)

Figure 66 plots the internal concentration data for the single door refrigerator resulting from a 150 g discharge. RI_26 was the baseline data and is overlaid by the data from RI_35 indicating minimal or zero damage to the door gaskets from the intervening igniter tests.

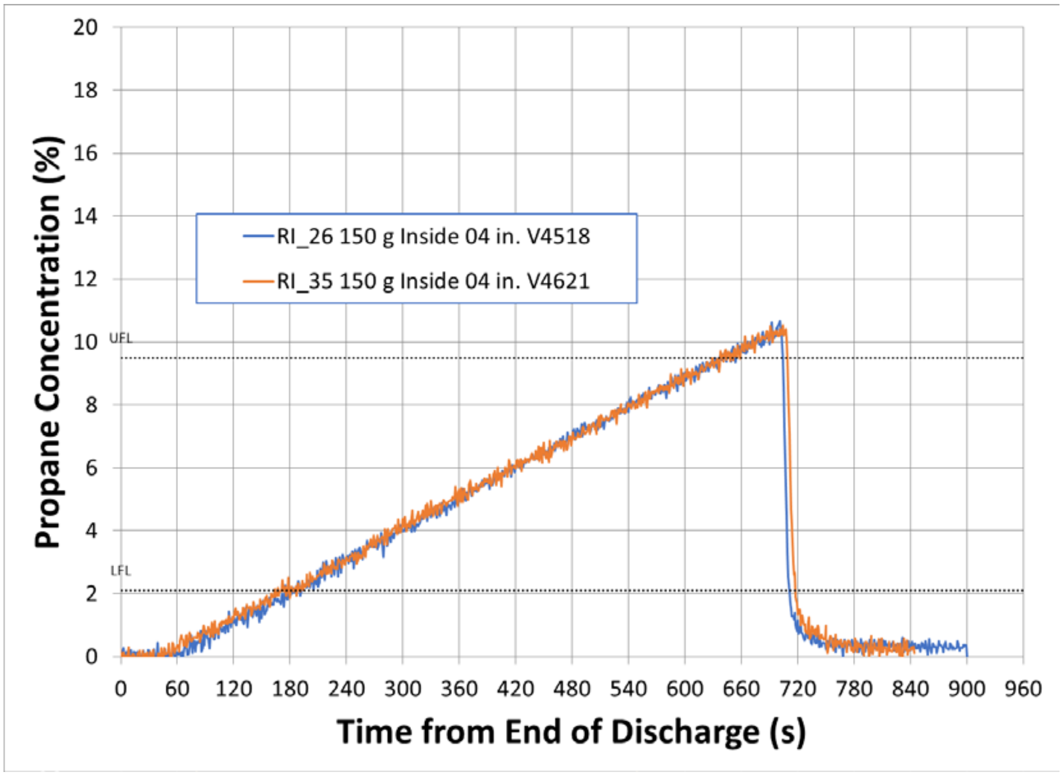


Figure 66 – Single door refrigerator: 150 g internal release (no igniters)

Figure 67 plots the concentrations at the floor level (50 mm or 2 inches) at front center face of the three door cooler (Location A). The internal fans and condenser fan was operating in test RI_03. The condenser fan quickly dispersed the concentration to less than LFL. There was a brief period of approximately 15 seconds above LFL (2.1%). The other two tests (RI_02 and RI_13) showed an initial drop to less than LFL, but then recovered to 3% after another 30 seconds as the dense propane/air mixture settled into a flammable mixture pool at floor level. For reference, the door was opened to 60° at time 703 seconds.

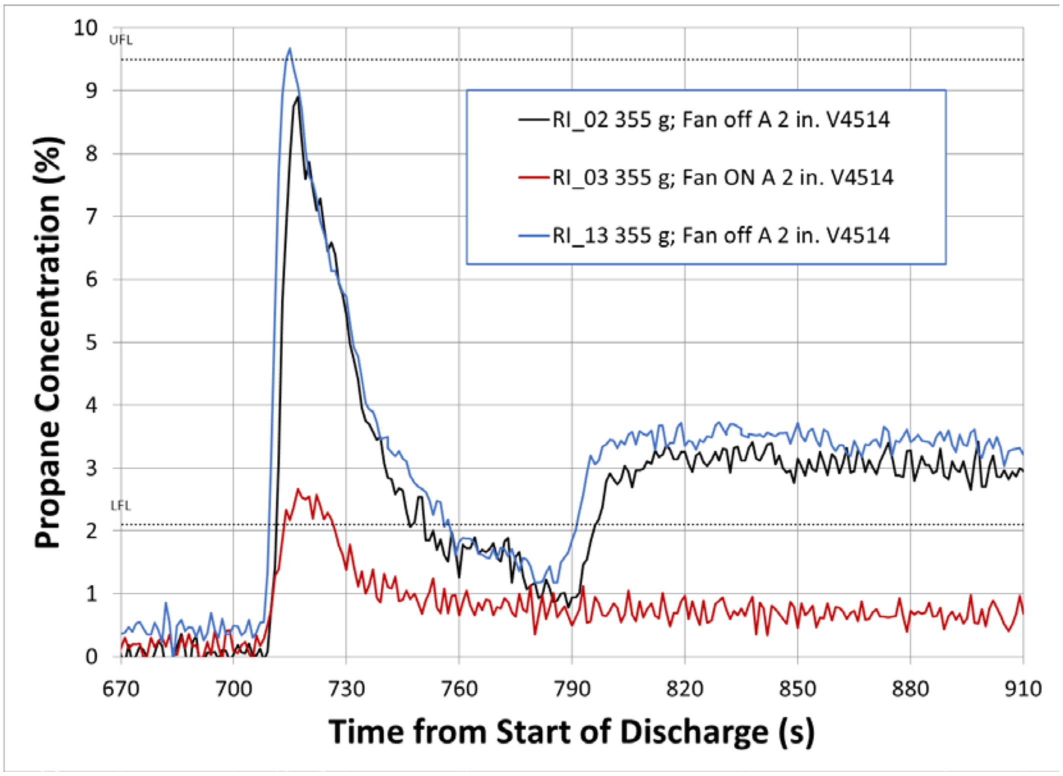


Figure 67 - Three door cooler 355g Internal Release Tests Location A 2-in. concentrations

Figure 68 plots similar data for the single door refrigerator. The data at location A 2-inch level is nearly identical in both tests. The final value of concentration at the 2-inch level is 2.0%, just below the LFL of 2.1%.

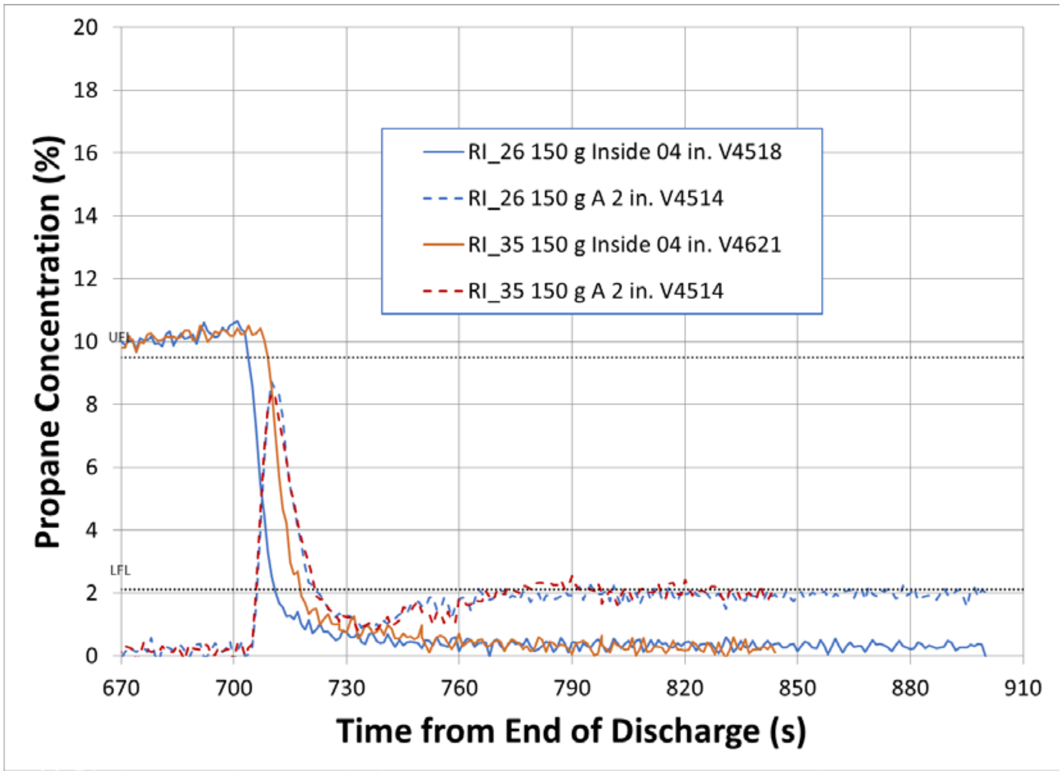


Figure 68 – Single door refrigerator: Concentrations resulting at Location A 2-inch height after door opening

Figure 69 highlights the wave-like action of the dense propane/air mixture. Location A 2-inch shows an initial peak as the wave falls out of the cooler and then dips below LFL. The sensor at Location B shows a delayed reaction due to the greater distance from the cooler door. As the wave action calms, both locations A and B settle to the same level of 3%. The location A sensor at the 8 inch level shows similar behavior and settles at a lower level indicating the presence of a gradient of concentration (higher at the floor and decreasing with elevation).

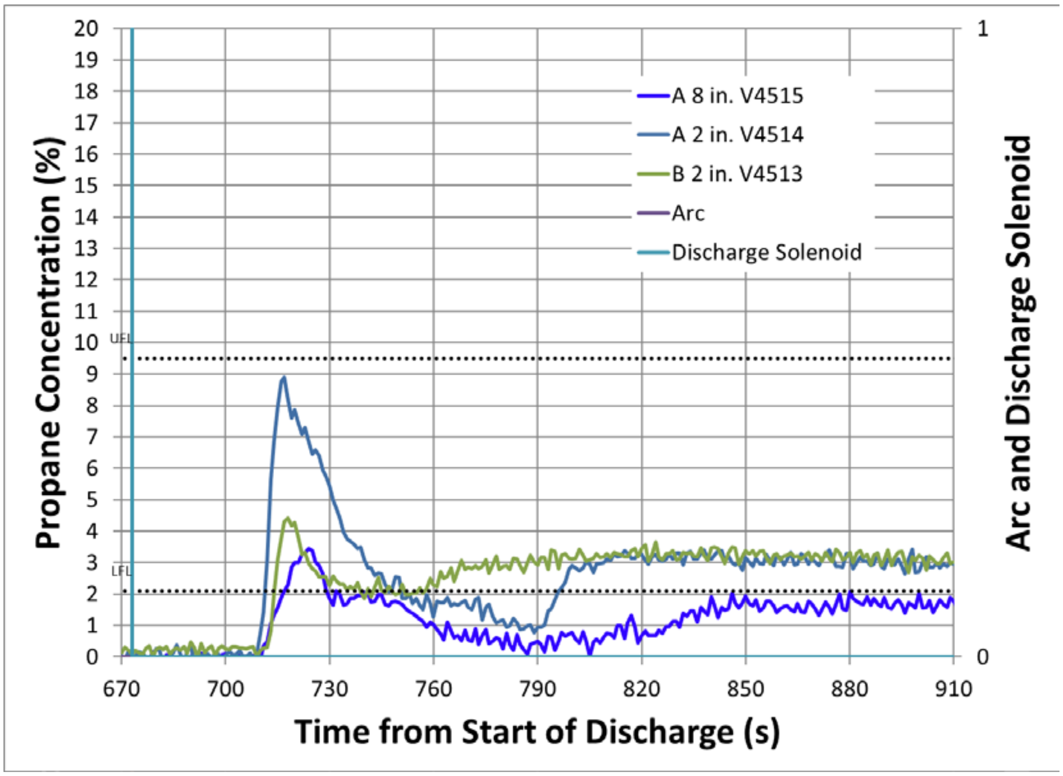


Figure 69 – Three Door test RI_02 (355 g) showing wave action and final settling at the 2 inch level

Figure 70 shows the progression of concentration at Location A, 2-inch level as total discharge was increased from 71 g to 200 g. The steep rise in concentration corresponds to door opening following the completion of the discharge (plus a 30 second wait time).

The 71g test shows that concentration at this location did not rise above the LFL and finally stabilized to about 0.5% concentration. The 114g and 150g tests showed brief periods above the LFL followed by stabilized concentrations of 1.0 to 1.5%. The 200 g test concentrations rose to 5% and settled at about 2.5% representing a flammable pool at floor level throughout the test room.

The peaks appear at different times because all four discharges were made at the rate of 150 g in 670 seconds or 0.224 g/s.

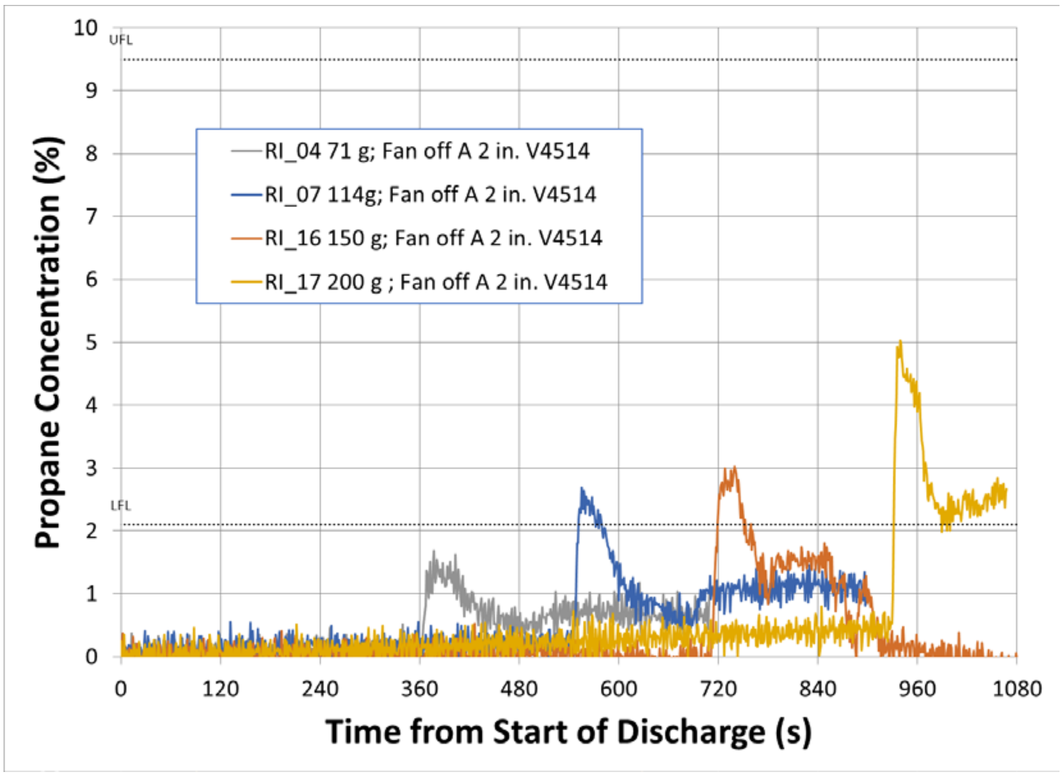


Figure 70 – Three door cooler step-wise progression at Location A, 2-inch level

Figure 71 plots single door refrigerator concentrations at location A 2-inch level from the step-wise progression from 25 g to 150 g releases. The peaks are larger than the three-door tests because the smaller volume of the single door refrigerator resulted in higher concentrations within the compartment from the same release amounts. The 25 g release did not rise above the LFL, while the other five had peaks well above the LFL. The 125 g and 150g releases settled at values close to LFL at the 2-inch level.

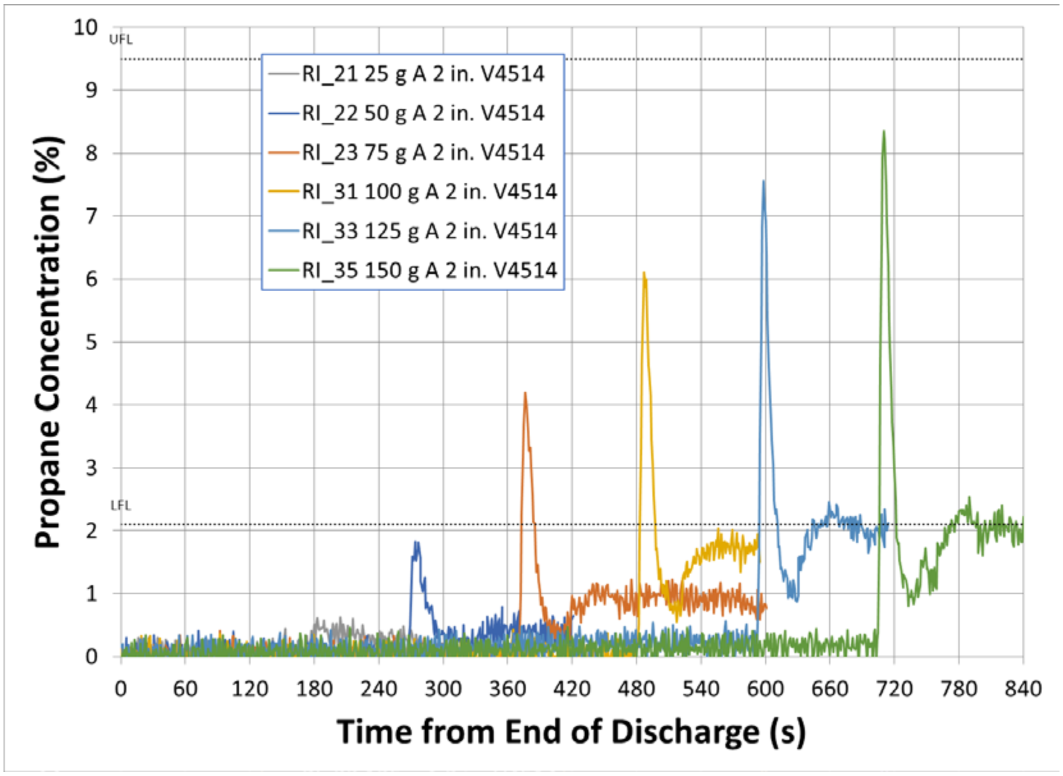


Figure 71 – Single door refrigerator step-wise progression at Location A, 2-inch level

12.4.4.3. *Concentration Tests - External Leak Tests*

The three door cooler's compressor and condenser were mounted at floor level, while the single door refrigerator's compressor/condenser were located on top of the unit. Tests in each unit were run with the condenser fan either running or off. The release amount in each case was within 5% of the specified discharge of 397g. These tests simulate a leak from the condenser coil.

Figure 72 shows the deconvoluted concentration data for the sensor located at the right-front of the cooler (50 mm or 2-in.) above the floor. The left-hand graph has a scale up to 10% and includes the three door cooler test with the fan off. Also included is the location A sensor at the 8-inch level.

In the three door cooler test with the fan off, concentration at the floor level exceeded LFL in approximately 2 minutes, reaching a final value of 5.5% at the end of data recording. The 8-inch level sensor recorded concentration approaching 3%. Observations during the igniter test showed a flammable mixture of gas had formed at the floor level throughout the test room.

The right-hand graph in Figure 72 shows the effect of the condenser fan in operation during the leak. With the condenser fan turned off, the three door cooler test resulted in concentrations only slightly higher than the single door refrigerator test. The single door refrigerator test with the condenser fan running created the lowest concentrations at this location. The calculated value of concentration for 397 g evenly mixed in the test room is 0.5%.

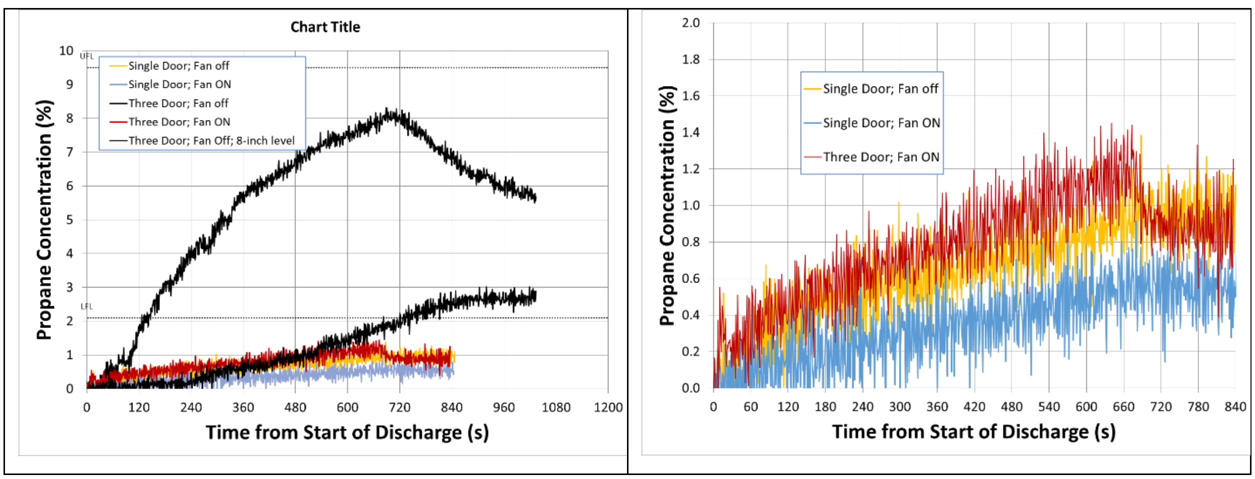


Figure 72 – External Leak Tests; 397 g; Three Door and Single door refrigerators

Figure 73 shows the non-deconvoluted concentration from throughout the test room (Test RI_28). Most sensors settled to concentrations between 0.4 and 0.6% at the end of data recording. The exception was the sensor located high on the right side of the single door refrigerator (Right High V4512). The exact reason for this behavior is unknown, but possibilities include air leakage from the test room exit door or air leakage from the attic through the video camera support.

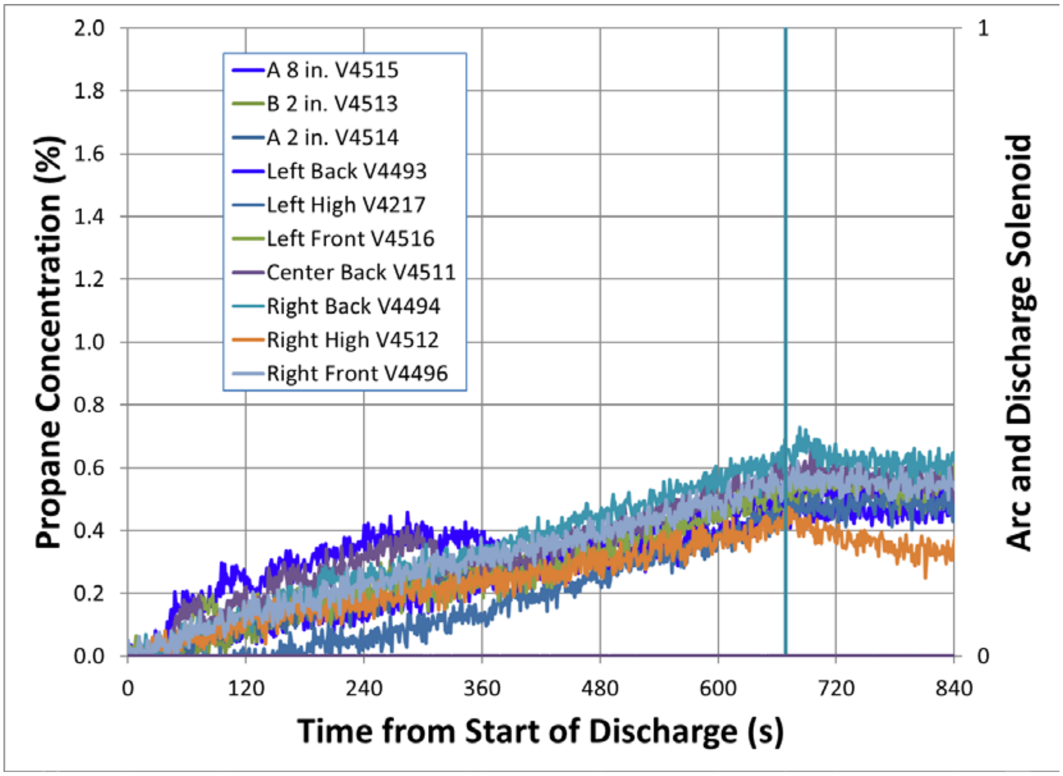


Figure 73 – Single door refrigerator test RI_28: 397 g, condenser fan operating

12.4.4.4. *Igniter tests*

The three door and single door refrigerator tests ignition are summarized in Table 20 and Table 21. The green highlight color is used to show those tests where ignition did not occur.

In these tables the internal leakage tests are listed first, followed by the external leakage tests. The abbreviation "Evap." refers to the discharge capillary tube placement at a return bend in the evaporator coil. "Cond." refers to the discharge capillary tube placement at a return bend in the condenser coil.

The tables record the cautious approach taken to the highest discharge quantities because of concern about overpressure events and risk to personnel and facilities. The three door cooler internal release series was stopped from further progression at the 200 g release (RI_18) when a near detonation event caused damage to the test facility from the overpressure.

Table 20 – Three Door Cooler Igniter tests

		Planned Discharge and Rate		Measured Discharge and Rate						
Test Code	**Fan State**	**(g)**	**(g/s)**	**(g)**	**(g/s)**	**Discharge Location**	**Max Temp (°F)**	**Max Temp Loc.**	**Max Ceiling Temp (°F)**	**Number of Vents Burst /Melted**
RI_05 [a]	Off	71	0.22	72	0.23	Evap.	110	A-08	83	0/0
RI_06 [b]	Off	92	0.22	96	0.23	Evap.	718	A-08	100	0/0
RI_08	Off	114	0.22	115	0.23	Evap.	886	A-88	671	1/1
RI_09	On	114	0.22	117	0.23	Evap.	84	A-04	82	0/0
RI_10	On	150	0.22	157	0.24	Evap.	919	A-18	378	3/0
RI_11	Off	132	0.22	133	0.23	Evap.	855	A-18	370	3/1
RI_12	Off	150	0.22	150	0.23	Evap.	835	A-18	429	5/0
RI_15	Off	150	0.22	154	0.23	Evap.	922	A-18	413	5/0
RI_18	Off	200	0.30	198	0.30	Evap.	1061	A-12	478	6/0
RI_20	Off	397	0.59	400	0.60	Cond.	1292	B-04	298	4/1 + Door
RI_37	On	397	0.59	392	0.59	Cond.	77	A-04	73	0/0

Notes:

[a] Ignition was visible only on the infrared camera as flaring close to the electric arcs.

[b] Ignition was visible only on the infrared camera.

The three door cooler external leak igniter test (RI_20, fan off) resulted an overpressure that opened the test room exit door. The door latch had been damaged in the RI_18 test, and closed with duct tape.

A substitute test (RI_37, 397g external) was added to the program in lieu of the canceled internal leak test at 355g. There was no ignition in this test because the condenser fan was operating continuously from before the start of the test.

Table 21 - Single door refrigerator Igniter Tests

Test Code	Fan State	Planned Discharge and Rate (g)	Planned Discharge and Rate (g/s)	Measured Discharge and Rate (g)	Measured Discharge and Rate (g/s)	Discharge Location	Max Temp (°F)	Max Temp Location	Max Ceiling Temp (°F)	Number of Vents Burst /Melted
RI_30	NA	75	0.22	81	0.24	Evap.	957	B-18	236	4/1
RI_32	NA	100	0.22	102	0.23	Evap.	788	A-08	316	2/2
RI_34	NA	125	0.22	128	0.23	Evap.	914	A-12	473	1/4
RI_36	NA	150	0.22	149	0.23	Evap.	774	A-18	440	1/3
RI_29	Off	397	0.59	406	0.61	Cond.	89	B-18	76	0/0

The internal volume of the single door refrigerator (0.6 m^3) was approximately one-third of the three-door cooler (1.8 m^3), so similar discharge masses resulted in much higher concentrations in the single door refrigerator internal release tests. The concentration testing showed concentrations nearest to stoichiometric concentration with 75 g in the single door refrigerator. This test was performed in test code RI_30 and resulted in the largest number of burst deflagration vents (four). Higher discharges (100, 125, and 150 g) resulted in smaller overpressures as indicated by the smaller number of burst deflagration vents. The videos of the higher discharges (100, 125, and 150 g) showed yellow diffusion flames as compared to the blue color of the pre-mixed flames at 75 g.

Figure 74 shows captured video frames from the three door cooler tests at 150 g and 200 g (RI_15 and RI_18). The deflagration in test RI_15 was sufficient to pop open both side doors, which immediately closed. The deflagration in test RI_18 resulted in bouncing both side doors open with enough momentum that they bounced off their stops and slammed shut.

The 200 g test also resulted in an explosion. This event was in the transition zone between a detonation (faster than the speed of sound) and a deflagration (less than the speed of sound). The highest flame speed was estimated at 130 m/s or about one-third of the speed of sound (432 m/s). The video also showed reaction forces rocking the cooler and the obstruction in front of the cooler.

RI_15: 150 g; Doors opened from overpressure

RI_18: 200 g; Doors opened from overpressure

RI_18: 200 g; Start of high-speed flame 200 g

RI_18: 200 g; Estimated flame speed 130 m/s

Figure 74 - Three Door Cooler Igniter Tests

Figure 75 shows the ignition of the pre-mixed gases in the 75 g discharge in the single door refrigerator. The initial flames are blue in color indicating a pre-mixed condition. The second frame shows pre-mixed flaming in the entire internal volume of the cooler.

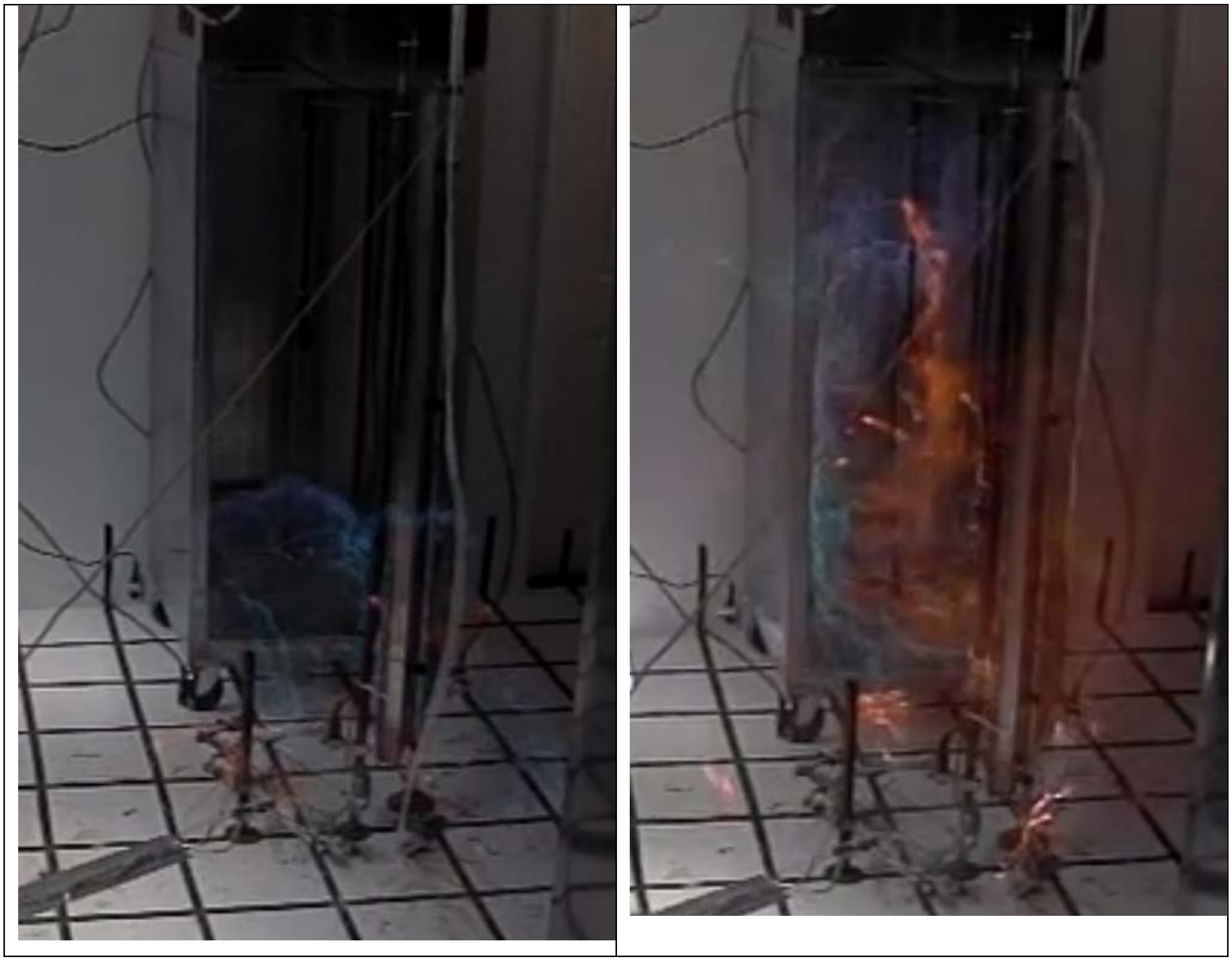


Figure 75 - Single door refrigerator RI_30 Pre-mixed flames filling the internal volume of the cooler

Figure 76 shows the ignition and flame development in the single door refrigerator 150 g discharge. The initial flaming is yellow in color indicating a diffusion flame with slight volumes of blue flames at the edge of the fireball. The second frame shows diffusion flaming as the primary burning mechanism. The pre-test data showed concentration above the UFL meaning that the higher concentration of propane could not burn until some mixing occurred.

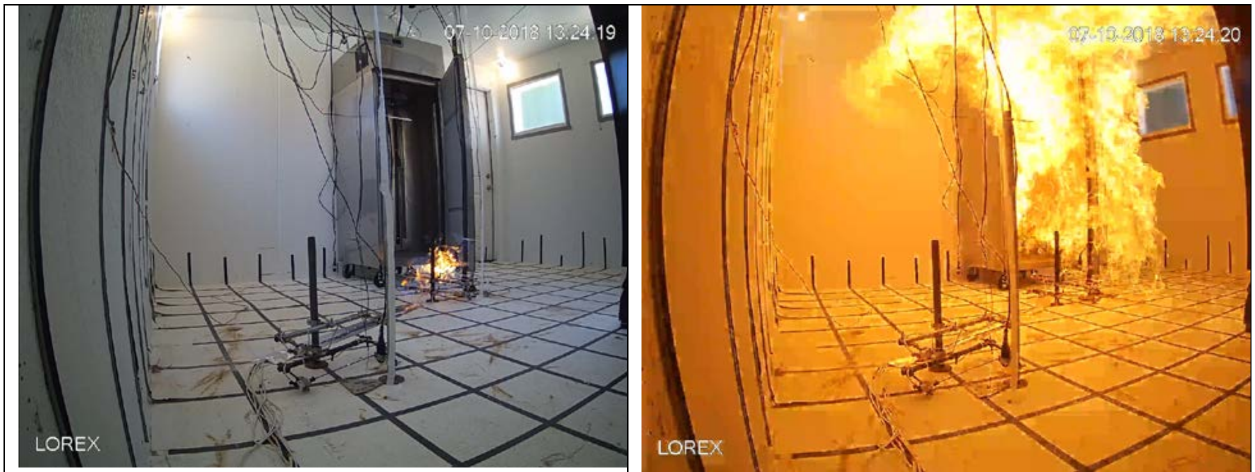


Figure 76 – Single door refrigerator RI_36 Diffusion flames and buoyant rise of hot gases

Appendix A

13. Summary of Findings

A general observation throughout this test program is that electrochemical oxygen sensors were effective at measuring propane concentrations. Fourteen sensors were used to provide more information on the distribution of propane concentrations. Data generated by more sensors will be useful for validating computer simulations of the risks and severity of flammable refrigerant leaks.

13.1. Task 1 – Parametric Tests

The obstruction effectively reduced the momentum and mixing of the propane discharge at the 0.2m height leading to ignitable concentrations on the side of the obstruction directly exposed to the discharge flow. All igniter tests at the 0.2m height, from 50 g to 400 g, resulted in ignition of a flammable gas layer at floor level. The 50 g test was primarily a pre-mixed flame (blue in color), while higher masses were clearly diffusion flames (yellow in color).

The bursting of deflagration vents gave an indication of rate and size of pressure rise from ignitions. Comparing ignition tests at the lowest discharge rate (6.8 g/s), the 200 g discharge resulted in all four vents bursting, while the 400 g release burst only two. The difference is due to the formation of a layer forming at the between the floor and the 8-inch height that was above the UFL of propane in the 400 g release. The 200 g release had an ignitable layer from the floor to the 12-inch height. The concentration test data shows that the 200 g discharge resulted in the largest volume of concentrations between LFL and UFL.

The 400 g discharge at the highest release rate (40 g/s) at the 0.2m height also resulted in bursting all four deflagration vents. The concentration test data showed that the discharge “splashed” off the side of obstruction and concentrated a flammable mixture on that side. The side opposite the discharge showed no flammable concentration at the time of ignition. The resulting fireball was almost entirely confined to the discharge side of the obstruction until gas expansion pushed the flames around the side of the obstruction.

All concentration tests at the 0.2m discharge height showed floor level concentrations remaining above the LFL for several minutes after completion of the discharge. The concentration was trending down due to diffusion or convective current effects.

13.2. Task 2 – Scenario Tests

The range of tests planned for Task 2 ranged from 114 g to 975 g of propane. When evenly mixed in the Task 2 test room (46 m^3) the resulting concentrations varied from 7% to 56% of the LFL for propane. Without some mitigation action, discharges from lowest to highest showed some period of time in which ignition was possible. Mitigation by use of the unit fan to cause circulation and reduce flammable concentrations was effective in some cases and not in others. Where fan circulation was effective, it either eliminated or greatly reduced the period of time when ignition was possible.

The effectiveness of elevation as a mitigating factor (leaks in a mini-split evaporator at 1.8 m or a top mounted condenser on the single door refrigerator) depended on discharge mass and the discharge rate and other factors not considered in these tests. A fast leak (40 g/s) in the mini-split indoor unit resulted in flammable concentrations at floor level, while a slow leak (6.8 g/s) from a top-mounted condenser on the refrigerator did not.

13.2.1. PTAC Tests

All concentration tests with the PTAC unit resulted in flammable concentrations at the floor level. Four igniter tests were performed and each resulted in ignition. Of these four tests, one of igniter tests was invalid because the igniters were energized too early. Rather than progressing to a fourth PTAC test, the test plan was stopped at three, with the extra test moved to the reach-in cooler series.

The first three concentration tests were performed with the discharge tube located at a return bend in the evaporator. This return bend volume of the PTAC was semi-enclosed by the front panel of the PTAC. Discharge tests resulted in an area of frost forming on the front panel. Formation of a liquid propane pool in this volume was suspected but could only be inferred by concentrations at floor level continuing above the LFL for more than 5 minutes after completion of the discharge.

All later concentration and igniter tests were performed with the discharge tube moved to the center of the evaporator coil. The tube was pointed directly into the front grill of the PTAC unit. Discharges were observed to be a jet-like mist. Liquid propane was seen forming on the surface of the grill and dropping to floor level. A liquid pool was formed. During ignition tests this pool was observed to continue burning for up to 15 seconds after all flammable vapor mixtures had ceased burning.

The discharge jet was opposite the normal air flow through the PTAC. The flow rate of the unit fan was 200 cfm. This volume flow rate was unable to overcome the speed of the discharge jet. As a result the operation of the unit fan showed little effect on the magnitude of flammable concentrations.

The one invalid igniter test was useful by comparison to the valid test with the same parameters. A delay of 4 seconds resulted in a much less severe ignition event. Four of the six deflagration vents burst in the invalid test, while two burst in the valid test. The associated concentration tests show that concentrations were rapidly decreasing following completion of the discharge (6.5% at 1s and 3.7% at 5s)

13.2.2. Mini-Split Tests

The mini-split indoor unit has a set of bottom air-directing flaps that are closed when the unit fan is not operating. Concentration and igniter tests with the fan off showed the unit collected a large concentration of propane within the unit. The discharge tube was installed in the center of the evaporator coil and pointed directly at the solid front panel of the unit. This panel resulted in eliminating the jet flow aspect and a buildup of propane with in the unit.

The concentration tests showed that a flammable mixture formed at floor level in every tested case. The igniter tests confirmed ignition occurrence in three of the four tests. The mitigation test (650 g) with the unit fan running continuously throughout the test did not ignite.

Another mitigation ignition test used a time delay of 15 s with the same discharge (650 g). The 15s interval was used as a reasonable time frame for a triggered mitigation action to take place following detection of a leak. The fan took approximately 10 seconds to come up to full speed. The delay plus ramp time was insufficient to prevent formation of an ignitable concentration at the floor level. The video of this test shows that a faster ramp time for the fan could have prevented ignition.

In the three igniter tests where ignition occurred the flames were observed to backup into the indoor unit and continue flaming due to the trapped propane. In each case, the flaming spread to other flammable components within the unit. The resulting fires were manually suppressed.

13.2.3. Reach-in Cooler Tests

Testing of the reach-in coolers was divided between external (condenser) leaks and internal (evaporator) leaks and between a single door and a three door cooler. Discharge amounts were based on current or proposed standards. The amounts selected ranged from 10% to 50% of LFL when mixed within the whole room volume.

13.2.3.1. *External Release Tests*

The single door refrigerator's condenser was top-mounted resulting in mixing propane-air concentrations to less than LFL. This was true whether the condenser fan was or was not operating. With the condenser fan operating concentration levels at all sensors in the room were observed to come close to the estimated well-mixed value in the entire volume of the room (50% of LFL).

The three door reach-in cooler's condenser was bottom-mounted. With the condenser fan off, a flammable mixture developed at floor level throughout the entire floor area of the room. This flammability was confirmed with an ignition event in the igniter test. Flames were observed traveling across the entire floor area.

With the three door cooler condenser fan running, the resulting concentrations were not ignitable and similar to the concentrations from the single door refrigerator.

13.2.3.2. *Internal Release Tests*

Concern about overpressure events resulted in a cautious approach to values in the test plan. Concentration tests showed that internal propane-air mixtures grew to large percentages, sometime close to stoichiometric conditions and in other cases over the UFL for propane (9.5%)

The single door refrigerator concentration tests were conducted in 25 g steps from 25 to 150g. Igniter tests were performed in 25 g steps from 75 to 150 g. The most deflagration vents were burst (4 of six) at the 75 g level. The concentration data for this test showed final interior concentration to be 5.5% which is slightly above the stoichiometric ratio for propane ignition. The resulting flaming was typical of a pre-mixed flame (blue in color). The following steps between 100 and 150 g were less energetic, opening fewer deflagration vents as the discharge amount increased. These larger amounts resulted in fuel-rich concentrations and required more combustion time due to the diffusion flaming process.

The same cautious approach was used with the three-door cooler. Igniter tests were performed in steps of 71, 92, 114, 132, 150, and 200 g. Ignition was not observed until the 92 g level, but the energy release was low in that no deflagration vents were burst. At the 114 g level with the internal fans off, there was an ignition bursting one of the deflagration vents. The same charge (114 g) with the internal fans running did not ignite because the fans quickly diffused concentrations at the igniters to less than LFL.

It was also found that the size of the ignition event depended on the sealing capability of the door gaskets. Gaskets were replaced twice to continue the test series after concentration tests showed increased gasket leak due to preceding igniter tests.

At 150g in the three door cooler igniter test, five of the six deflagration vents burst. At 200g all six deflagration vents burst. The test room door latch was also damaged by this overpressure event. Estimates of the flame speed were approximately one-third of the speed of sound, placing this overpressure event near to having been a detonation [3].

Because of this last overpressure, the progression of tests in the three door cooler was stopped. The replacement test was the external release from the condenser with the fan running.

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Appendix A Parametric Test Data and Summary

This appendix summarizes the parametric tests in the ISO 9705 test room (2.44 m x 3.66 m x 2.43 m)

The following table summarizes all parametric tests. The sections that follow describe each test in detail.

Temperatures are color coded according to the following legend:

Range
< 0°F
0 – 105 °F
105 – 400 °F
400°F and higher

Table 22 – Parametric Tests

			Planned Discharge		Measured Discharge				Maximum Temperature						Maximum at Location B		Maximum at Location D						Video Events			
Test Number	Discharge Location (m)	Discharge Opening	Mass (g)	Rate (g/s)	Mass (g)	Rate (g/s)	Objective	Result	(°F)	Location	Maximum Ceiling Temperature (°F)	Minimum Temperature (Pooling) (°F)	Peak Heat Flux (kW/m²)	Peak Pressure (mmHg)	Conc. (%)	Height (in.)	Conc. (%)	Height (in.)	Time sensors <LFL (s)	Discharge Start Time (s)	Discharge Stop (s)	Analysis File	Vents Burst / Melted	Discharge Start Time (HH:MM:SS)	Ignition Time (HH:MM:SS)	Date
CP_01	0.2	25	50	6.8	48	5.8	Concentration	NA	NA			65	NA		9.9	2	1.6	4	235.1	175.7	8.3	CP_01_2018-02-28-1411 Analysis.xlsx	NA			2018-Feb-28
CP_02	0.2	25	50	6.8	49	7.8	Ignition	Ignited	79	A1_92	79	66	0	0.02	8.9	6	0.1	4	NA	203.3	6.3	CP_02_2018-02-28-1506 Analysis.xlsx	1/0	15:10:10	15:10:24	2018-Feb-28
CP_03	0.2	25	50	6.8	48	7.0	Ignition	Ignited	809	A1_84	237	65	15	0.03	8.7	6	0.1	4	NA	161.2	6.9	CP_03_2018-03-01-1051 Analysis.xlsx	2/0	10:54:33	10:54:46	2018-Mar-01
CP_04	0.2	25	100	6.8	106	1.0	Concentration	NA	NA			71	NA		10.9	2	6.0	4	> 306.4	156.4	106.1	CP_04_2018-03-01-1311 Analysis.xlsx	NA			2018-Mar-01
CP_05	0.2	25	100	6.8	98	7.8	Concentration	NA				69			10.9	6	2.4	4	> 132.9	144.2	12.5	CP_05_2018-03-01-1513 Analysis.xlsx				2018-Mar-01
CP_06	0.2	25	100	6.8	97	6.4	Ignition	Ignited	826	A1_08	510	68	73	0.05	10.2	6	0.1	4	NA	152.4	15.1	CP_06_2018-03-02-0829 Analysis.xlsx	2/1	8:31:46	8:32:03	2018-Mar-02
CP_07	0.2	25	150	6.8	148	8.8	Concentration	NA	NA			67	NA		10.7	6	3.0	4	> 301.5	237.4	16.7	CP_07_2018-03-02-1023 Analysis.xlsx	NA			2018-Mar-02
CP_08	0.2	25	150	6.8	149	7.0	Ignition	Ignited	799	A1_12	757	68	89	0.02	10.8	2	0.1	4	NA	151.5	21.4	CP_08_2018-03-02-1108 Analysis.xlsx	3/1	11:10:34	11:10:59	2018-Mar-02
CP_09	0.2	25	200	6.8	198	7.6	Concentration	NA	NA			68	NA		11.0	2	4.0	4	> 134.4	130.0	26.1	CP_09_2018-03-02-1327 Analysis.xlsx	NA			2018-Mar-02
CP_10	0.2	25	200	6.8	198	6.7	Ignition	Ignited	1081	B2_18	1043	69	107	0.02	11.4	2	0.5	4	NA	213.0	29.5	CP_10_2018-03-02-1427 Analysis.xlsx	4/0	14:30:59	14:31:27	2018-Mar-02
CP_11	0.2	25	250	6.8	248	6.6	Concentration	NA	NA			62	NA		13.3	2	5.1	4	> 165.9	127.1	37.3	CP_11_2018-03-05-0906 Analysis.xlsx	NA			2018-Mar-05
CP_12	0.2	25	250	6.8	248	7.1	Ignition	Ignited	1055	A1_12	613	66	77	0.14	11.6	2	1.6	4	NA	141.8	35.0	CP_12_2018-03-05-0944 Analysis.xlsx	3/1	9:46:50	9:47:25	2018-Mar-05
CP_13	0.2	25	300	6.8	299	6.9	Concentration	NA	NA			-48	NA		12.5	2	5.7	4	> 158.4	119.8	43.1	CP_13_2018-03-05-1104 Analysis.xlsx	NA			2018-Mar-05
CP_14	0.2	25	300	6.8	299	7.0	Ignition	Ignited	998	E3_18	783	-59	74	0.06	13.3	2	2.4	4	NA	126.6	42.4	CP_14_2018-03-05-1124 Analysis.xlsx	3/1	11:26:20	11:27:03	2018-Mar-05
CP_15	0.2	25	100	6.8	99	7.3	Ignition	Ignited	725	B2_12	679	71	67	0.03	9.6	6	0.1	4	NA	199.4	13.5	CP_15_2018-03-05-1352 Analysis.xlsx	3/1	13:56:21	13:56:34	2018-Mar-05
CP_16	0.2	25	350	6.8	348	6.4	Concentration	NA	NA			-72	NA		13.3	2	8.1	4	> 179.9	237.3	54.7	CP_16_2018-03-05-1439 Analysis.xlsx	NA			2018-Mar-05
CP_17	0.2	25	350	6.8	353	7.1	Ignition	Ignited	1232	B2_18	1066	-57	69	0.05	13.1	2	3.1	4	NA	155.7	49.8	CP_17_2018-03-05-1511 Analysis.xlsx	3/1	15:13:41	15:14:32	2018-Mar-05
CP_18	0.2	25	400	6.8	400	6.9	Concentration	NA	NA			-68	NA		14.4	2	7.4	4	> 196.7	126.5	58.0	CP_18_2018-03-06-0912 Analysis.xlsx	NA			2018-Mar-06
CP_19	0.2	25	400	6.8	401	7.2	Ignition	Ignited	1092	A1_92	1092	-63	64	0.07	15.6	2	4.6	4	NA	177.4	55.9	CP_19_2018-03-06-0942 Analysis.xlsx	2/2	9:45:21	9:46:19	2018-Mar-06
CP_20	1.8	25	200	6.8	201	7.2	Concentration	NA	NA			66	NA		6.7	72	1.6	4	36.4	120.0	27.9	CP_20_2018-03-06-1412 Analysis.xlsx	NA			2018-Mar-06
CP_21	1.8	25	200	6.8	201	6.7	Ignition	Ignited	530	D2_92	530	66	2	0.03	7.6	72	1.1	4	NA	194.4	29.9	CP_21_2018-03-06-1458 Analysis.xlsx	2/0	15:01:25	15:02:38	2018-Mar-06
CP_22	1.8	25	400	40	419	47	Concentration	NA	NA			70	NA		9.8	72	4.2	60	18.1	121.4	9.0	CP_22_2018-03-12-1045 Analysis.xlsx	NA			2018-Mar-12
CP_23	1.8	25	400	40	417	44	Ignition	Ignited	335	B2_92	335	61	1	0.09	11.1	72	2.5	60	NA	166.2	9.5	CP_23_2018-03-12-1125 Analysis.xlsx	0/0	11:28:13	11:29:36	2018-Mar-12
CP_24	0.2	25	400	40	406	42	Concentration	NA	NA			-68	NA		13.3	6	2.7	4	> 300.1	132.0	9.6	CP_24_2018-03-12-1433 Analysis.xlsx	NA			2018-Mar-12
CP_25	0.2	25	400	40	411	42	Ignition	Ignited	892	E3_04	853	-61	84	0.12	12.0	6	0.2	4	NA	163.1	9.9	CP_25_2018-03-12-1511 Analysis.xlsx	4/0	15:14:12	15:14:23	2018-Mar-12
CP_26	1.8	25	400	40	417	46	Ignition	Ignited	628	B2_84	614	59	2	0.03	10.1	72	3.1	60	NA	228.5	9.0	CP_26_2018-03-14-1320 Analysis.xlsx	3/1	11:25:05	13:25:15	2018-Mar-14

Notes:

- The times recorded for the raw video are from the date/time stamp (time portion only) in the video.
- Maximum Temperatures are recorded in the cases where ignition occurred.
- Maximum deconvoluted propane concentrations are recorded in cases where the igniters were not used.
- Refer to the main body of the report for the description of sensor locations.
- Peak Pressures reported are informational. The deflagration vents limited pressure rise in the room to safe operating levels for continued operation

The test room layouts are included here for reference.

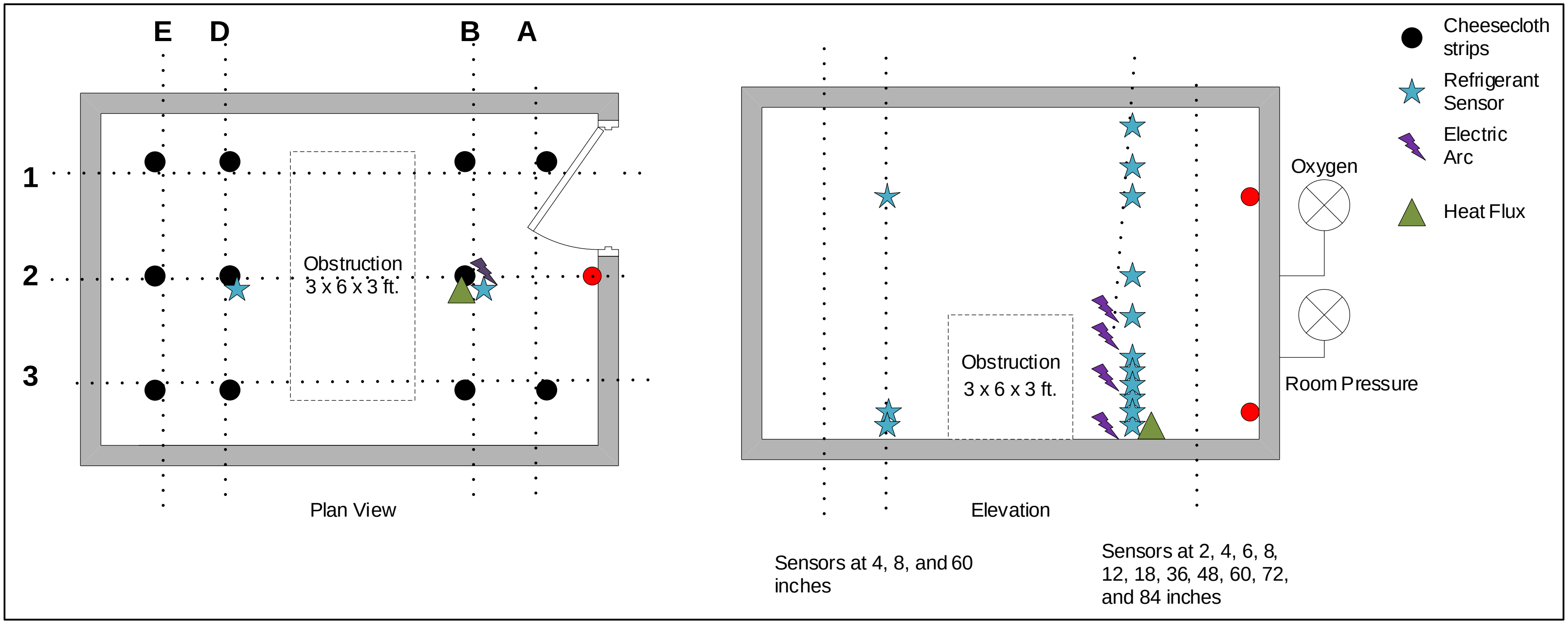


Figure 77 – Task 1 Instrumentation Locations

Videos for each test are stored separately. The correspondence of channel number to camera view is as follows:

Video Channels	Usage
1	Northeast Upper Corner
2	Northwest Upper Corner (Hi Def)
3	Northeast Floor Corner
4	Southeast Upper Corner
6	East Side Vents
7	West Side Vents
8	Northeast Floor IR Camera
9	Test Marquee and Clock
10	Southwest Upper Corner

High speed camera videos are stored in the same folder for each test. High speed cameras were used where ignition was expected. The following table matches the test number with the high-speed camera video:

High Speed Cameras		
Test	**Floor Level**	**High Level**
CP_02	CIMG3334 Lo.MOV	CIMG3334 Hi.MOV
CP_03	CIMG3335.MOV	CIMG3335hi.MOV
CP_06	CIMG3337.MOV	CIMG3337Hi.MOV
CP_08	CIMG3338.MOV	CIMG3338Hi.MOV
CP_10	CIMG3339.MOV	CIMG3339 1.MOV
CP_12	CIMG3340 (2).MOV	CIMG3340.MOV
CP_14	CIMG3341 (2).MOV	CIMG3341.MOV
CP_17	CIMG3342 (2).MOV	CIMG3342.MOV
CP_19	CIMG3343 (2).MOV	CIMG3343.MOV
CP_23		CIMG3344.MOV
CP_25	CIMG3344.MOV	CIMG3345.MOV
CP_26	CIMG3345.MOV	CIMG3346.MOV

Note: The cameras assigned file names automatically. Some filenames are identical and are stored separately. For example CIMG3444.MOV appears twice on the list above, but they contain different video.

Test CP_01 (50 grams; 6.8 g/s; 0.2 height)

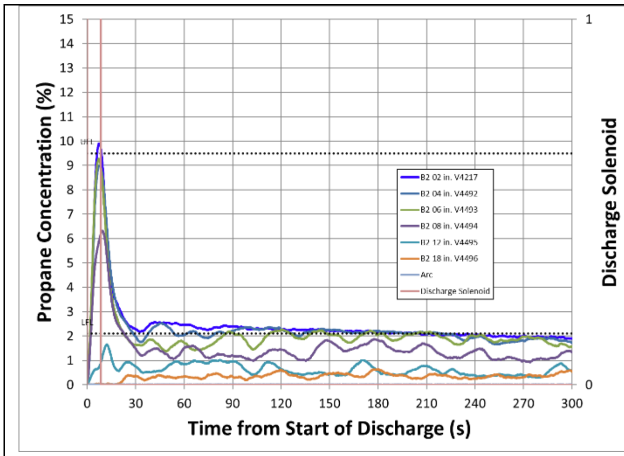
Test CP_01 was performed without ignition sources to measure propane concentrations. The associated tests with ignniters are CP_02 and CP_03. This test involved release of 50 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed near location B between 2 and 6 inches above the floor. Concentrations at D did not increase above the LFL. All sensors recorded less than LFL concentrations after 235 seconds.

Table 23 – CP_01 Summary

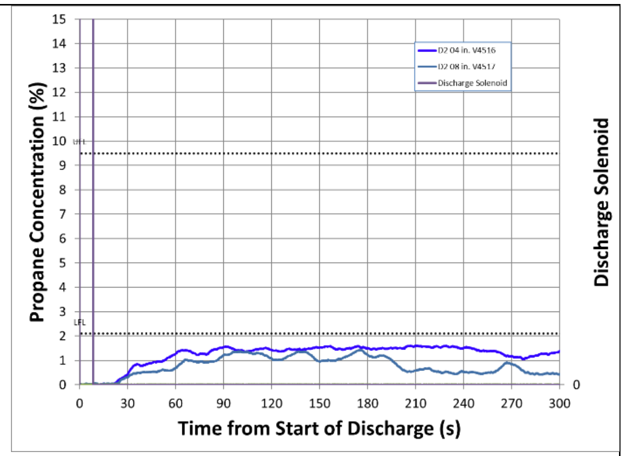
	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	50	7.4	6.8	0.2 m	0.13	Calculated if well Mixed in whole room
Measured	48	8.3	5.8		9.9 1.6	Location B 2-inch Location D 4-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

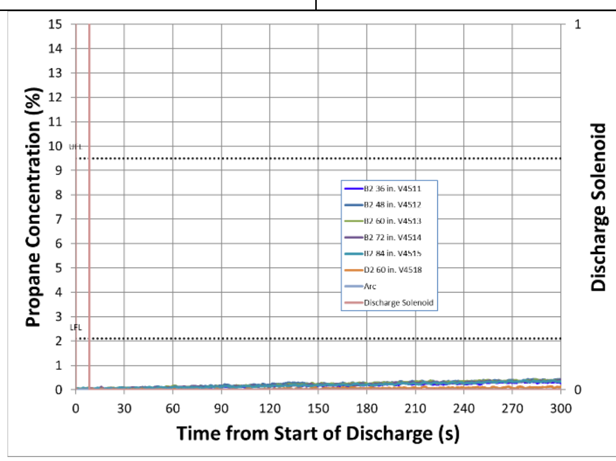
Figure 78 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 2-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 78 – CP_01 Concentrations

Figure 79 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

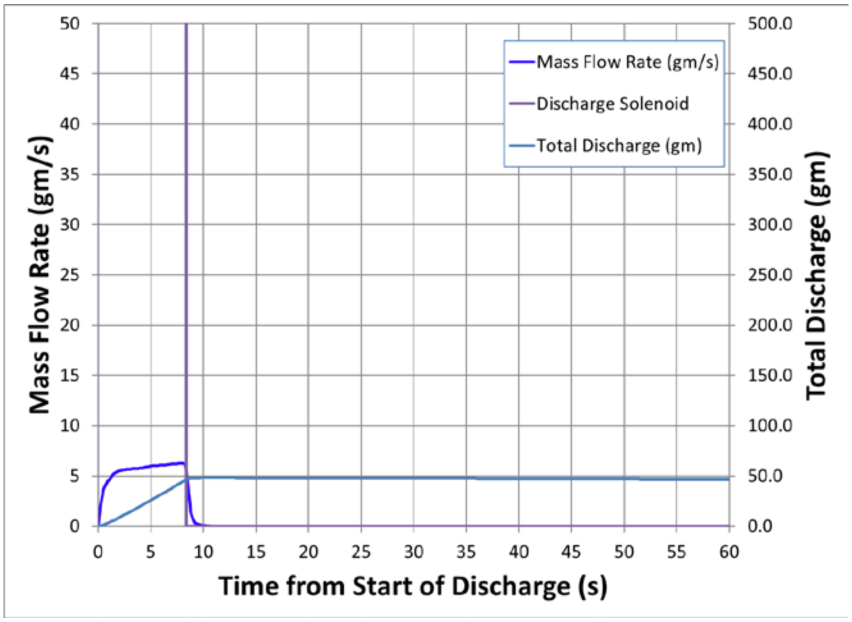


Figure 79 – CP_01 Mass Flow

Figure 80 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

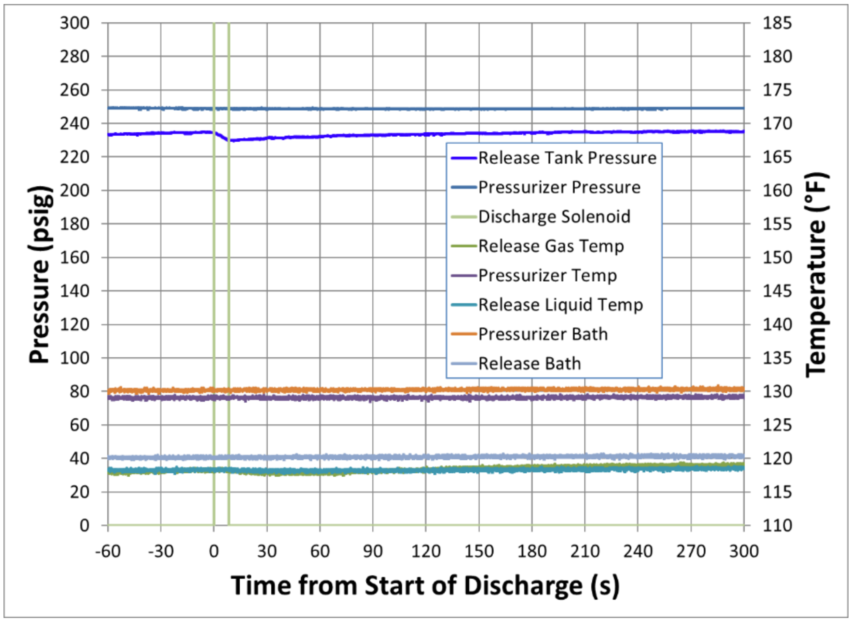


Figure 80 – CP_01 Pressurizer and Release Tank Pressure and Temperatures

Figure 81 shows no evidence of liquid propane forming near the thermocouples on the floor near the discharge tube opening.

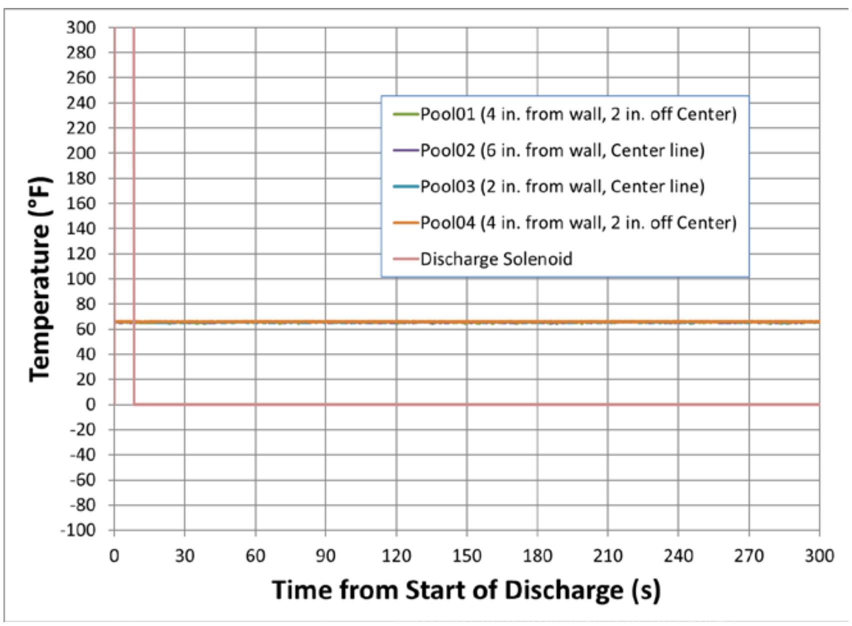


Figure 81 – CP_01 Liquid pooling at the floor

Test CP_02 (50 grams; 6.8 g/s; 0.2 height; with Igniters)

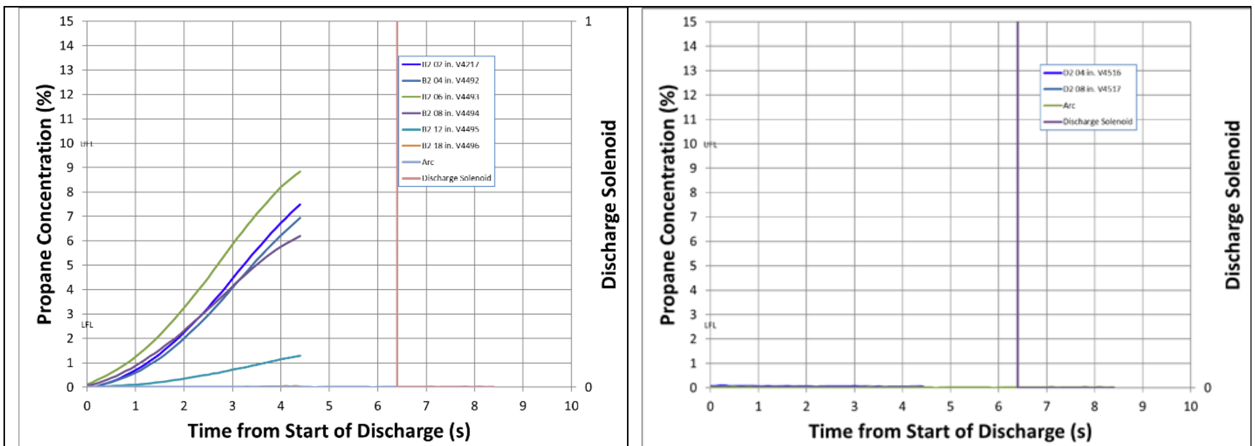
Test CP_02 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). There was a delay of 2.8 seconds after the arcs were energized before flaming was observed. Flames in this test were small and did not rise above floor level except for the cheesecloth targets.

Table 24 – CP_02 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	50	7.4	6.8	0.2 m
Measured	49	6.3	7.8	

This test was early in the program while test procedures were in development. As a result data was not recorded for a longer time following the observation of ignition.

Figure 82 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration between the 2-inch and 12-inch levels. The highest concentration was at the 6-inch level.



Location B2 concentrations just prior to ignition

Location D2 concentrations just prior to ignition

Figure 82 – CP_02 Concentrations

Figure 83 compares the concentration and igniter test (CP_01 and CP_02) concentrations at the 2-inch and 6-inch levels at location B2. The difference at the 6-inch level is due to the difference in discharge rates between the two tests (5.8 g/s and 7.8 g/s for CP_01 and CP_02, respectively).

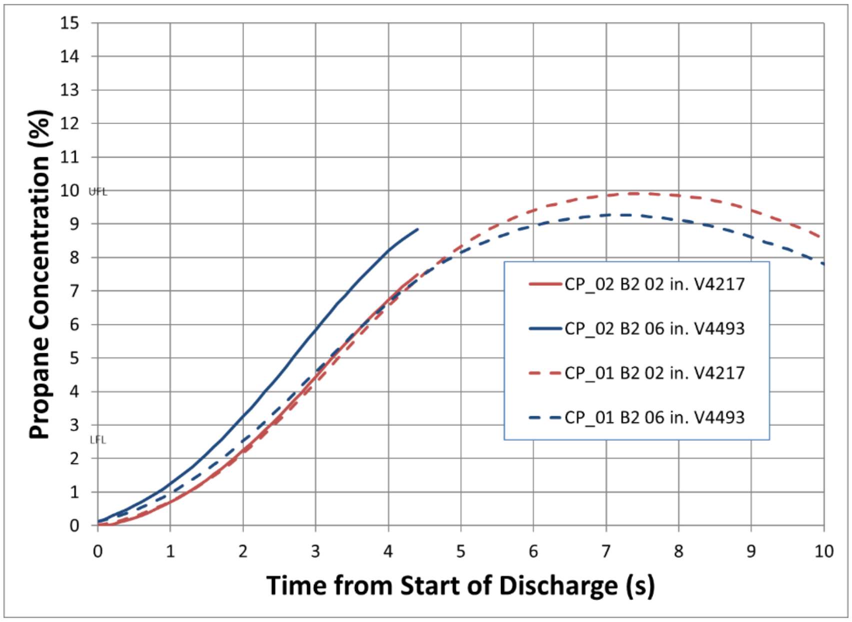


Figure 83 – CP_01 and CP_02 Concentration Comparison

Figure 84 shows the mass flow rate and total mass flow.

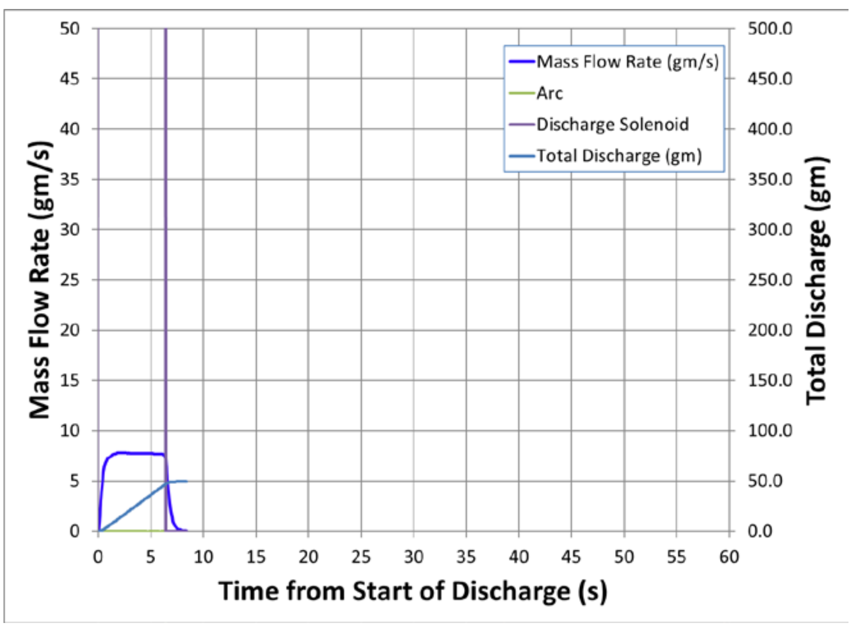


Figure 84 – CP_02 Mass Flow

Figure 85 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

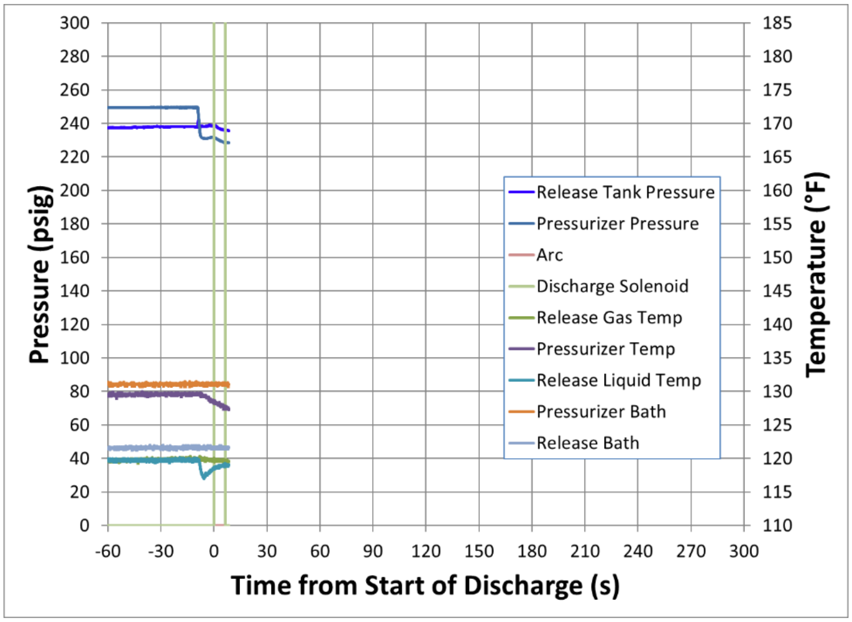


Figure 85 – CP_02 Pressurizer and Release Tank Pressure and Temperatures

Due to the short duration of data recording and the small size of the ignition event, there was no observed increase in any of the thermocouples. Figure 86 shows the temperatures recorded up to the point of ignition. The cooling effect at the 4 and 8 inch levels was due to the impact of the discharge at those locations.

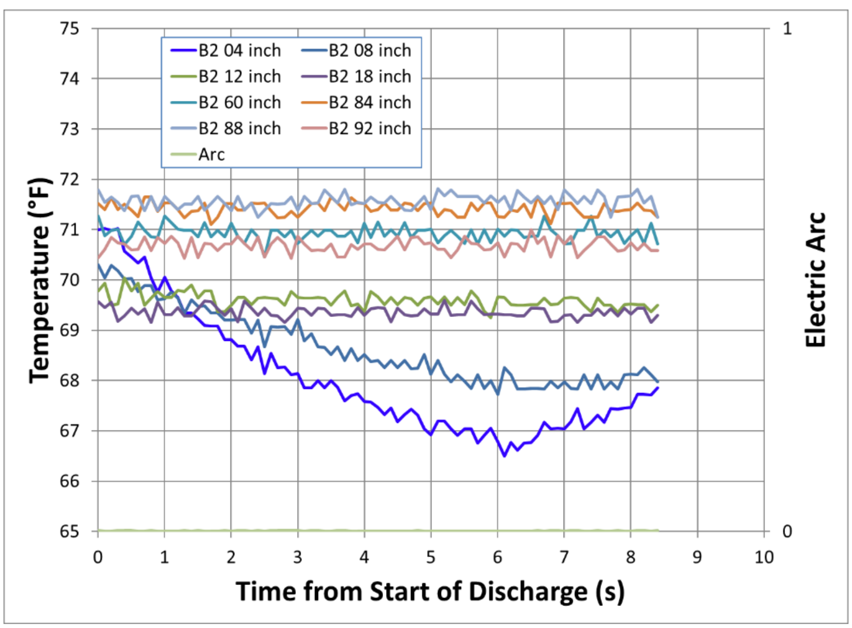


Figure 86 – CP_02 Temperatures at the location B2 thermocouple tree

There was no observable effect of liquid propane pooling at the floor level. Neither was there a measurable heat flux.

Selected frames from the videos are shown in Figure 87. Ignition occurred at location B2 1-inch level 2.8 seconds after the electric arcs were energized. The flaming was barely visible and was only observed in post-test review of the videos. One deflagration vents was burst due to the ignition.

(A) Ignition at Location B2 1-inch Level

(B) Flame spread at floor level

Figure 87 – CP_02: Frames of flaming from videos

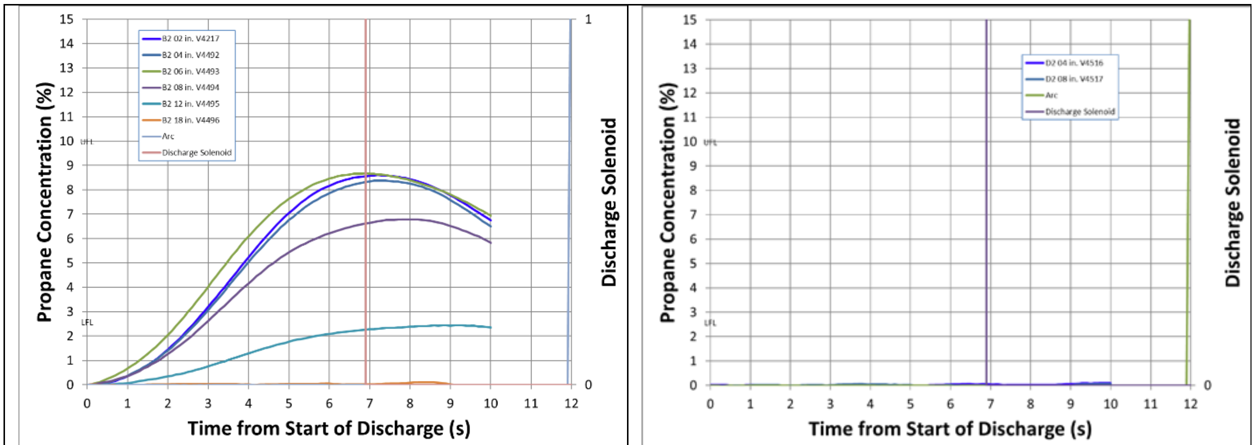
Test CP_03 (50 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_03 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels).

Table 25 – CP_03 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	50	7.4	6.8	0.2 m
Measured	48	8.7	6.9	

Figure 88 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors.



Location B2 concentrations just prior to ignition	Location D2 concentrations just prior to ignition

Figure 88 – CP_03 Concentrations

Figure 89 compares the concentration and igniter tests (CP_01 and CP_03) concentrations at the 1-inch and 12-inch levels at location B2. The rates of discharge differed by 20% which accounts for the differences in resulting concentrations. CP_01 rate was 5.8 g/s, while CP_03 was 6.0 g/s.

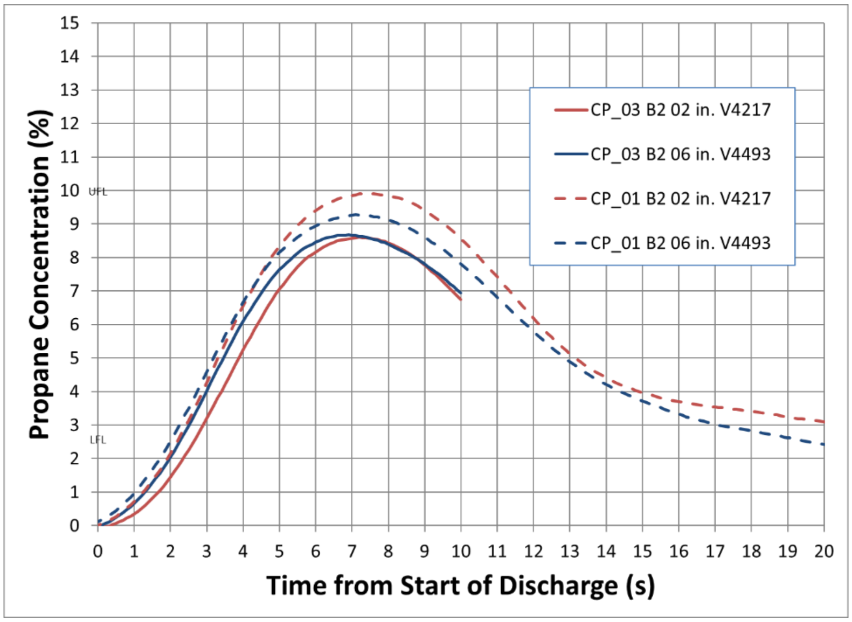


Figure 89 – CP_01 and CP_03 Concentration Comparison

Figure 90 shows the mass flow rate and total mass flow.

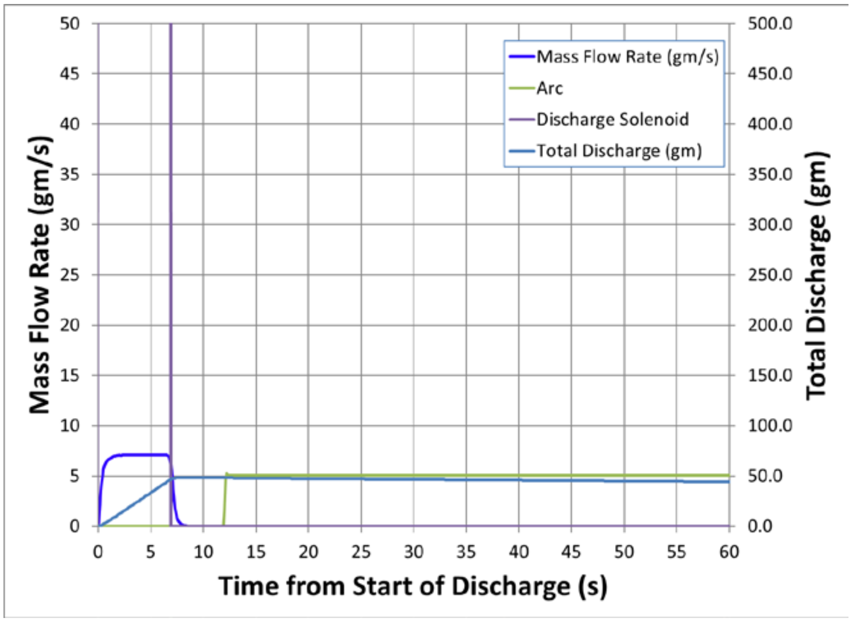


Figure 90 – CP_03 Mass Flow

Figure 91 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The drop in pressures after the discharge completed was due to a valve misalignment (not into the test room).

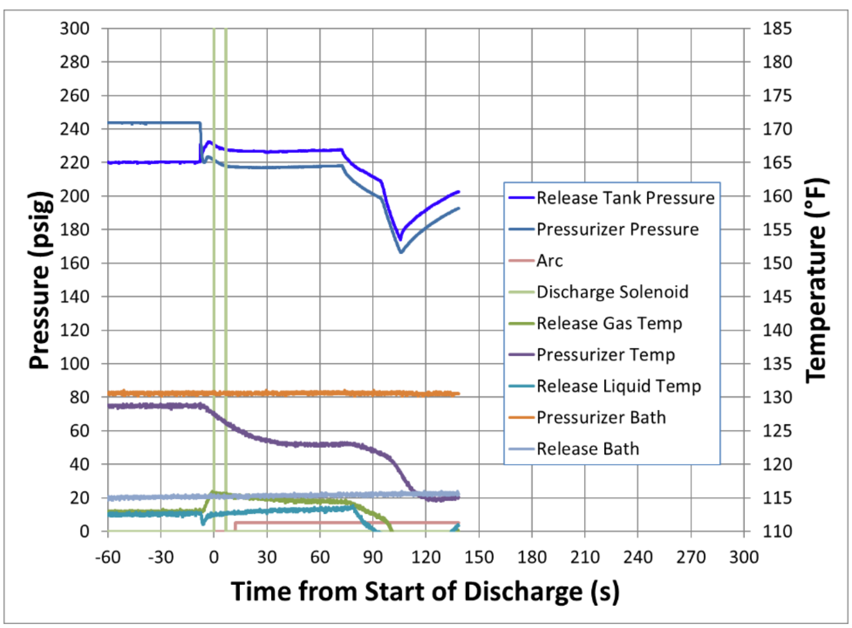


Figure 91 – CP_03 Pressurizer and Release Tank Pressure and Temperatures

Figure 92 shows the temperatures developed at the various locations following ignition. The delayed peak temperatures (after the arc was de-energized) are due to small pieces of burning, floating cheesecloth becoming attached to the thermocouple junction.

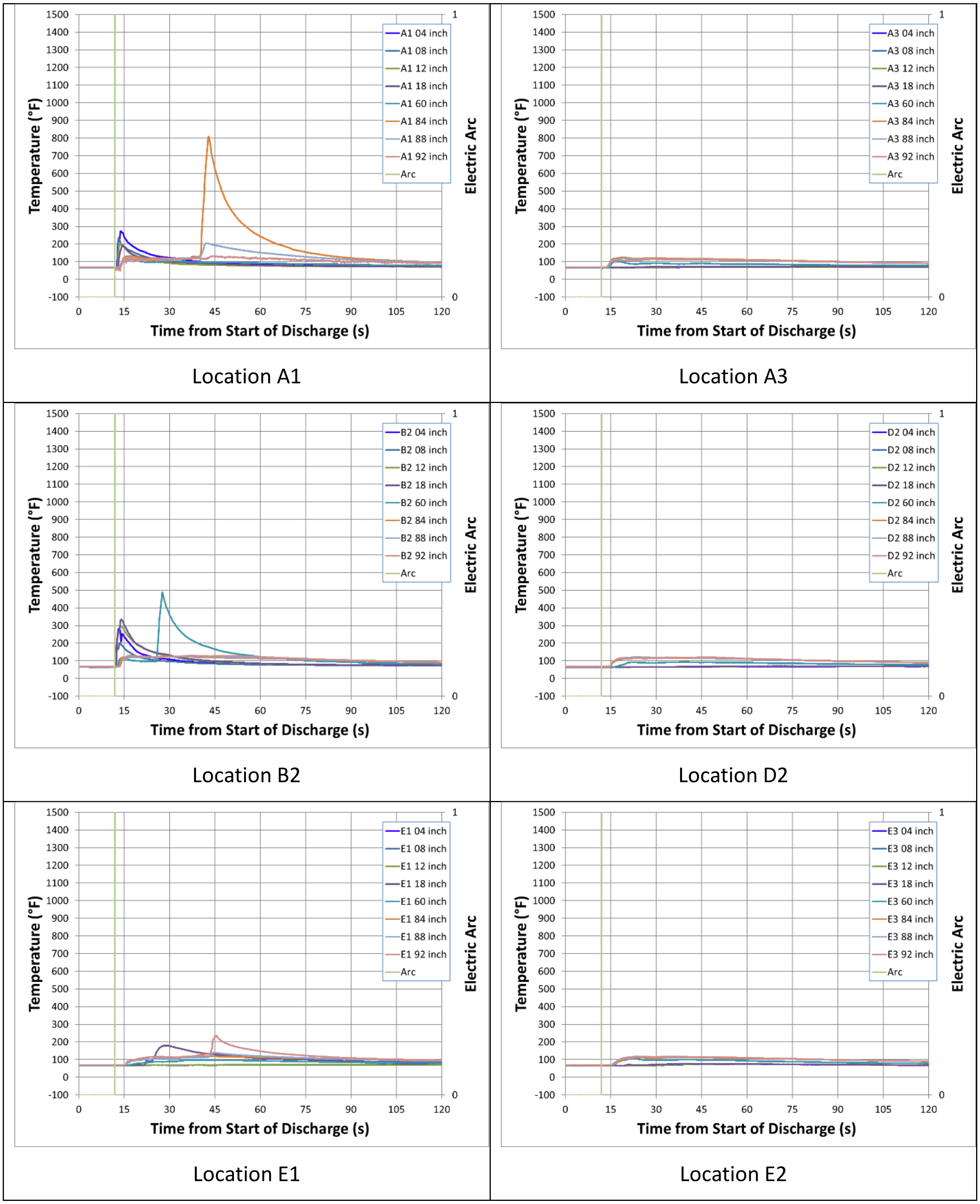


Figure 92 – CP_03 Temperatures at thermocouple trees

Figure 93 shows the temperatures recorded by the pool thermocouples. The data shows no cooling at any of the four thermocouples meaning that no liquid propane was detected in those locations.

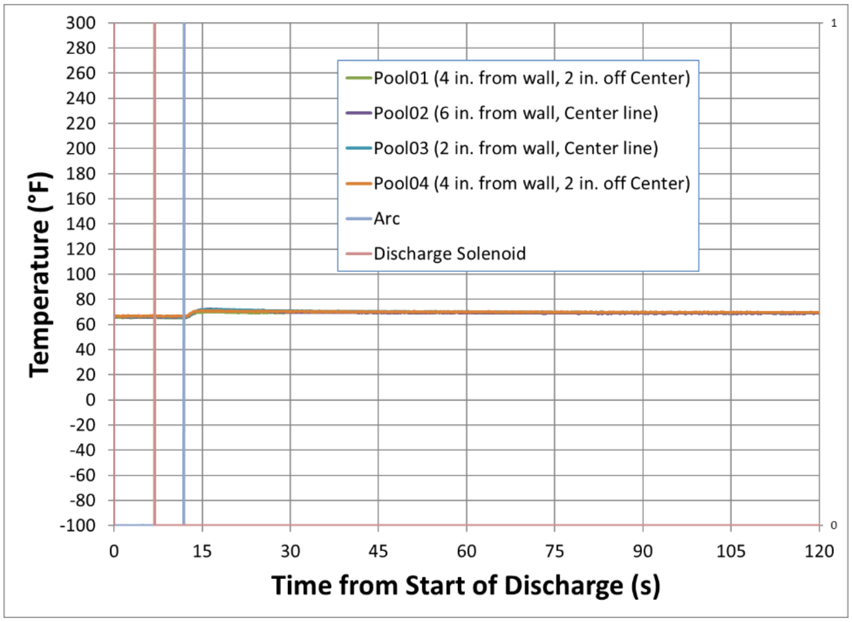


Figure 93 – CP_03 Liquid Propane Pool Temperatures

Figure 94 shows the heat flux measured at floor level at Location B2. This location is within 6 inches of the arc at the 1-inch level.

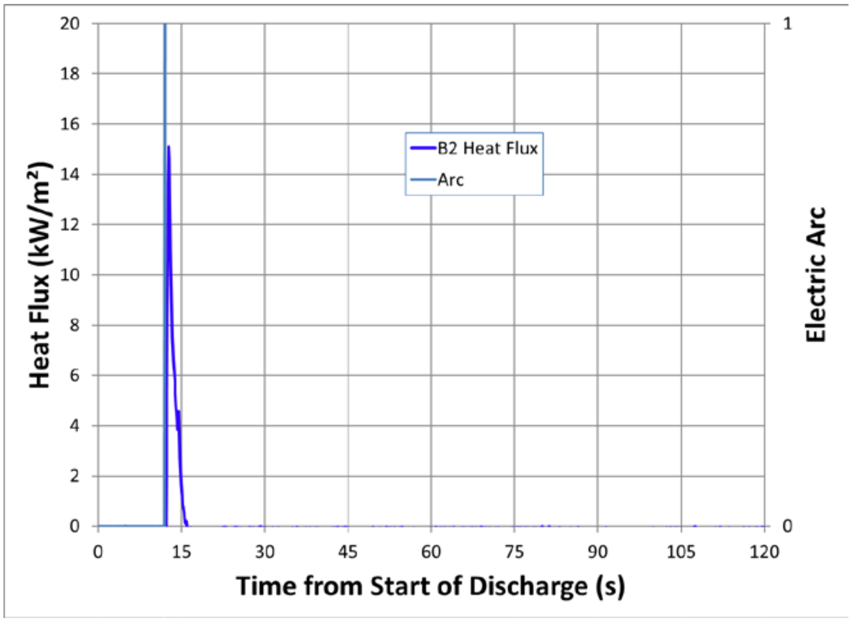


Figure 94 – CP_03 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 95. Ignition and burning were very faint in the camera view. Propane-air flames lasted for less than 1 second. Cheesecloth continued to burn after they were ignited.

Ignition	Maximum Spread of flame

Figure 95 – CP_03: Frames of flaming from videos

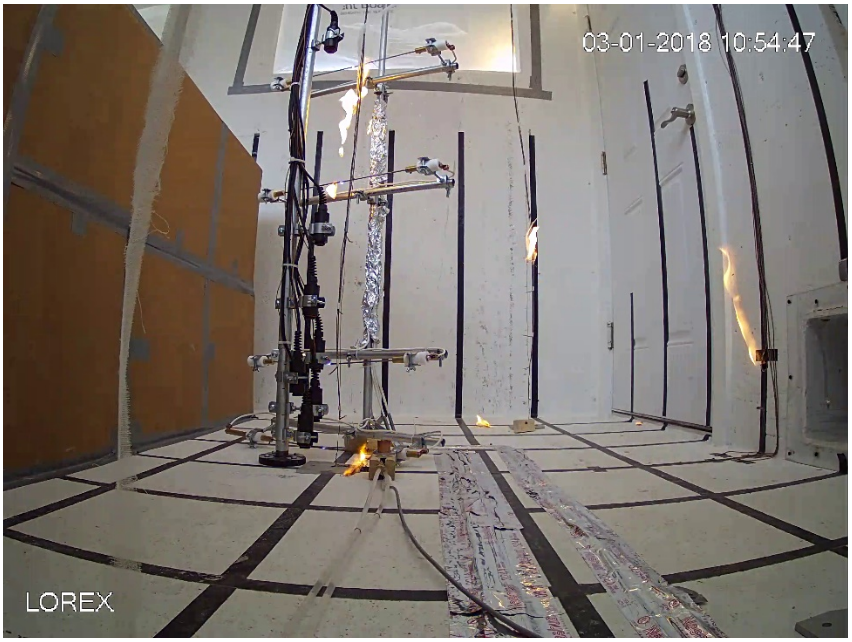


Figure 96 shows burning cheesecloth and a flame at the discharge tube. The solenoid was closed at the end of the discharge but some propane was still in the tube and continued to burn.

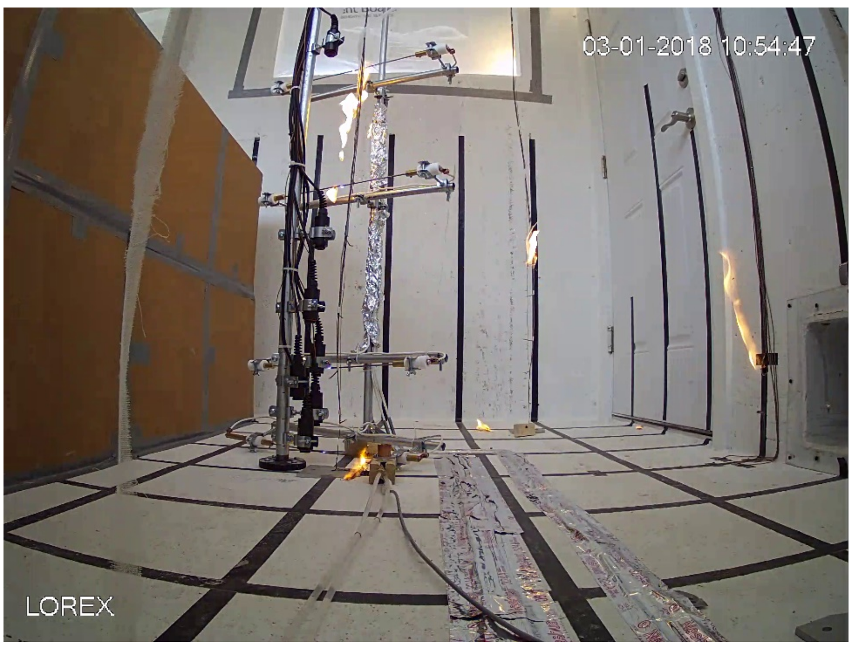


Figure 96 – CP_03: Cheesecloth and discharge tube flames

Test CP_04 (100 grams; 6.8 g/s; 0.2 height)

Test CP_04 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_06. This test involved release of 100 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the floor and 6 inch level. The discharge tube side of the obstruction also showed a flammable mixture at the 8 inch level. This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

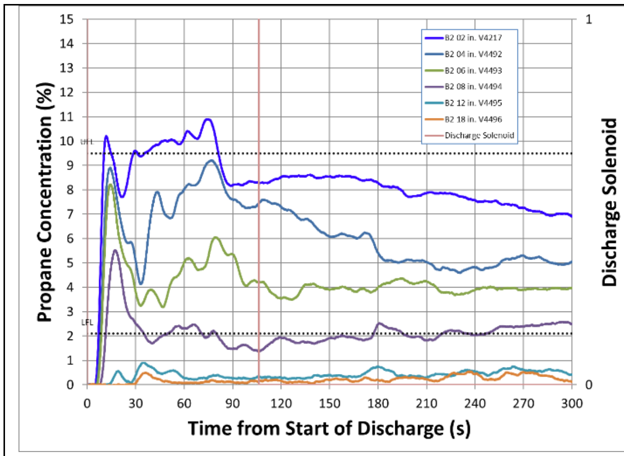
The discharge rate in this test was lower than specified. The test was repeated in test CP_05

Table 26 – CP_04 Summary

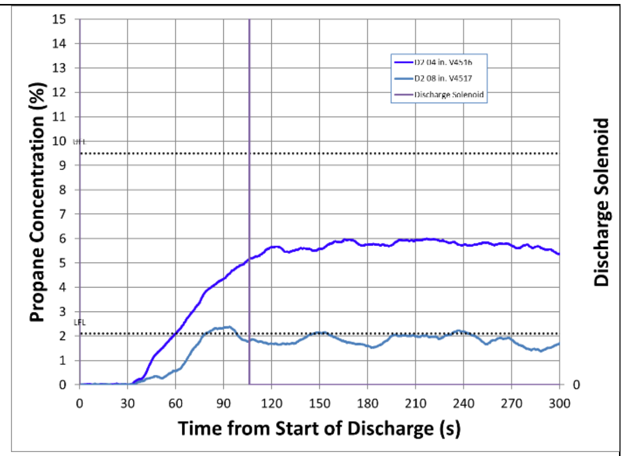
	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	100	14.7	6.8	0.2 m	0.25	Calculated if well Mixed in whole room
Measured	100	106	1.0		8.3 5.2	Location B2 2-inch Location D2 4-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

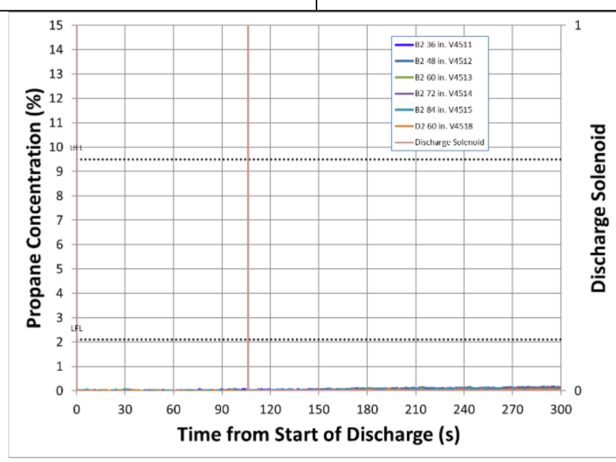
Figure 97 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. Sensors at location B2 8-inch level and lower showed concentrations above LFL of 2.1% to the end of data recording, but were slowly decreasing. The sensor at location D2 4-inch level showed concentration above LFL of 2.1%, while the 8-inch level was just below LFL. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 4-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 97 – CP_04 Concentrations

Figure 98 shows the mass flow rate and total mass flow. The control system did not establish the correct flow rate of 6.8 g/s. The average rate was 1 g/s. The test was repeated in CP_05.

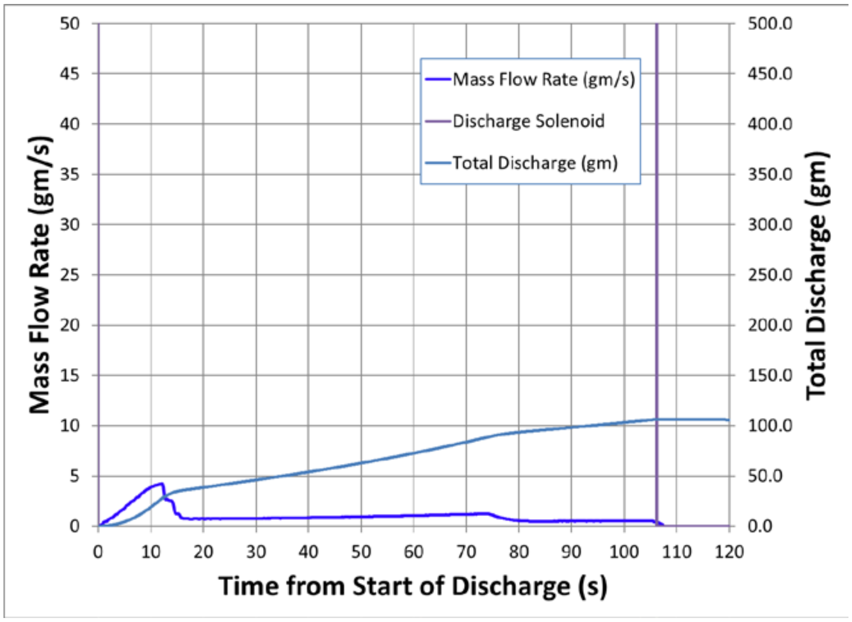


Figure 98 – CP_04 Mass Flow

Figure 99 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures. The pressurizer does not show this increase because the pressurizer was not isolated from the release tank until after data recording was completed.

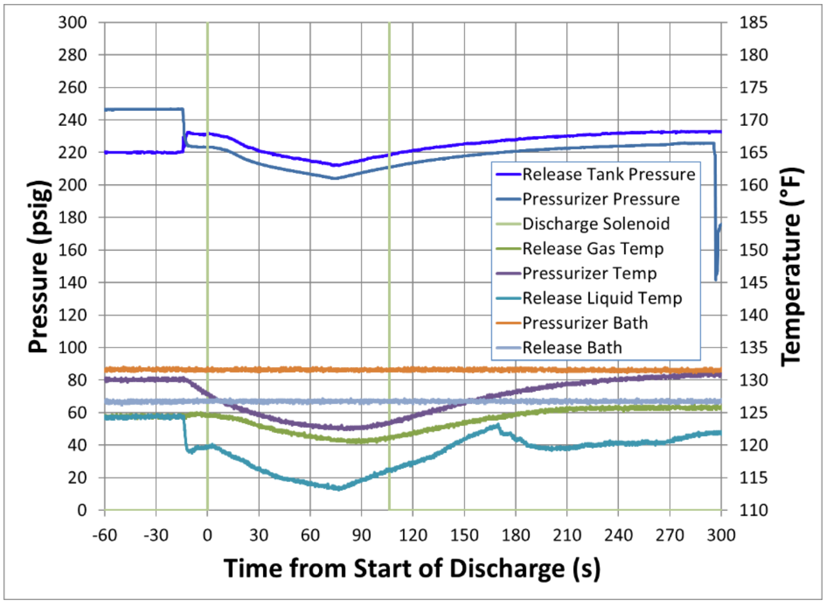


Figure 99 – CP_04 Pressurizer and Release Tank Pressure and Temperatures

Figure 100 shows the thermocouple response to potential liquid propane pooling on the floor in front of the discharge tube. There was no evidence of cooling at these thermocouples.

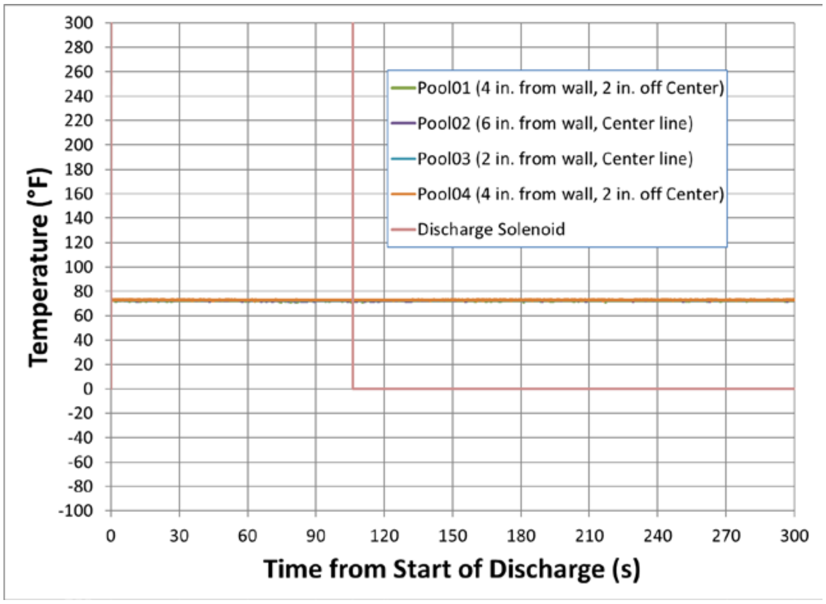


Figure 100 – CP_04 Liquid pooling at the floor

Test CP_05 (100 grams; 6.8 g/s; 0.2 height)

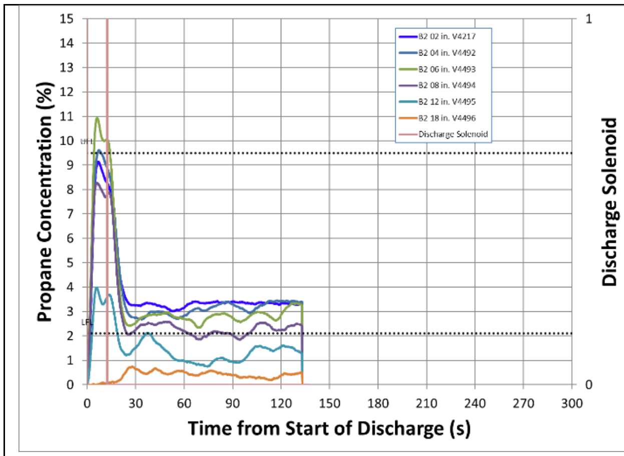
Test CP_05 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_06. This test involved release of 100 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the floor and 6 inch level. The discharge tube side of the obstruction also showed a flammable mixture at the 8 inch level. This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

Table 27 – CP_05 Summary

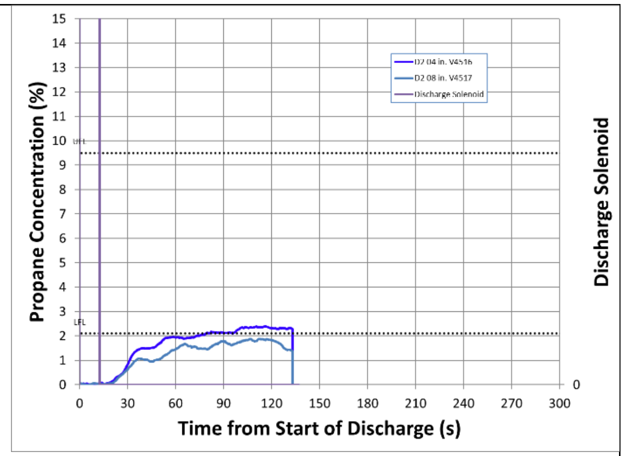
<table>
<tr><th></th><th>Discharge Amount (g)</th><th>Duration of Discharge (Seconds)</th><th>Discharge Rate (g/s)</th><th>Leak Location</th><th colspan="2">Concentration at Discharge Completion (%)</th></tr>
<tr><td>Planned</td><td>100</td><td>14.7</td><td>6.8</td><td rowspan="2">0.2 m</td><td>0.25</td><td>Calculated if well Mixed in whole room</td></tr>
<tr><td>Measured</td><td>98</td><td>12.5</td><td>7.8</td><td>10.9
2.4</td><td>Location B2 2-inch
Location D2 4-inch</td></tr>
</table>

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

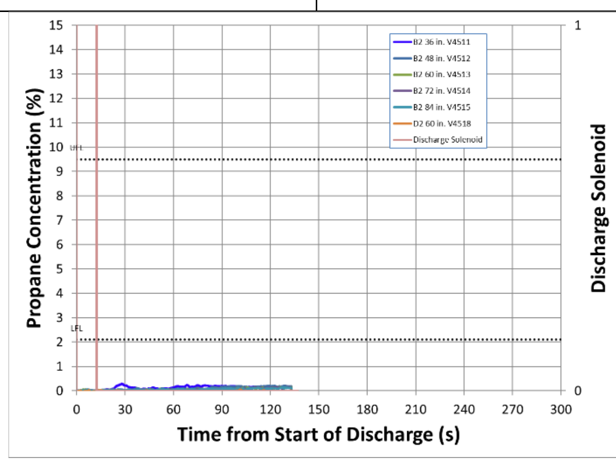
Figure 101 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. At the end of data recording, concentrations at location B2 8-inch level and lower showed levels above the LFL of 2.1%. Levels showed signs of a slow decrease. The sensor at location D2 4-inch level showed a concentration above LFL. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 4-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 101 – CP_05 Concentrations

Figure 102 compares the concentrations at the 4-inch level at location B2 and D2 for tests CP_04 and CP_05. The lower flow rate in CP_04 (1 g/s) resulted in less turbulent mixing resulting in uniformly higher concentrations than in test CP_05 (7.8 g/s).

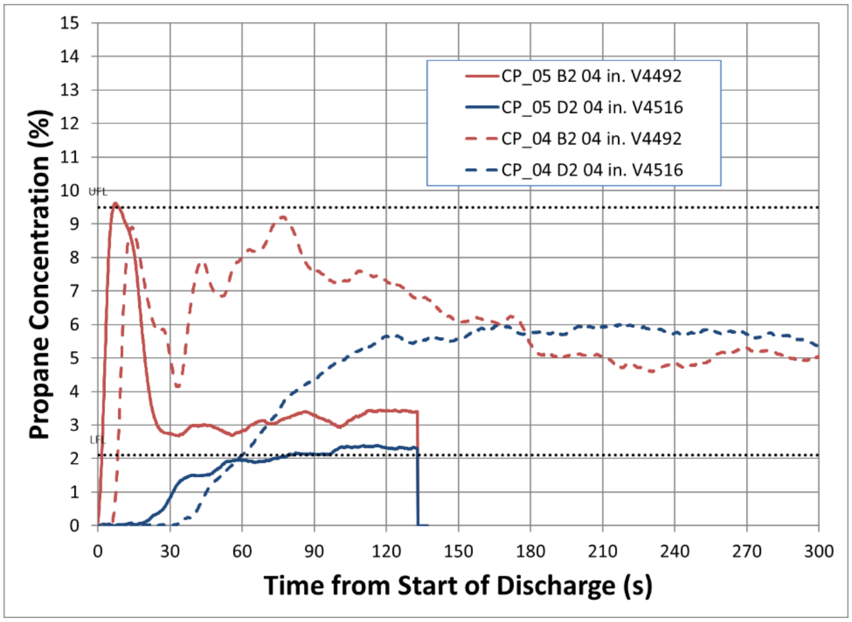


Figure 102 – Compare CP_05 and CP_04 4-inch level concentrations

Figure 103 shows the mass flow rate and total mass flow.

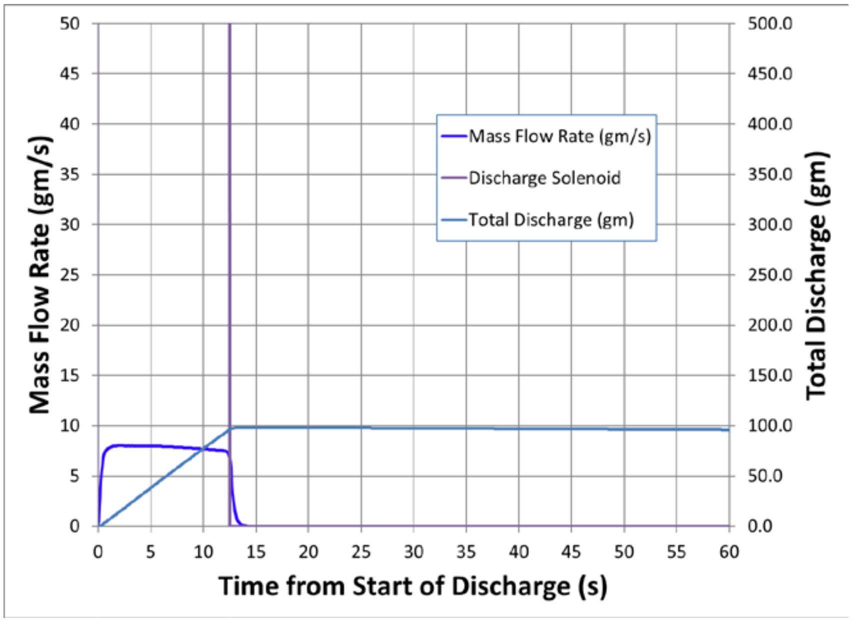


Figure 103 – CP_05 Mass Flow

Figure 104 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

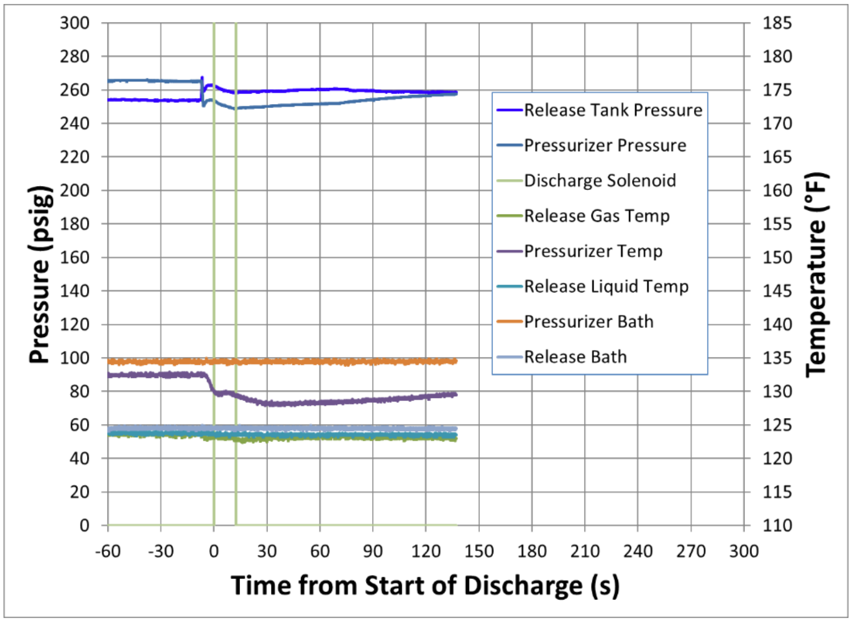


Figure 104 – CP_05 Pressurizer and Release Tank Pressure and Temperatures

Figure 105 shows the thermocouple response to potential liquid propane pooling on the floor in front of the discharge tube. There was a slight cooling after the discharge was completed, but appears to be a low-speed, cold vapor exiting the end of the discharge tube.

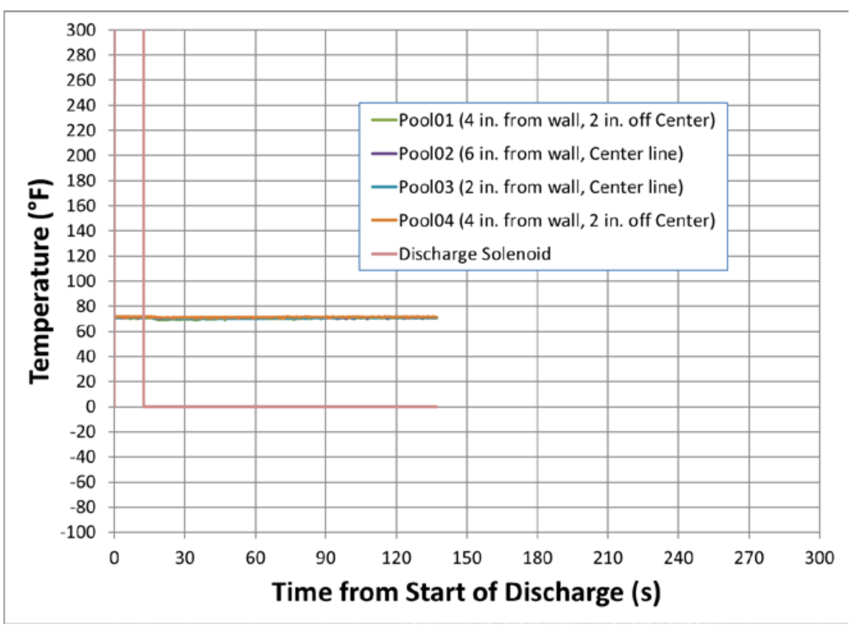


Figure 105 – CP_05 Liquid pooling at the floor

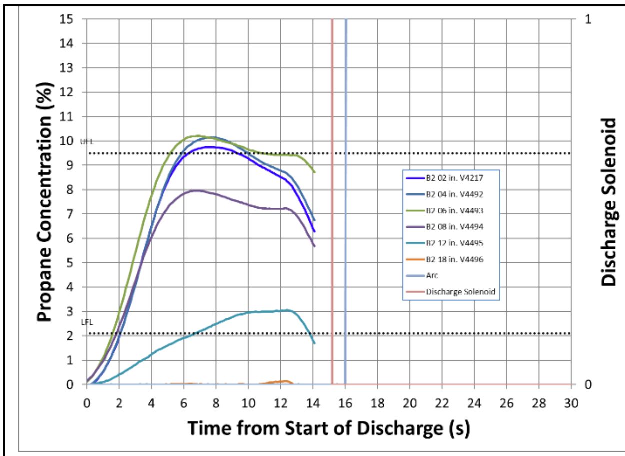
Test CP_06 (100 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_06 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_05 showed concentration at the 2-inch level was between the LFL and UFL.

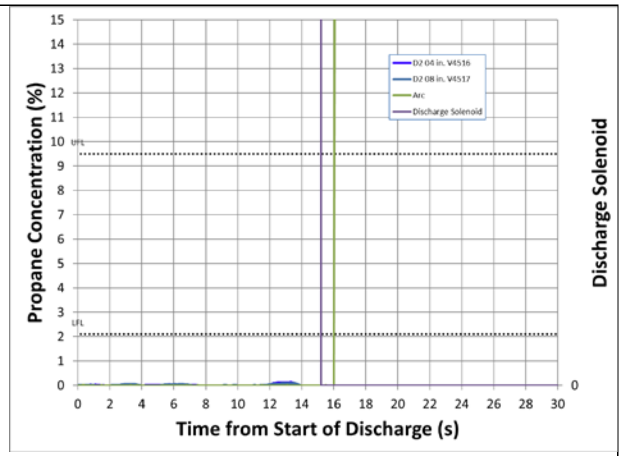
Table 28 – CP_06 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	100	12.5	6.8	0.2 m
Measured	97	15.1	6.4	

Figure 106 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration from the floor to the 12-inch level. At the time of ignition concentrations at location D2 were nearly zero.



Location B2 concentrations just prior to ignition



Location D2 concentrations just prior to ignition

Figure 106 – CP_06 Concentrations

Figure 107 compares the concentration and igniter test(CP_05 and CP_06) concentrations at the 2-inch and 6-inch levels at location B2. The highest concentrations at discharge completion were at the 6-inch level which was nearly directly in front of the discharge tube (8-inch or 0.2 m).

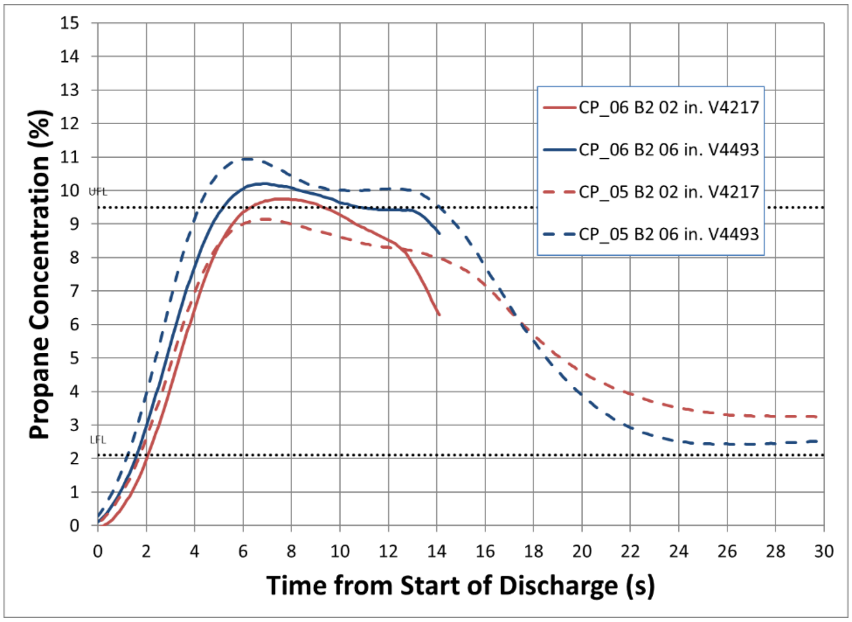


Figure 107 – CP_05 and CP_06 Concentration Comparison

Figure 108 shows the mass flow rate and total mass flow.

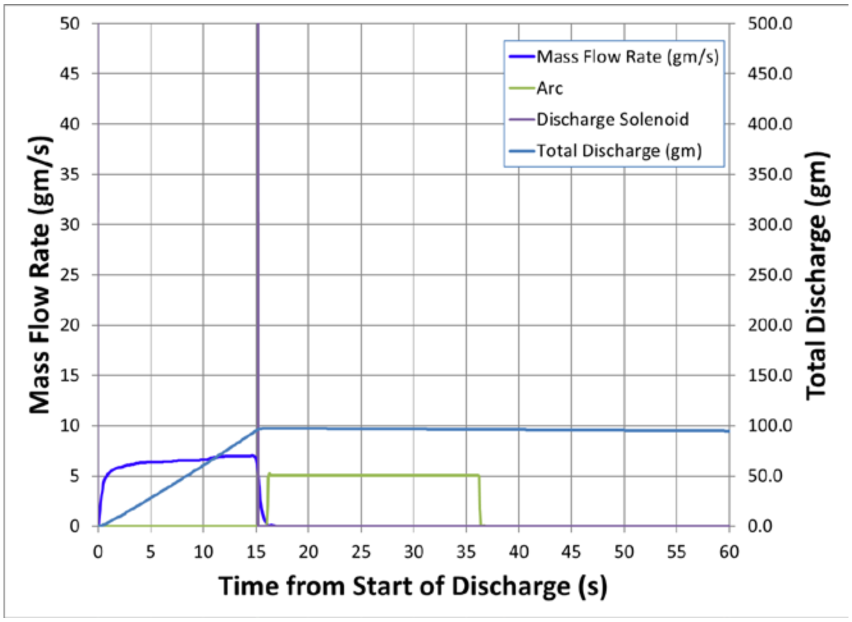


Figure 108 – CP_06 Mass Flow

Figure 109 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

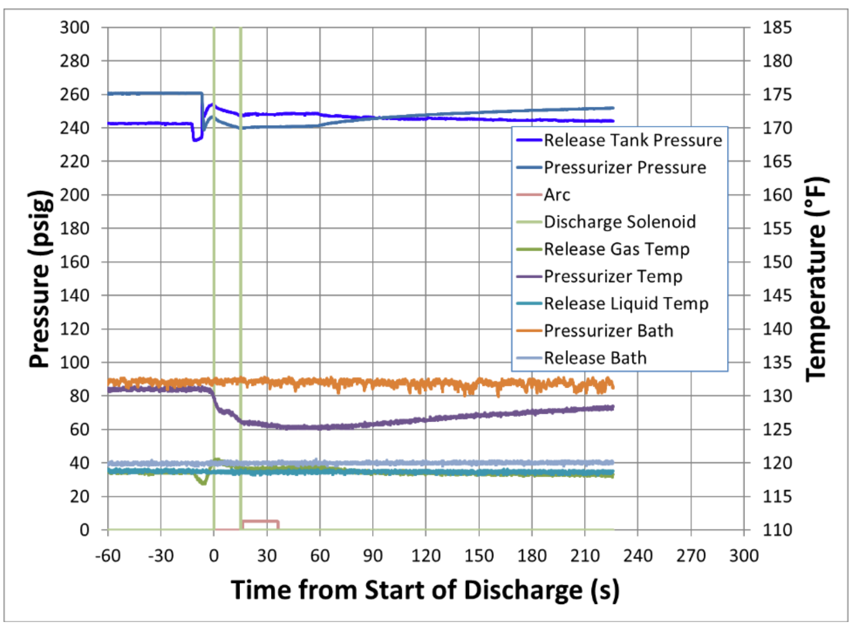


Figure 109 – CP_06 Pressurizer and Release Tank Pressure and Temperatures

Figure 110 shows the temperatures developed at the various locations following ignition.

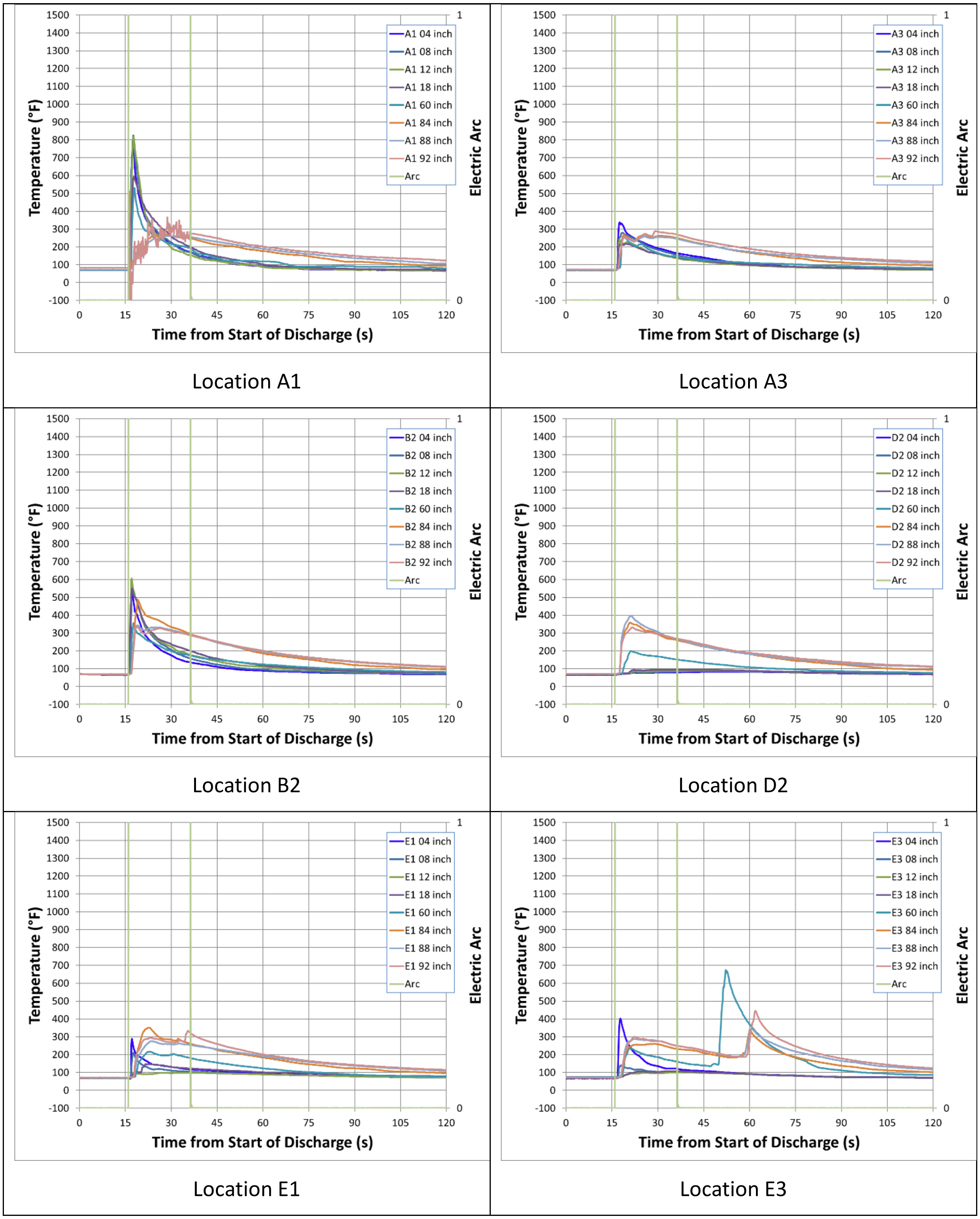


Figure 110 – CP_06 Temperatures at thermocouple trees

Notes to Figure 110:

- Location A1 92-inch level thermocouple was erratic. This thermocouple was replaced in later tests.
- Location E1 and E3 secondary temperature peaks were due to cheesecloth strips burning and attached to the thermocouple tree.

Figure 111 shows the temperatures recorded by the pool thermocouples. There was no indication of the formation of a pool of liquid propane.

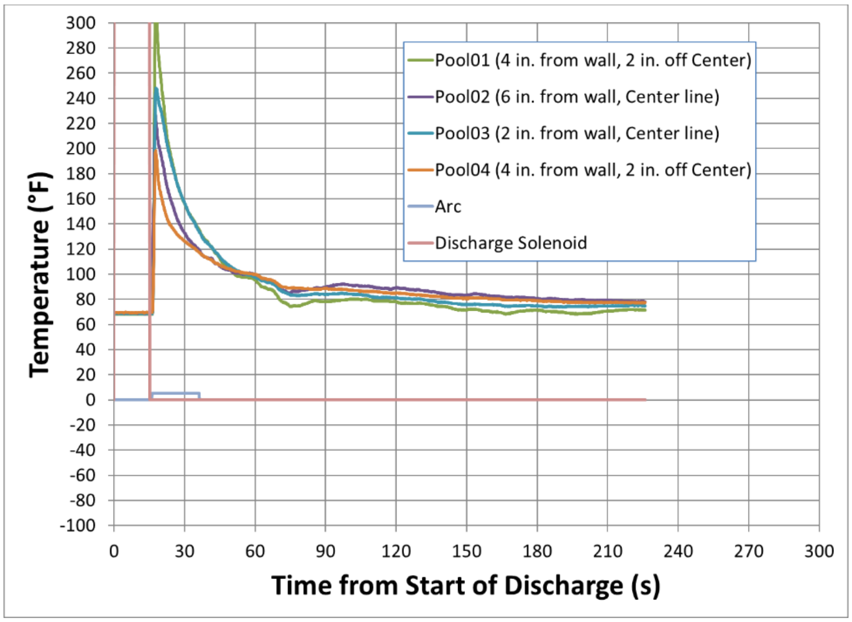


Figure 111 – CP_06 Liquid Propane Pool Temperatures

Figure 112 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 73 kW/m² exceeds the calibrated range of this heat flux sensor (0-50 kW/m²).

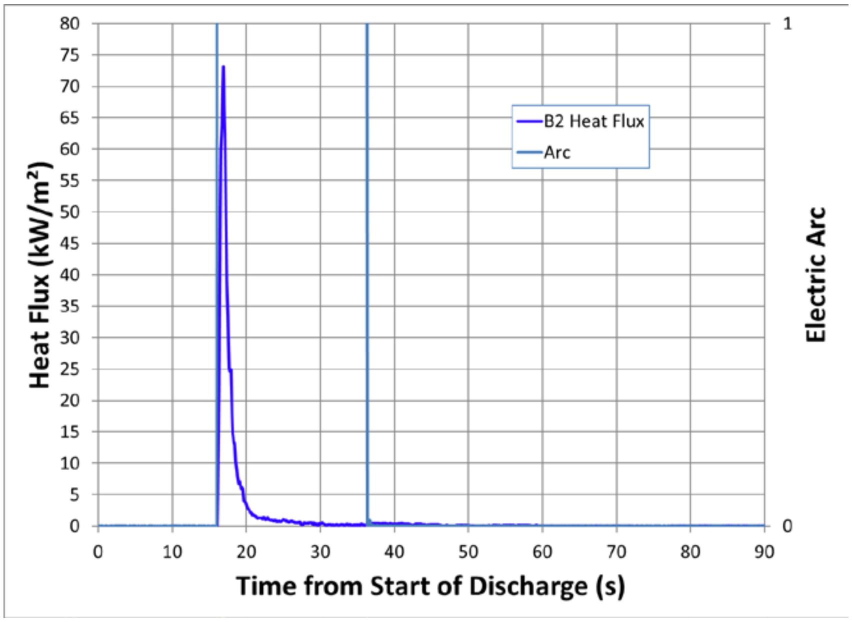
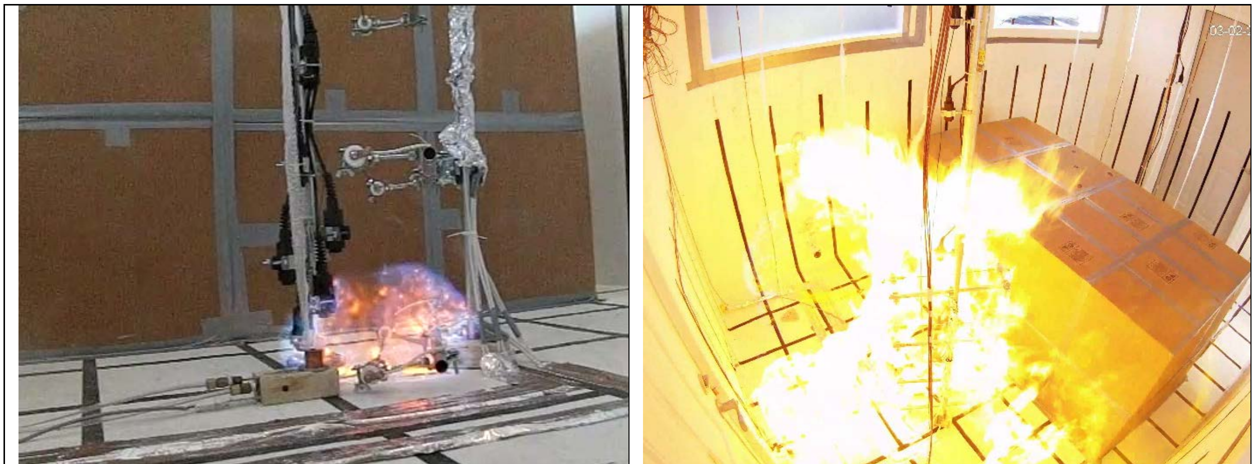


Figure 112 – CP_06 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 113. The ignition initially had the appearance of a pre-mixed flame, but quickly transitioned into a diffusion flame. Two deflagration vents were burst and one melted due to hot gases.



Ignition at the 1-inch level	Estimated maximum extent of propane-air flaming.

Figure 113 – CP_06: Frames of flaming from videos

Test CP_07 (150 grams; 6.8 g/s; 0.2 height)

Test CP_07 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_08. This test involved release of 150 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the floor and the 8-inch level. The discharge tube side of the obstruction also showed a flammable mixture at the 12-inch level. This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

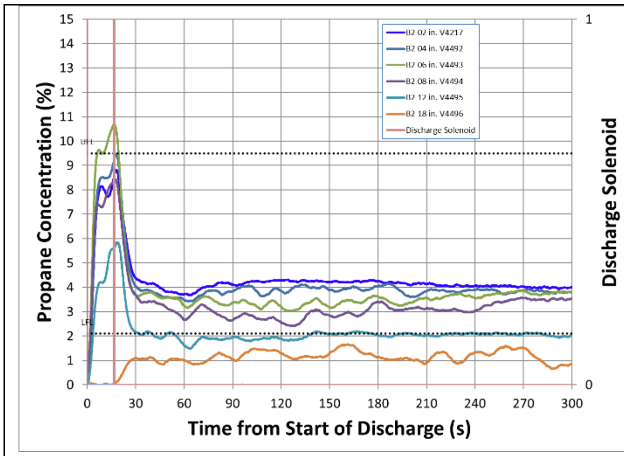
Table 29 – CP_07 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	150	22.0	6.8	0.2 m	0.38	Calculated if well Mixed in whole room
Measured	148	16.7	8.8		10.7 3.0	Location B2 2-inch Location D2 4-inch

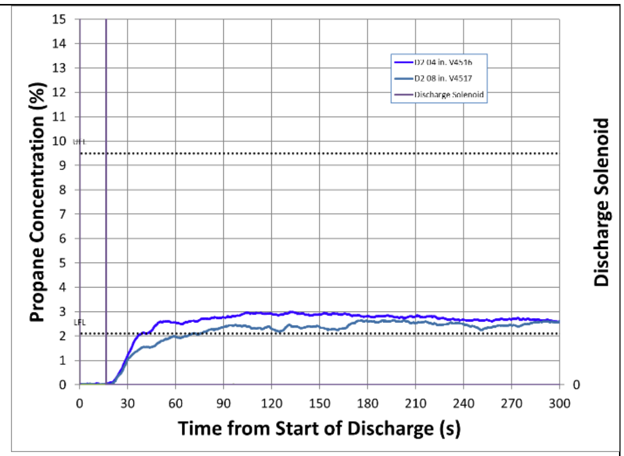
Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 114 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. At the end of data recording, concentrations at location B2 12-inch level and lower showed levels above the LFL of 2.1%. Levels showed signs of a slow decrease. The sensors at location D2 4-inch and 8-inch levels showed a concentration above LFL. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.

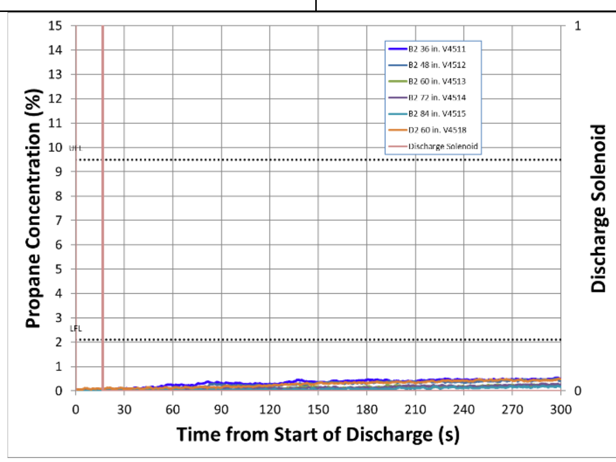
Immediately after completion of the discharge the concentration at location B2 2-inch level was above the upper flammability limit (UFL) of 9.5%.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 4-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 114 – CP_07 Concentrations

Figure 115 shows the mass flow rate and total mass flow.

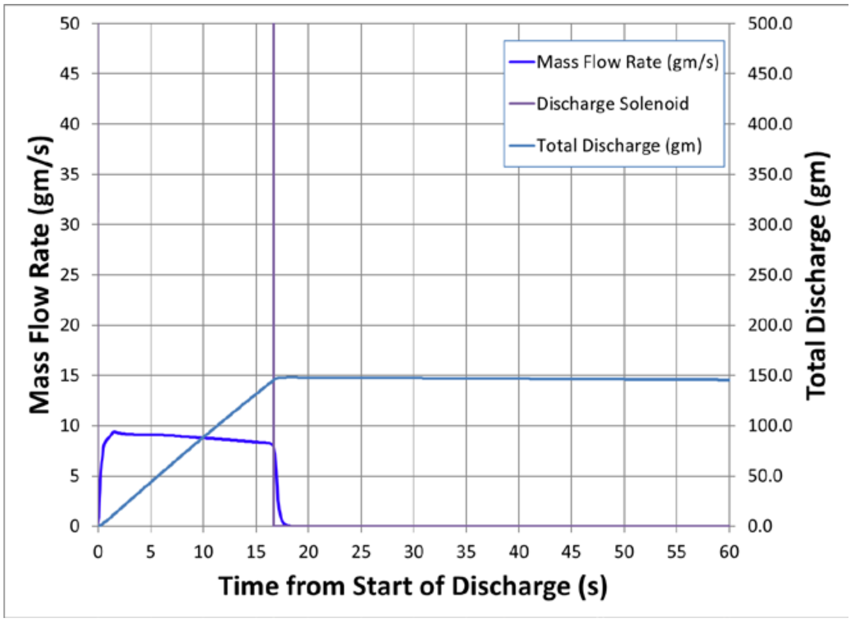


Figure 115 – CP_07 Mass Flow

Figure 116 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

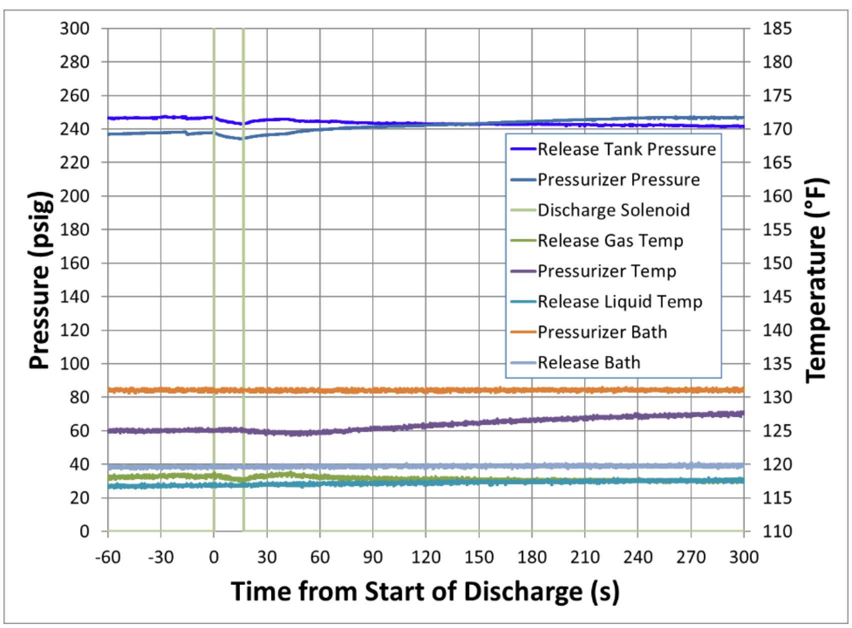


Figure 116 – CP_07 Pressurizer and Release Tank Pressure and Temperatures

Figure 117 shows the thermocouple response to potential liquid propane pooling on the floor in front of the discharge tube. There was a slight cooling after the discharge was completed, but appears to be a low-speed, cold vapor exiting the end of the discharge tube.

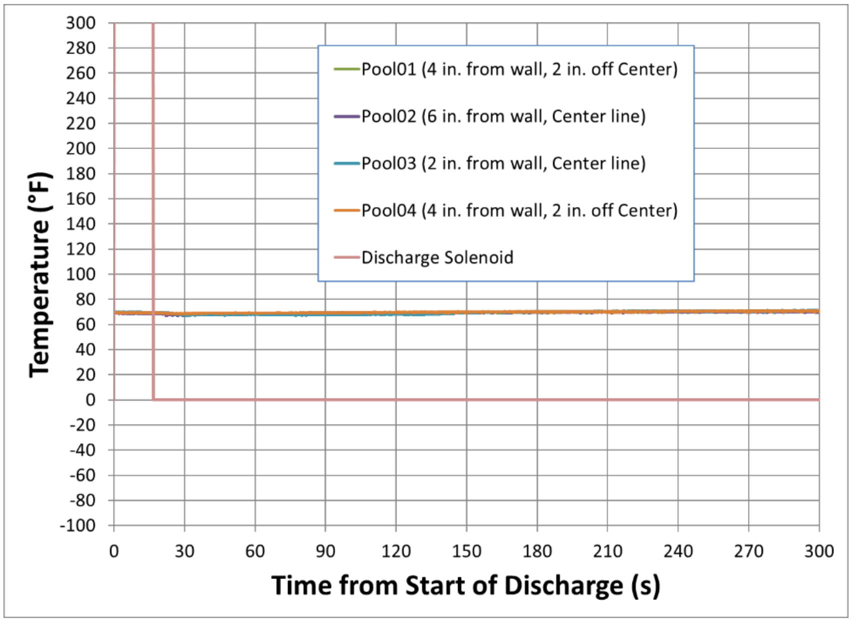


Figure 117 – CP_07 Liquid pooling at the floor

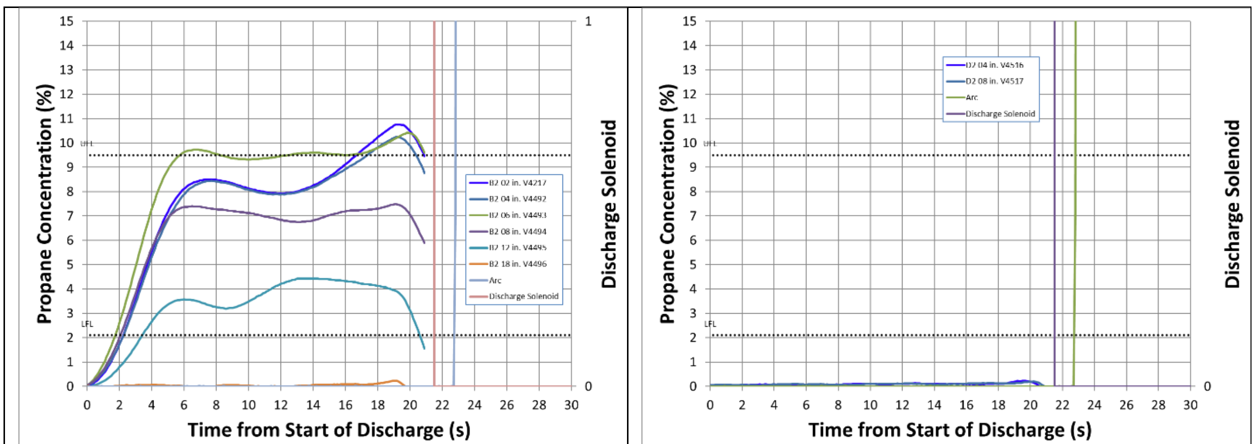
Test CP_08 (150 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_08 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_07 showed concentration at the 2-inch level was close to the UFL for propane (9.5%). The propane-air mixture ignited at the 1-inch level with a blue (pre-mixed) flame which quickly expanded and change to a diffusion flame. The propane-air mixture flaming lasted 2 seconds.

Table 30 – CP_08 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	150	22.0	6.8	0.2 m
Measured	150	21.4	7.0	

Figure 118 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration from the floor level to the 8-inch level.



Location B2 concentrations just prior to ignition | Location D2 concentrations just prior to ignition

Figure 118 – CP_08 Concentrations

Figure 119 compares the concentration and igniter test(CP_07 and CP_08) concentrations at the 2-inch and 6-inch levels at location B2. The highest concentrations at discharge completion were at the 6-inch level which was nearly directly in front of the discharge tube (8-inch or 0.2 m).

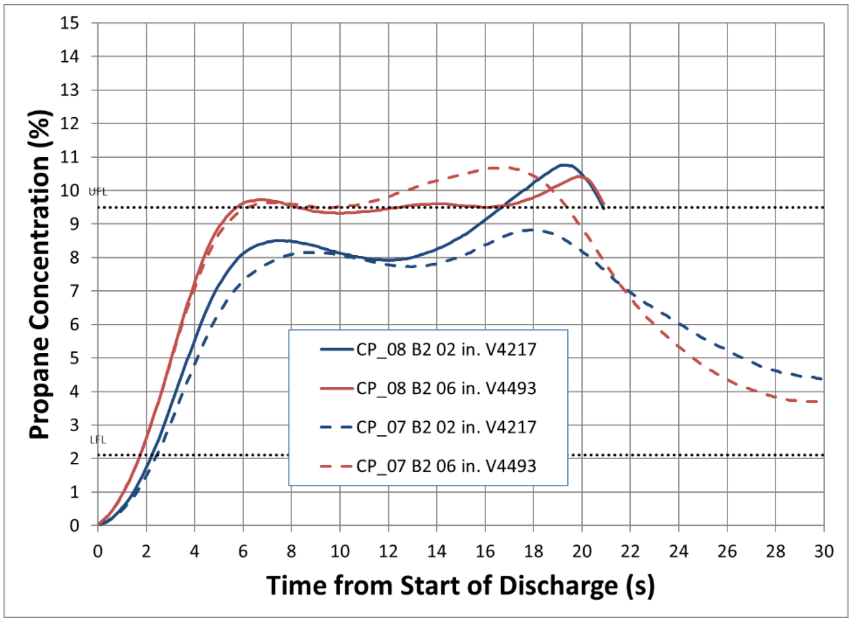


Figure 119 – CP_07 and CP_08 Concentration Comparison

Figure 120 shows the mass flow rate and total mass flow.

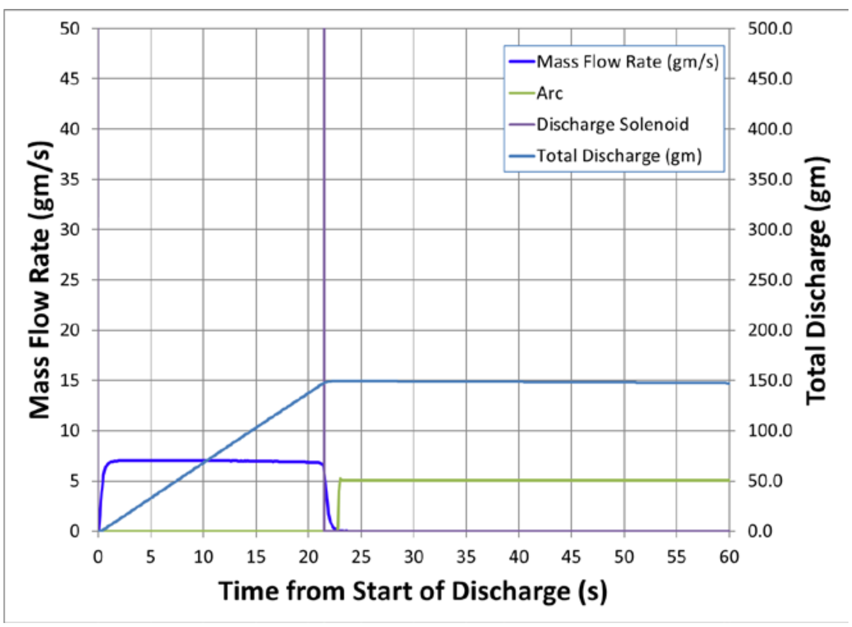


Figure 120 – CP_08 Mass Flow

Figure 121 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

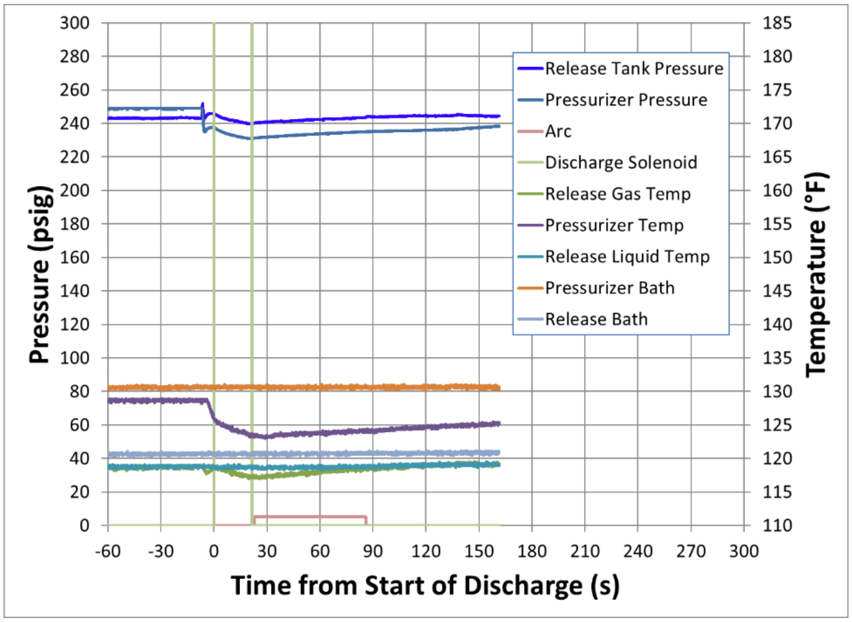


Figure 121 – CP_08 Pressurizer and Release Tank Pressure and Temperatures

Figure 122 shows the temperatures developed at the various locations following ignition.

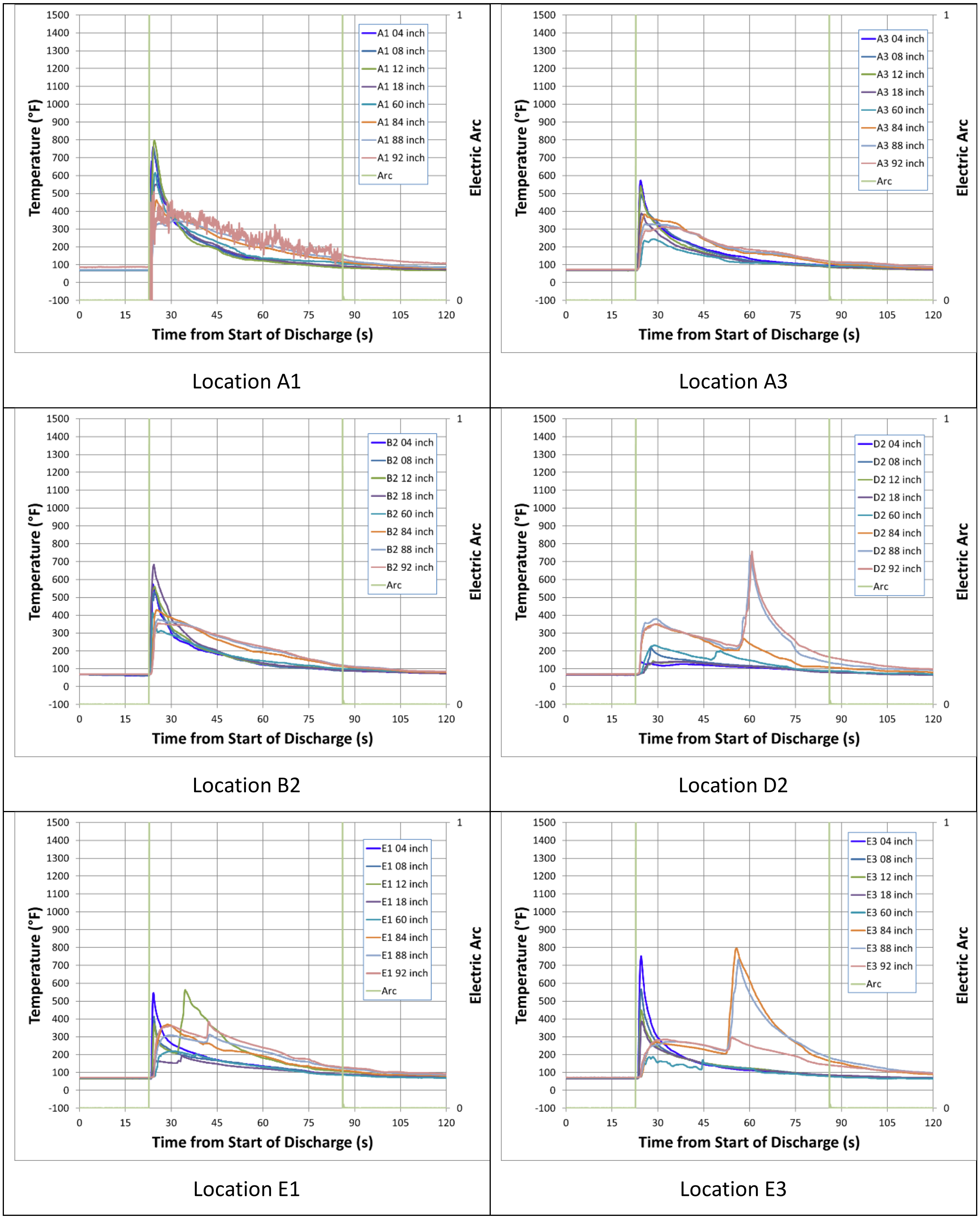


Figure 122 – CP_08 Temperatures at thermocouple trees

Notes to Figure 122:

- Location A1 92-inch level thermocouple was erratic. This thermocouple was replaced in later tests.
- Locations D2, E1, and E3 show some delayed peaks in temperature. These are due to bits of flaming cheesecloth that were burning near or on the thermocouple bead.
- All locations show a more rounded approach to peak temperatures at the 60-inch to ceiling levels due to the buoyancy of the gases ignited at the floor level.

Figure 123 shows the temperatures recorded by the pool thermocouples. There was no cooling effect observed during the discharge. No evidence of liquid propane was observed.

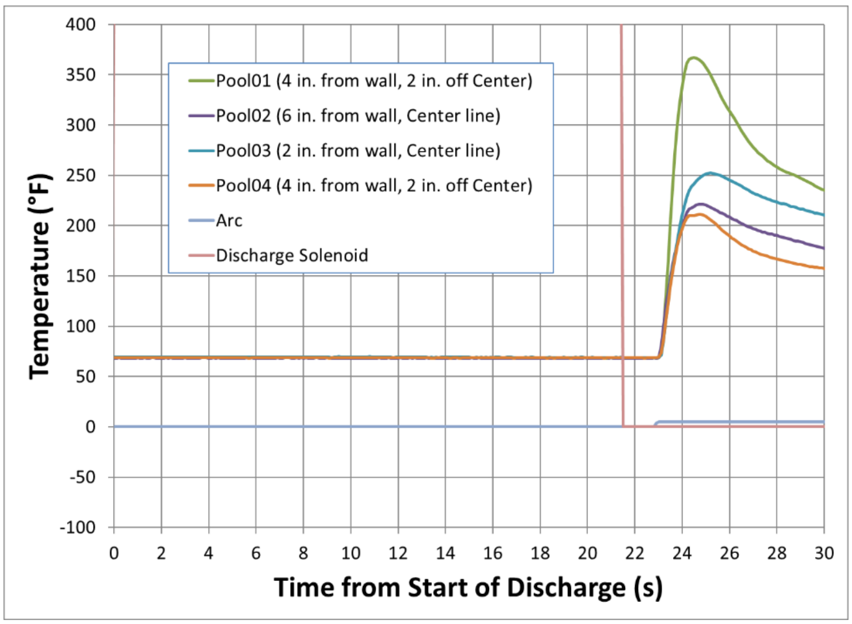


Figure 123 – CP_08 Liquid Propane Pool Temperatures

Figure 124 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 85 kW/m^2 exceeds the calibrated range of this heat flux sensor (0-50 kW/m^2).

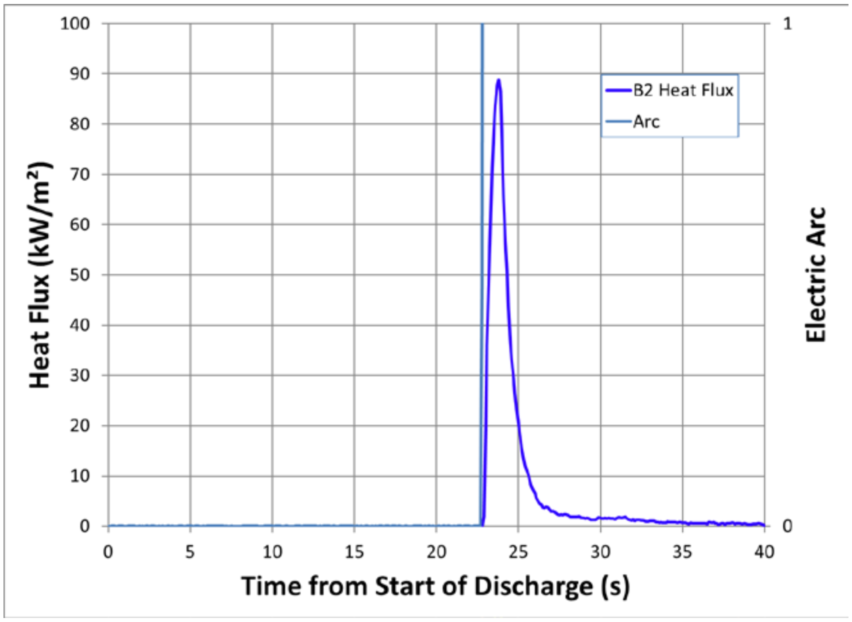
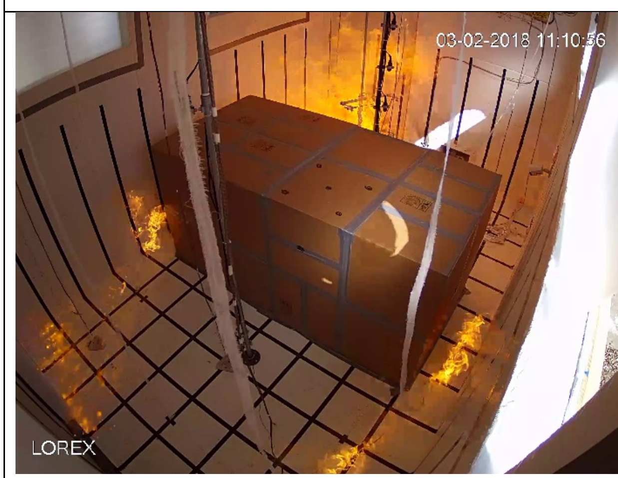


Figure 124 – CP_08 Heat Flux at Location B2, Floor Level

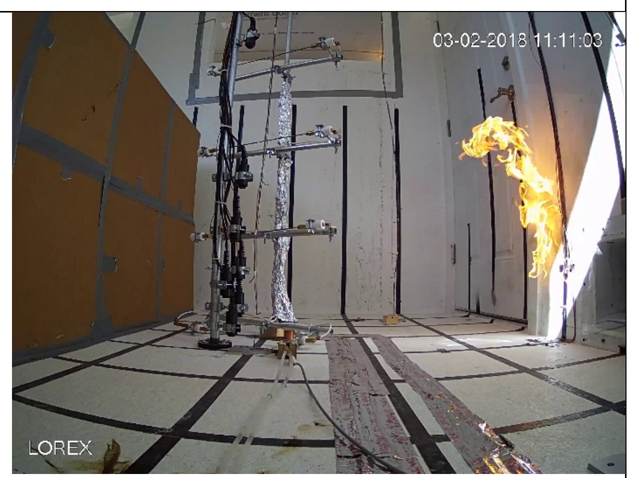
Selected frames from the videos are shown in Figure 125. Ignition first appeared as a pre-mixed (blue) flame at the 1-inch level. This flame transitioned to a diffusion flame. The flames continued to the opposite side of the obstruction to ignition the flammable layer at the floor level. Burning of these air mixtures stopped after 2 seconds. Propane continued flaming at the discharge due to the propane vapor trapped in the tube after the discharge solenoid valve had closed.

Ignition at the 1-inch level

Estimated maximum extent of propane-air flaming.



Flaming extended around the obstruction to the flammable layer at floor level



Flames continued at discharge tube due to trapped propane in the tubing.

Figure 125 – CP_08: Frames of flaming from videos

At the time of ignition, three deflagration vents burst with some flames extending out from the west side vents as shown in Figure 126. The last vent was melted open by the hot gases.

Figure 126 – CP_08 Flame extension through the west side vent

Test CP_09 (200 grams; 6.8 g/s; 0.2 height)

Test CP_09 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_10. This test involved release of 200 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the floor and the 8-inch level. This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

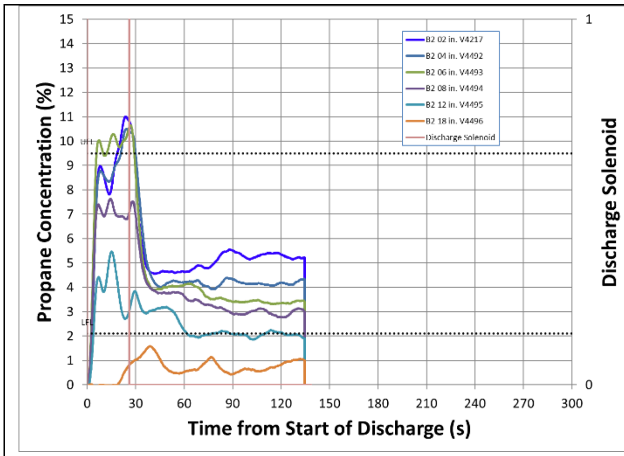
Table 31 – CP_09 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	200	29.4	6.8	0.2 m	0.51	Calculated if well Mixed in whole room
Measured	198	26.1	7.6		11.0 4.0	Location B2 2-inch Location D2 4-inch

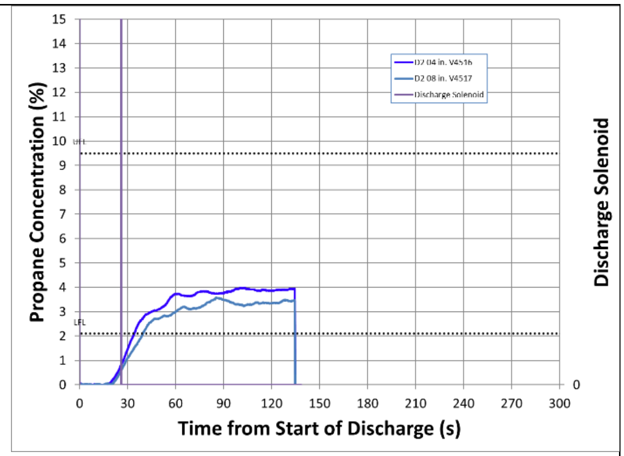
Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 127 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. At the end of data recording, concentrations at location B2 12-inch level and lower showed levels above the LFL of 2.1%. Levels showed signs of a slow decrease. The sensors at location D2 4-inch and 8-inch levels showed a concentration above LFL. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.

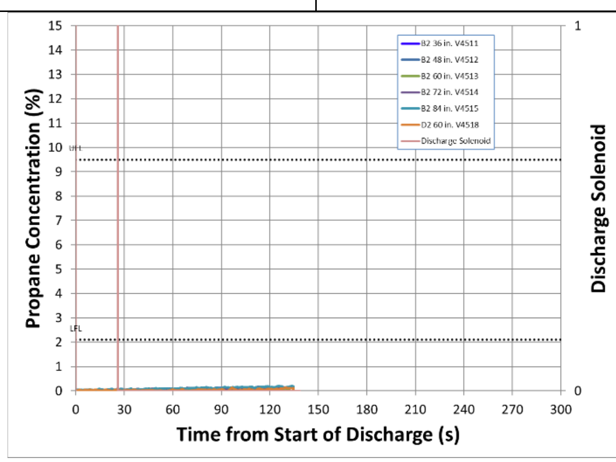
Immediately after completion of the discharge the concentration at location B2 2-, 4- and 6-inch levels was above the upper flammability limit (UFL) of 9.5%.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 4-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 127 – CP_09 Concentrations

Figure 128 shows the mass flow rate and total mass flow.

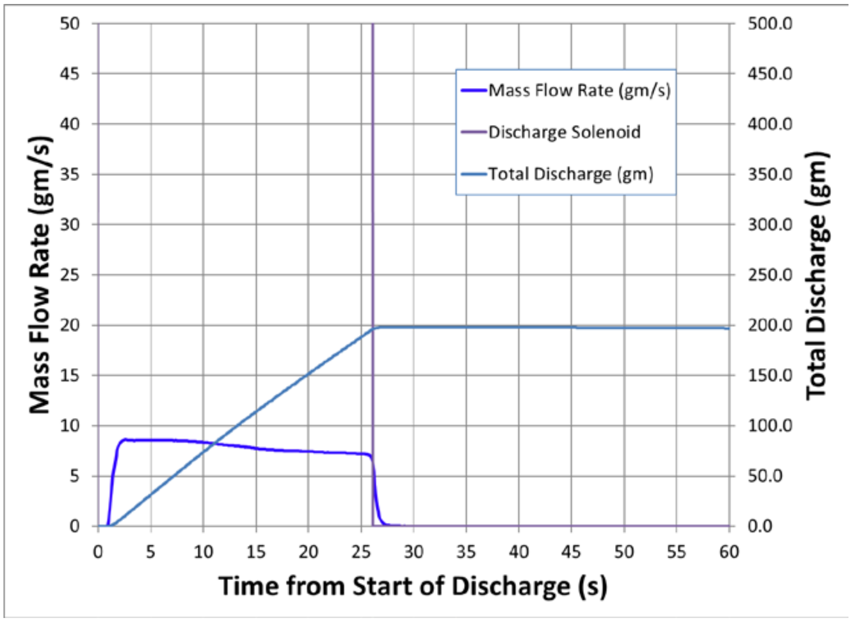


Figure 128 – CP_09 Mass Flow

Figure 129 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

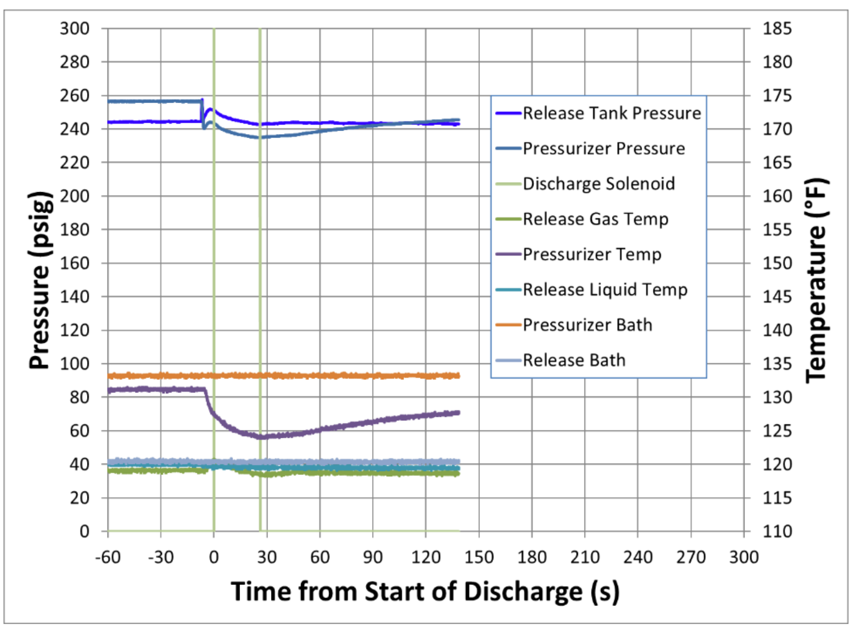


Figure 129 – CP_09 Pressurizer and Release Tank Pressure and Temperatures

Figure 130 shows the thermocouple response to potential liquid propane pooling on the floor in front of the discharge tube. There was a slight cooling after the discharge was completed, but appears to be a low-speed, cold vapor exiting the end of the discharge tube.

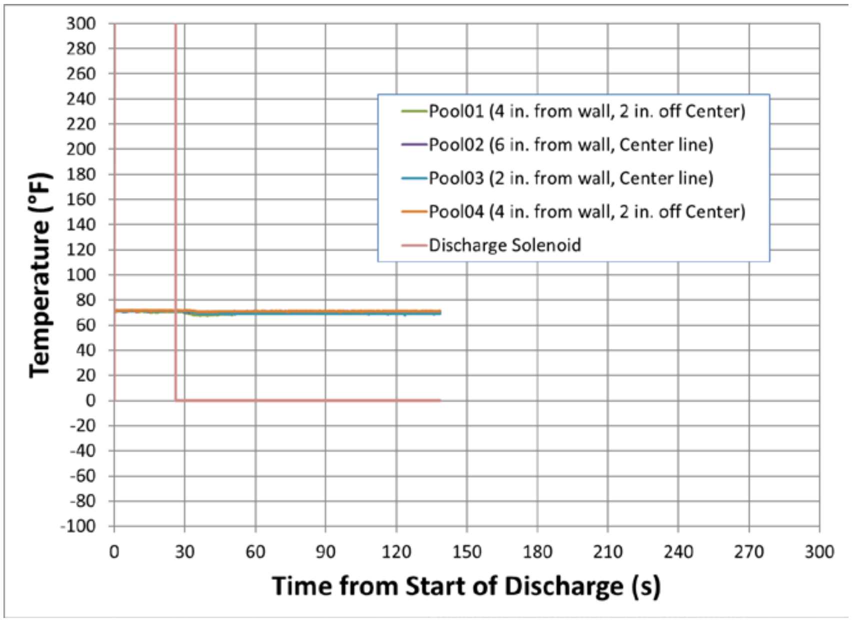


Figure 130 – CP_09 Liquid pooling at the floor

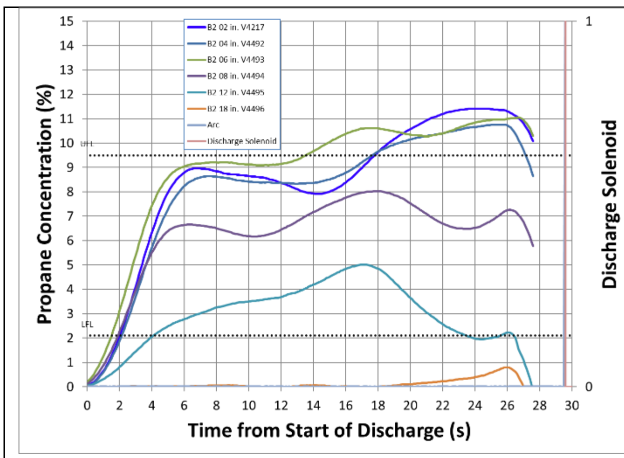
Test CP_10 (200 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_10 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_09 showed concentration at the 2-inch level was close to the UFL for propane (9.5%). The propane-air mixture ignited at the 1-inch level with a blue (pre-mixed) flame which quickly expanded and changed to a diffusion flame. The propane-air mixture flaming lasted 2 seconds.

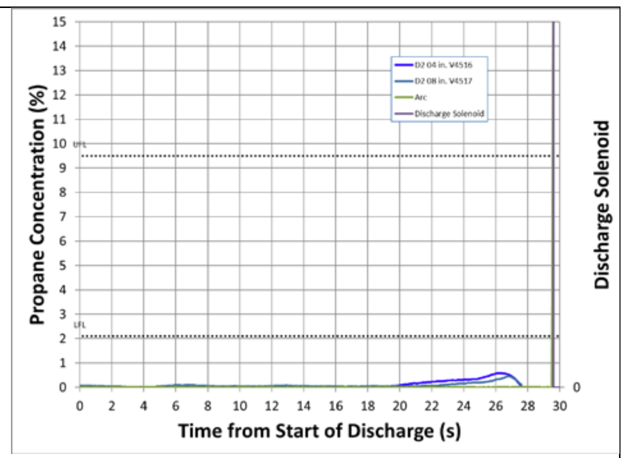
Table 32 – CP_10 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	200	29.4	6.8	0.2 m
Measured	198	29.5	6.7	

Figure 131 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration from the floor level to the 8-inch level.



Location B2 concentrations just prior to ignition



Location D2 concentrations just prior to ignition

Figure 131 – CP_10 Concentrations

Figure 132 compares the concentration and igniter test(CP_09 and CP_10) concentrations at the 2-inch and 8-inch levels at location B2. The highest concentrations at discharge completion were at the 2-inch level.

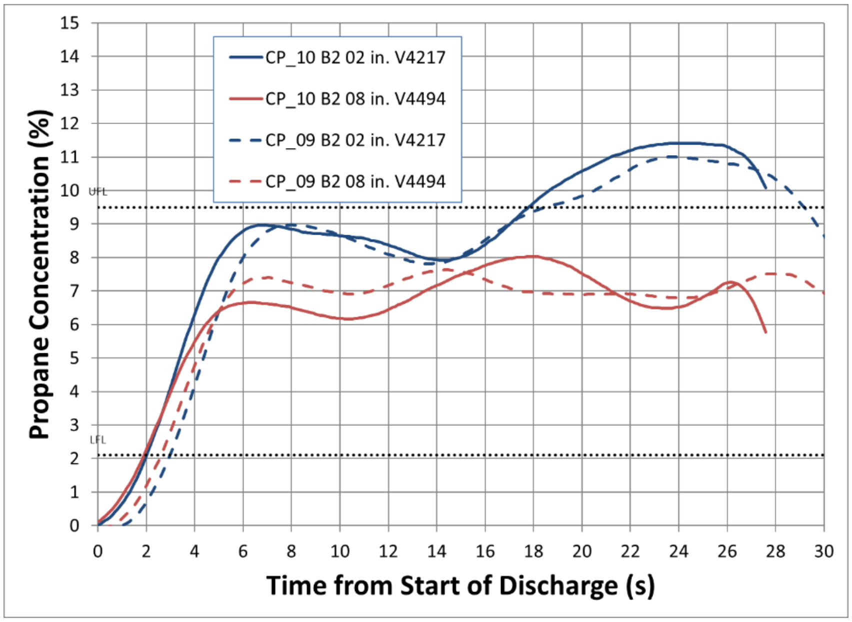


Figure 132 – CP_09 and CP_10 Concentration Comparison

Figure 133 shows the mass flow rate and total mass flow.

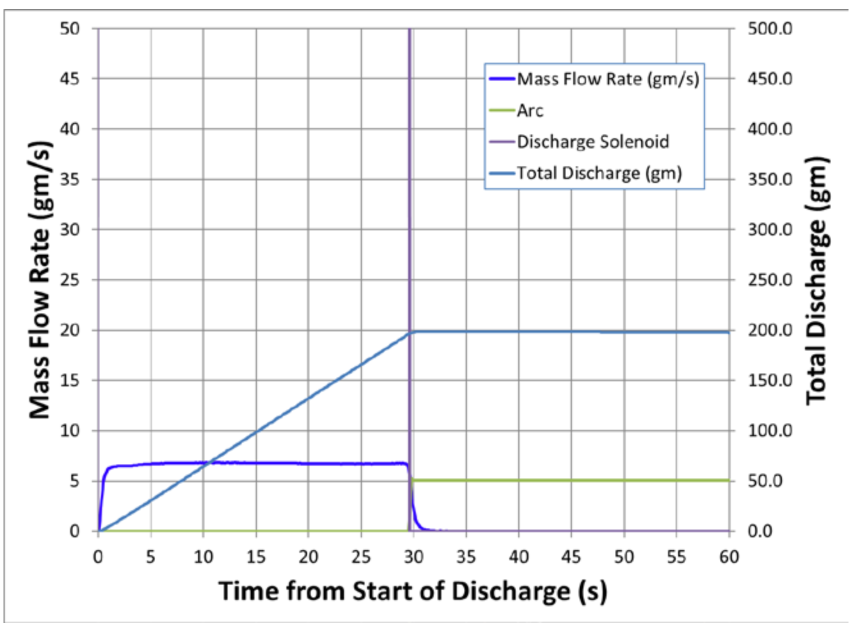


Figure 133 – CP_10 Mass Flow

Figure 134 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

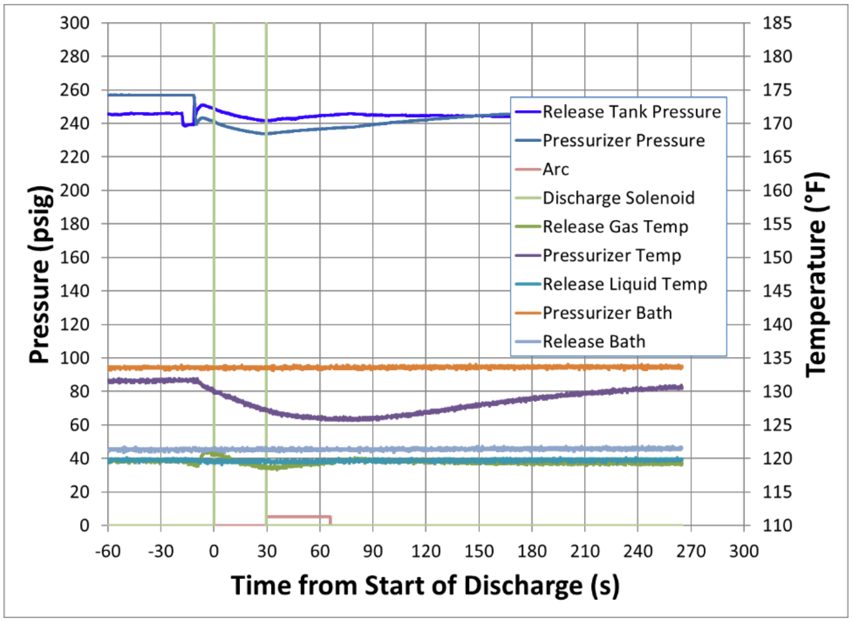
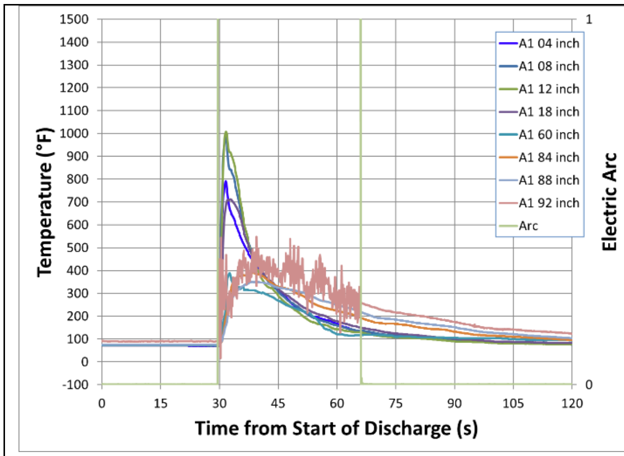
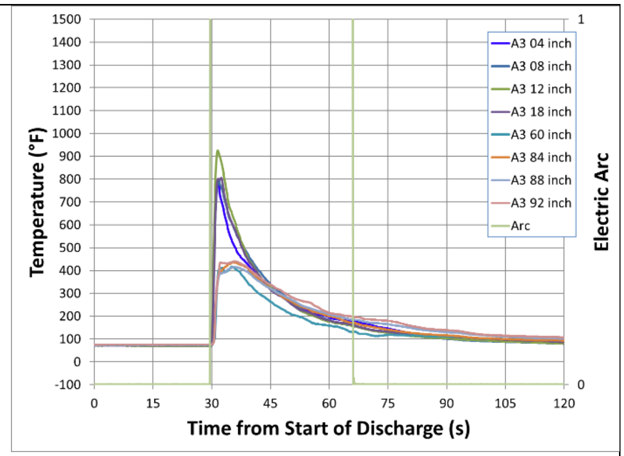


Figure 134 – CP_10 Pressurizer and Release Tank Pressure and Temperatures

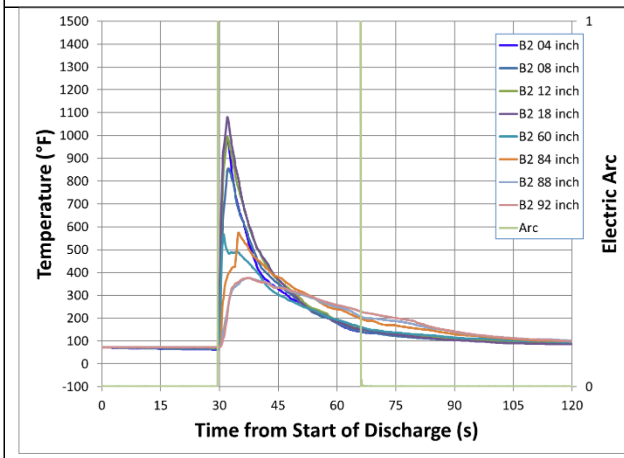
Figure 135 shows the temperatures developed at the various locations following ignition.



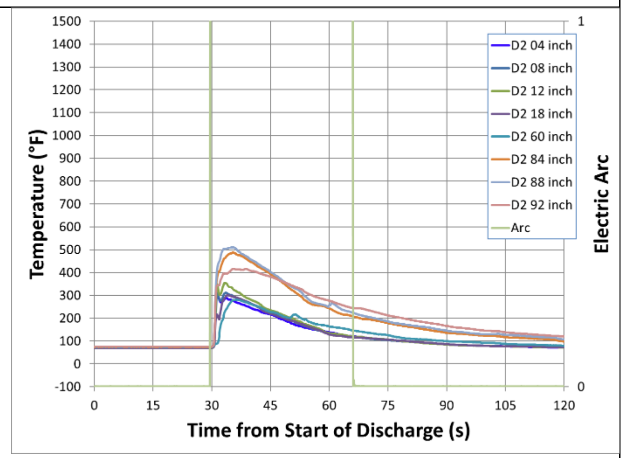
Location A1



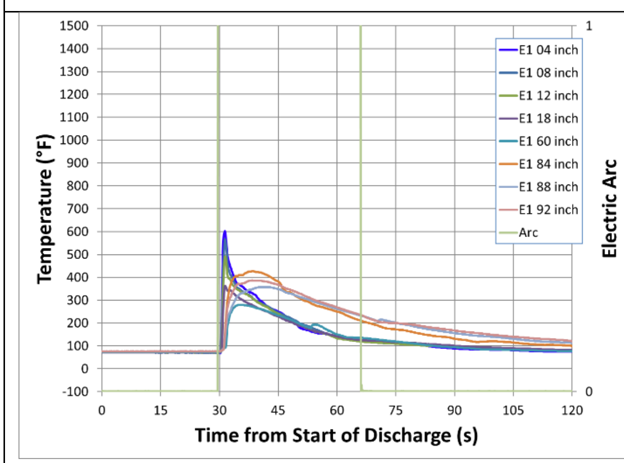
Location A3



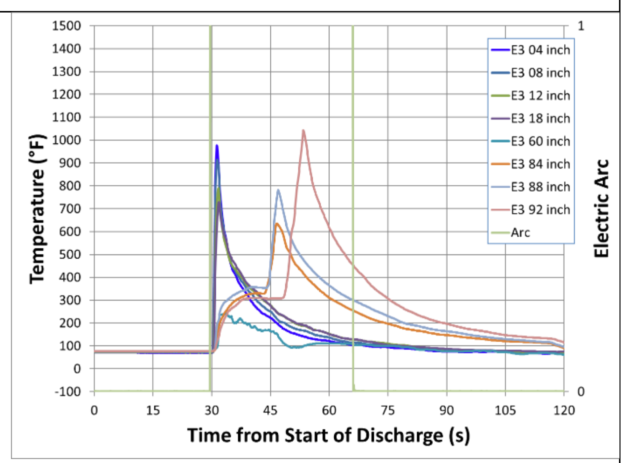
Location B2



Location D2



Location E1



Location E3

Figure 135 – CP_10 Temperatures at thermocouple trees

Notes to Figure 135:

- Location A1 92-inch level thermocouple was erratic. This thermocouple was replaced in later tests.
- Location E3 showed some delayed peaks in temperature. These are due to bits of flaming cheesecloth that were burning near or on the thermocouple bead.
- All locations show a more rounded approach to peak temperatures at the 60-inch to ceiling levels due to the buoyancy of the gases ignited at the floor level.

Figure 136 shows the temperatures recorded by the pool thermocouples. There was no cooling effect observed during the discharge. No evidence of liquid propane was observed.

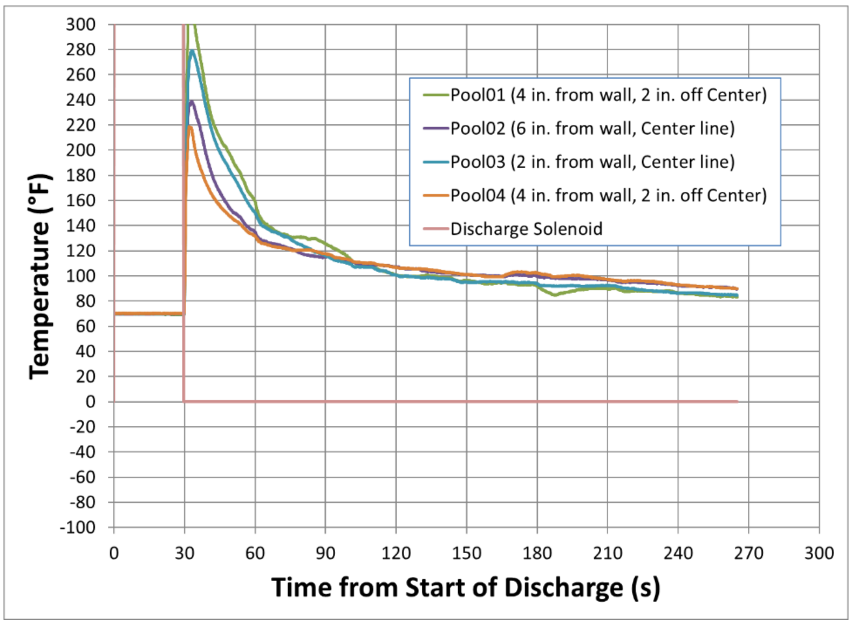


Figure 136 – CP_10 Liquid Propane Pool Temperatures

Figure 137 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 105 kW/m² exceeds the calibrated range of this heat flux sensor (0-50 kW/m²).

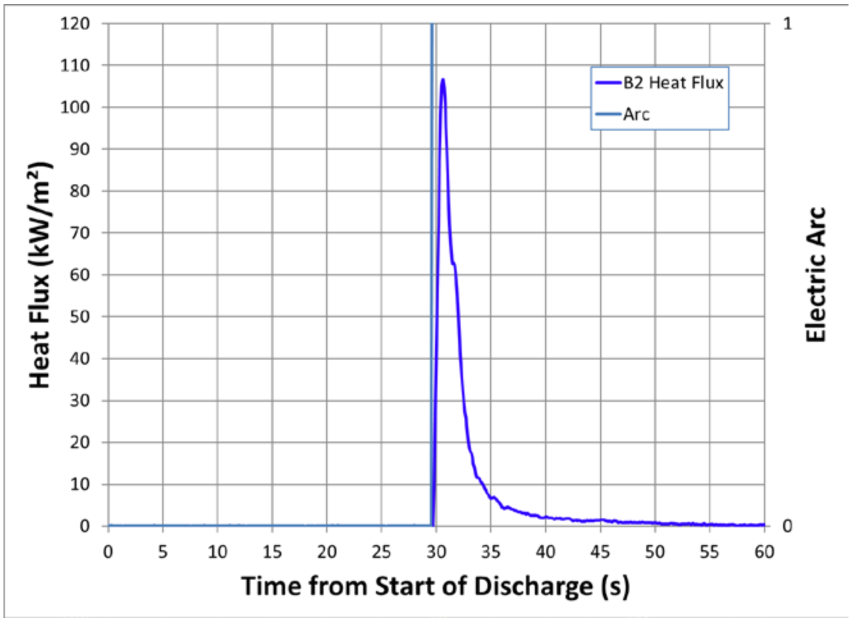
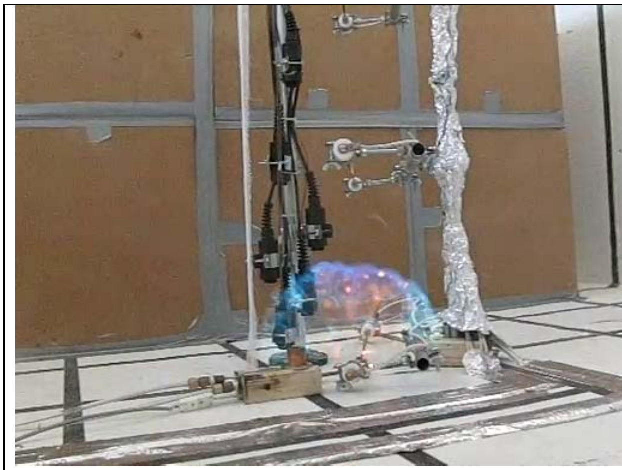
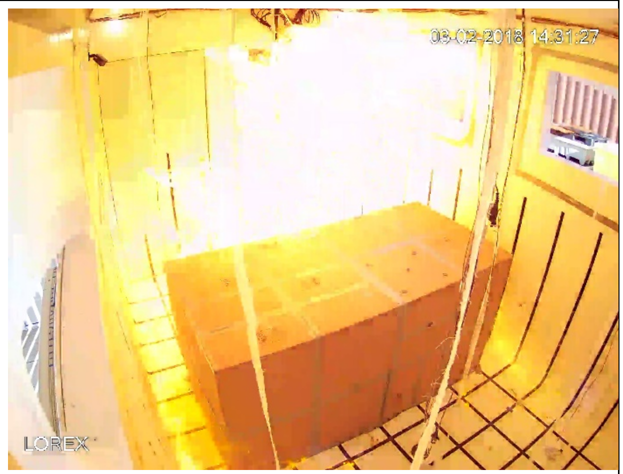


Figure 137 – CP_10 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 138. Ignition first appeared as a pre-mixed (blue) flame at the 1-inch level. This flame transitioned to a diffusion flame. The flames continued to the opposite side of the obstruction to ignition the flammable layer at the floor level. Burning of these air mixtures stopped after 2 seconds. Propane continued flaming at the discharge due to the propane vapor trapped in the tube after the discharge solenoid valve had closed.



Ignition at the 1-inch level



Estimated maximum extent of propane-air flaming.

Flaming extended around the obstruction to the flammable layer at floor level

Flames continued at discharge tube due to trapped propane in the tubing.

Figure 138 – CP_10: Frames of flaming from videos

At the time of ignition, all four deflagration vents burst with some flames extending out from the east side vents as shown in Figure 139.

Figure 139 – CP_10 Flame extension through the west side vent

Test CP_11 (250 grams; 6.8 g/s; 0.2 height)

Test CP_11 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_12. This test involved release of 250 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the floor and the 12-inch level. This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

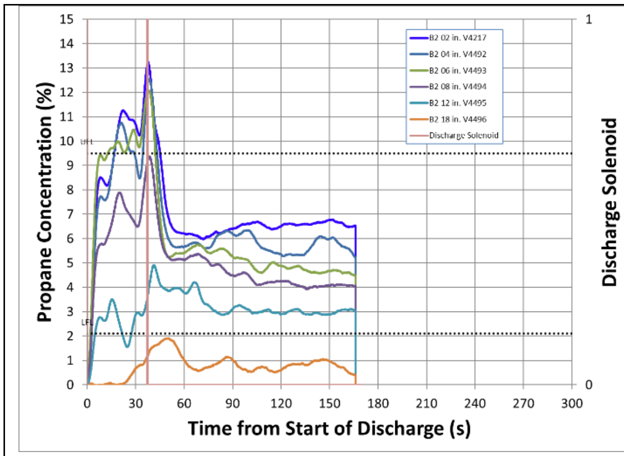
Table 33 – CP_11 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	250	36.8	6.8	0.2 m	0.64	Calculated if well Mixed in whole room
Measured	248	37.3	6.6		13.2 5.1	Location B2 2-inch Location D2 4-inch

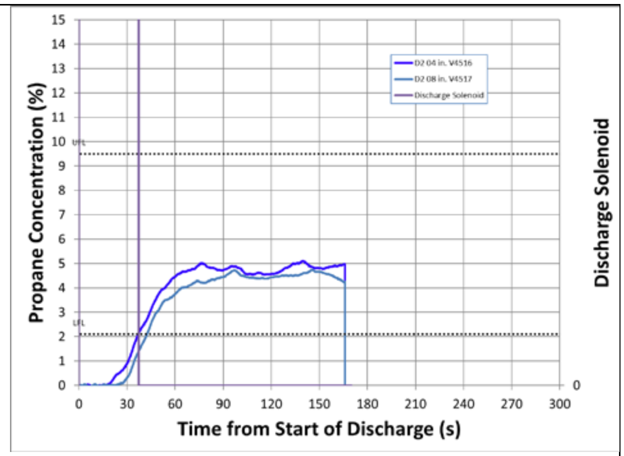
Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 140 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. At the end of data recording, concentrations at location B2 12-inch level and lower showed levels above the LFL of 2.1%. Levels showed signs of a slow decrease. The sensors at location D2 4-inch and 8-inch levels showed a concentration above LFL. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.

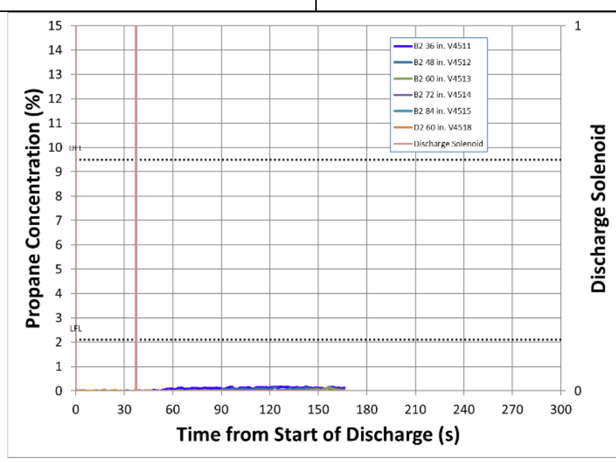
Immediately after completion of the discharge the concentration at location B2 2-, 4- and 6-inch levels was above the upper flammability limit (UFL) of 9.5%.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 4-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 140 – CP_11 Concentrations

Figure 141 shows the mass flow rate and total mass flow.

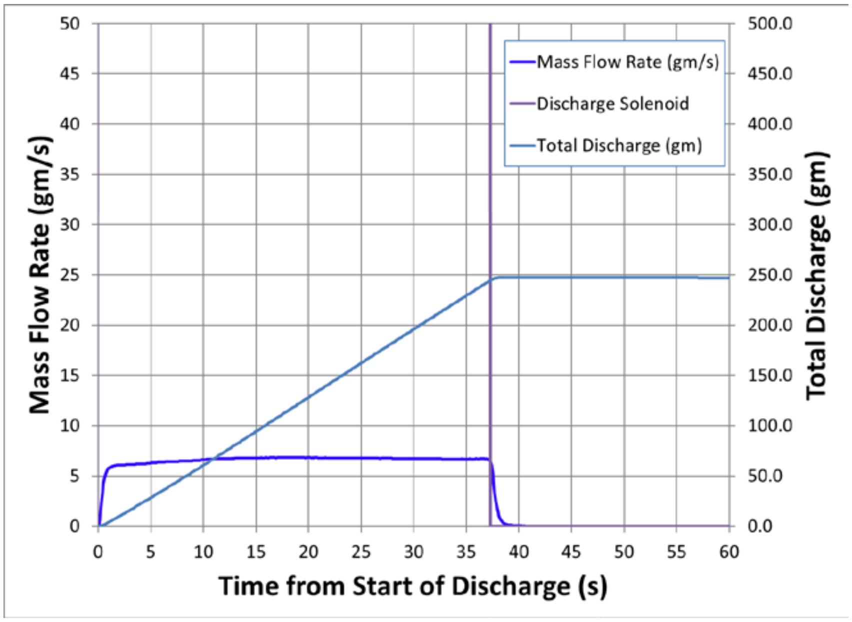


Figure 141 – CP_11 Mass Flow

Figure 142 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

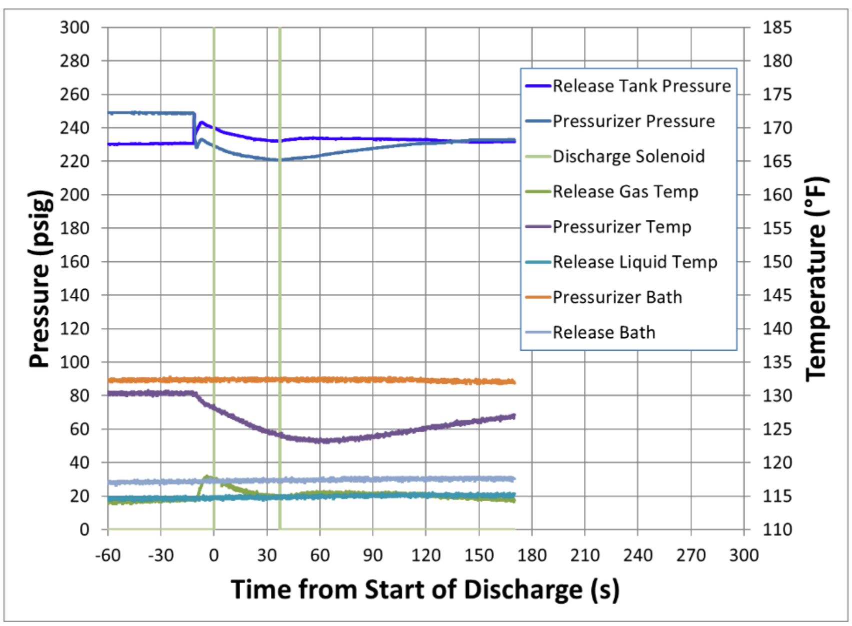


Figure 142 – CP_11 Pressurizer and Release Tank Pressure and Temperatures

Figure 143 shows the thermocouple response to potential liquid propane pooling on the floor in front of the discharge tube. There was a slight cooling after the discharge was completed, but appears to be a low-speed, cold vapor exiting the end of the discharge tube.

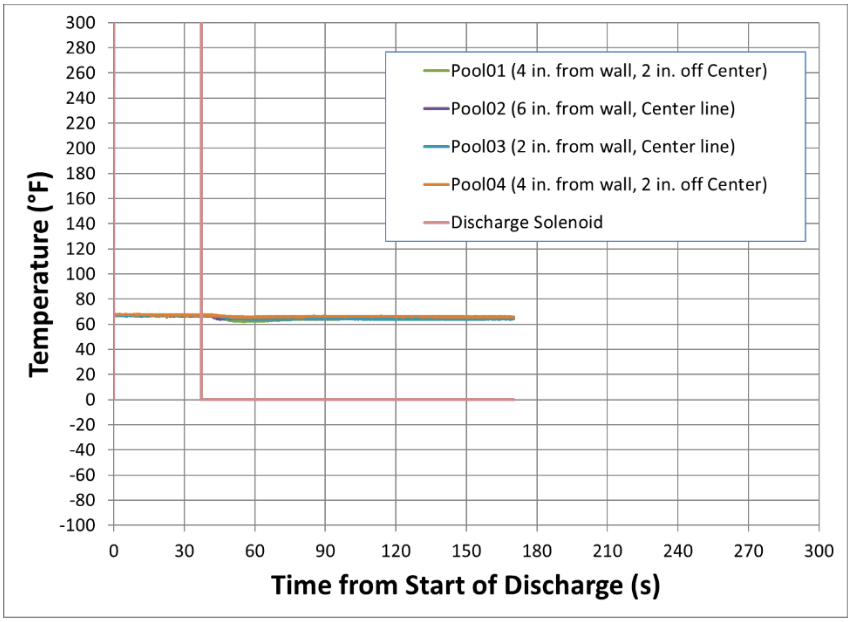


Figure 143 – CP_11 Liquid pooling at the floor

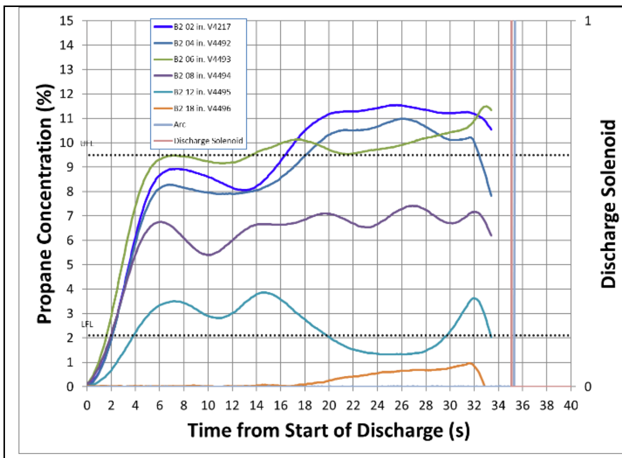
Test CP_12 (250 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_12 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. Ignition at location B2 12-inch level followed the 1-inch level before the fireball could expand to the 12-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_11 showed concentration at the 2-inch level was close to the UFL for propane (9.5%). The propane-air mixture ignited at the 1-inch level with a blue (pre-mixed) flame which quickly expanded and changed to a diffusion flame. The propane-air mixture flaming lasted 2 seconds.

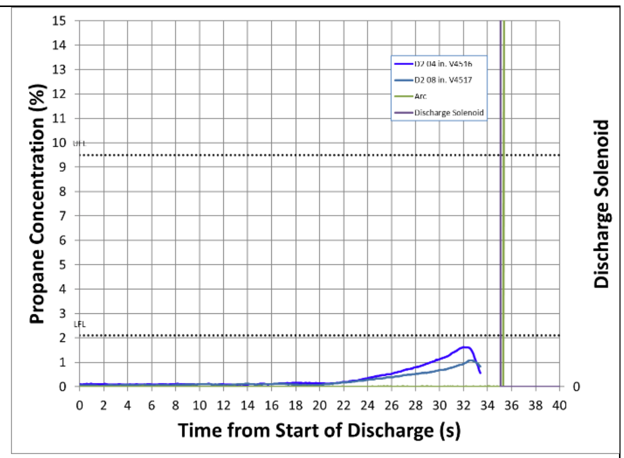
Table 34 – CP_12 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	250	36.8	6.8	0.2 m
Measured	248	35.0	7.1	

Figure 144 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration from the floor level to the 12-inch level.



Location B2 concentrations just prior to ignition



Location D2 concentrations just prior to ignition

Figure 144 – CP_12 Concentrations

Figure 145 compares the concentration and igniter tests (CP_11 and CP_12) concentrations at the 2-inch and 8-inch levels at location B2. The highest concentrations at discharge completion were at the 2-inch level.

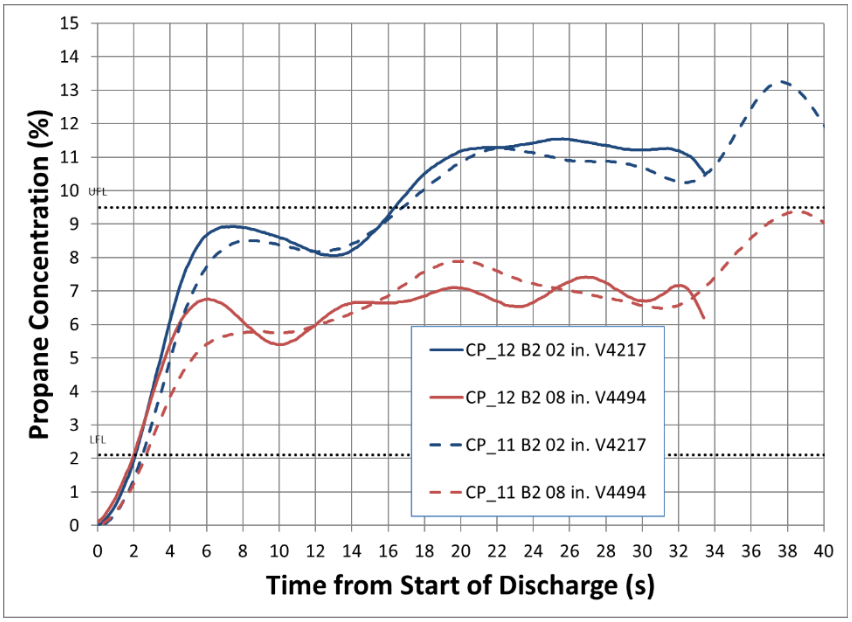


Figure 145 – CP_11 and CP_12 Concentration Comparison

Figure 146 shows the mass flow rate and total mass flow.

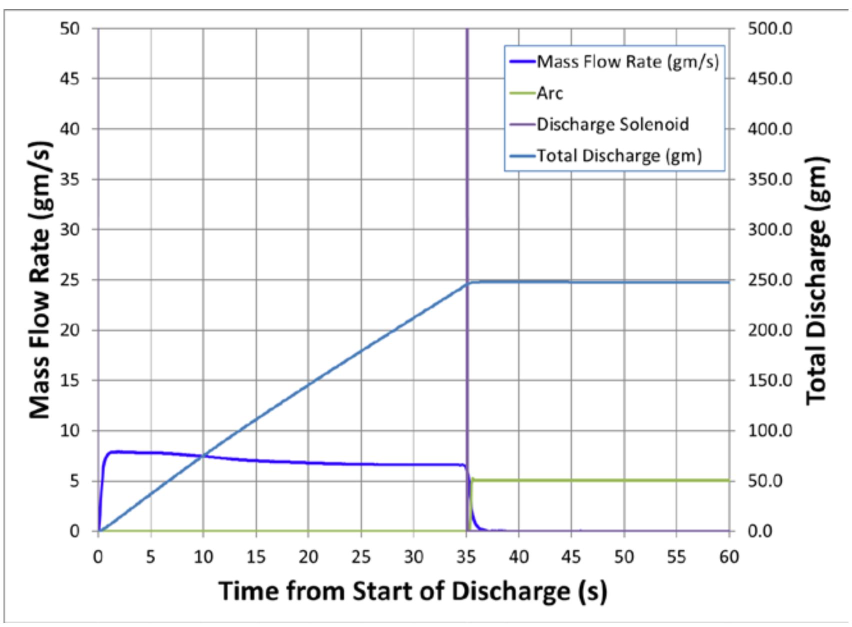


Figure 146 – CP_12 Mass Flow

Figure 147 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

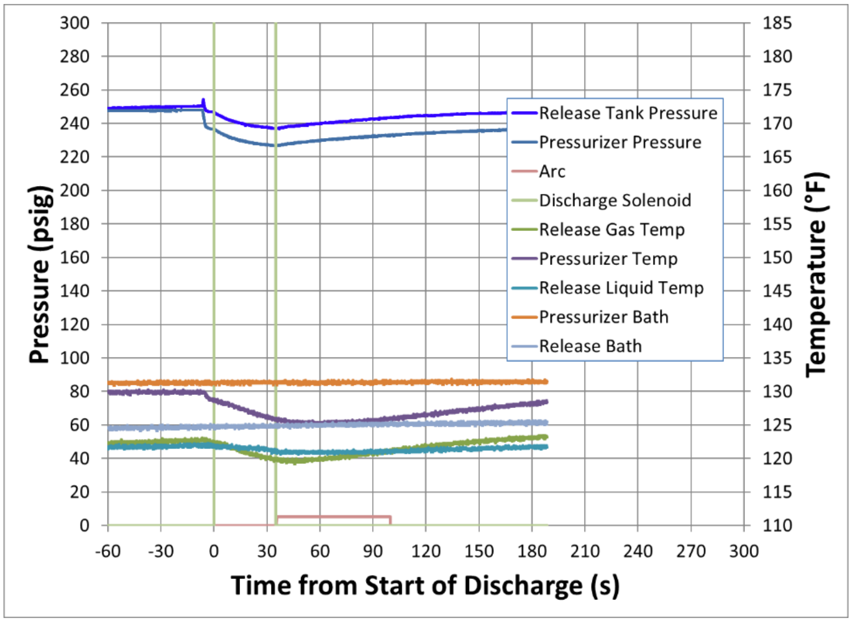


Figure 147 – CP_12 Pressurizer and Release Tank Pressure and Temperatures

Figure 148 shows the temperatures developed at the various locations following ignition.

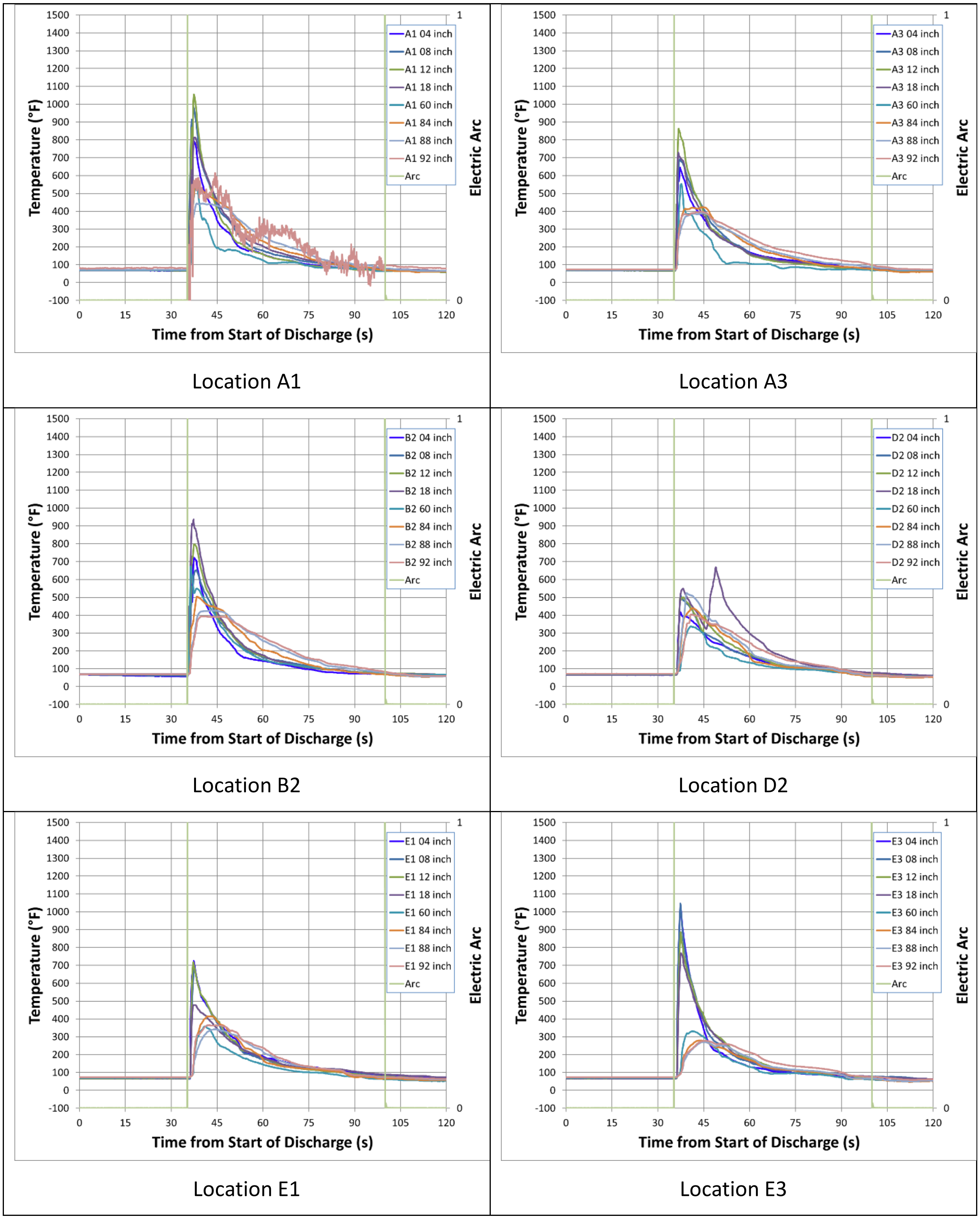


Figure 148 – CP_12 Temperatures at thermocouple trees

Notes to Figure 148:

- Location A1 92-inch level thermocouple was erratic. This thermocouple was replaced in later tests.
- Location D2 showed a delayed peak in temperature. This was due to bits of flaming cheesecloth that were burning near or on the thermocouple bead.
- All locations show a more rounded approach to peak temperatures at the 60-inch to ceiling levels due to the buoyancy of the gases ignited at the floor level.

Figure 149 shows the temperatures recorded by the pool thermocouples. There was no cooling effect observed during the discharge. No evidence of liquid propane was observed.

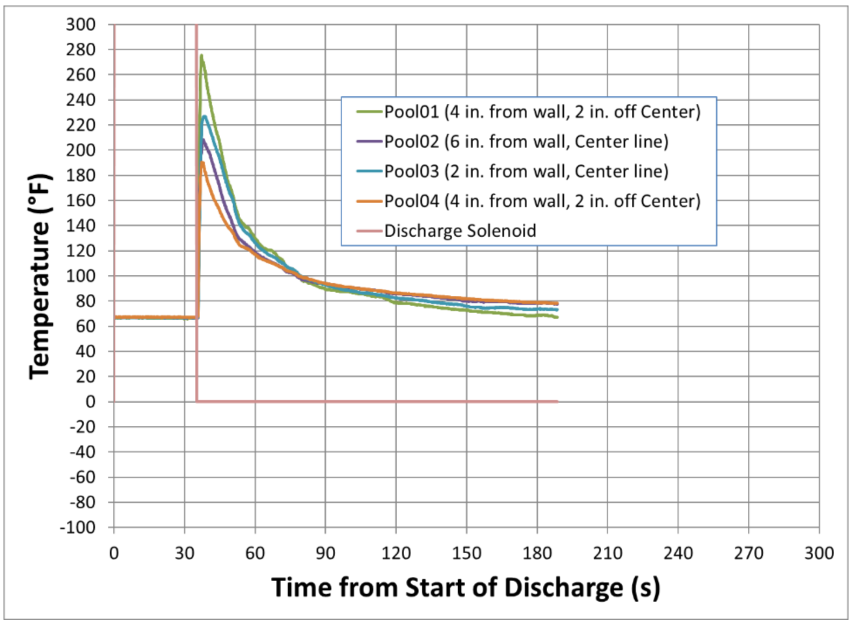


Figure 149 – CP_12 Liquid Propane Pool Temperatures

Figure 150 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 76 kW/m² exceeds the calibrated range of this heat flux sensor (0-50 kW/m²).

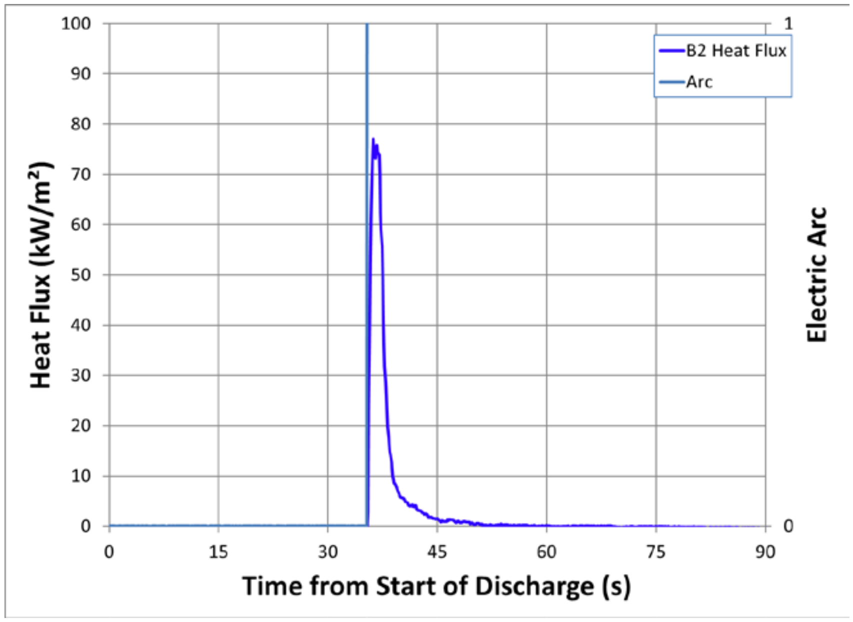


Figure 150 – CP_12 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 151. Ignition first appeared as a pre-mixed (blue) flame at the 1-inch level. This flame transitioned to a diffusion flame. The flames continued to the opposite side of the obstruction to ignition the flammable layer at the floor level. Burning of these air mixtures stopped after 2 seconds. Continued flaming at the discharge due did not occur in this test either due to insufficient oxygen and an ignition source in close proximity.

Ignition at the 1-inch and 12-inch level. Very faint sphere at the 12-inch level.

Estimated maximum extent of propane-air flaming.

Flaming extended around the obstruction to the flammable layer at floor level

Figure 151 – CP_12: Frames of flaming from videos

At the time of ignition, all three deflagration vents burst with some flames extending out from the west side vents as shown in Figure 152. The last vent melted open due to hot gases.

Figure 152 – CP_12 Flame extension through the west side vent

Test CP_13 (300 grams; 6.8 g/s; 0.2 height)

Test CP_13 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_14. This test involved release of 300 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the floor and the 12-inch level. This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

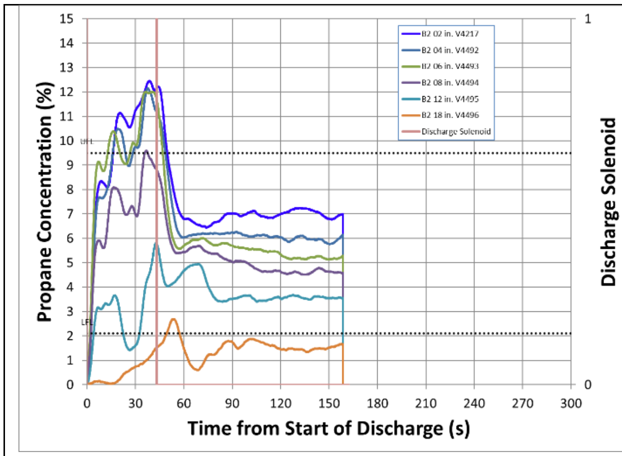
Table 35 – CP_13 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	300	44.1	6.8	0.2 m	0.76	Calculated if well Mixed in whole room
Measured	299	43.1	6.9		12.5 2.6	Location B2 2-inch Location D2 4-inch

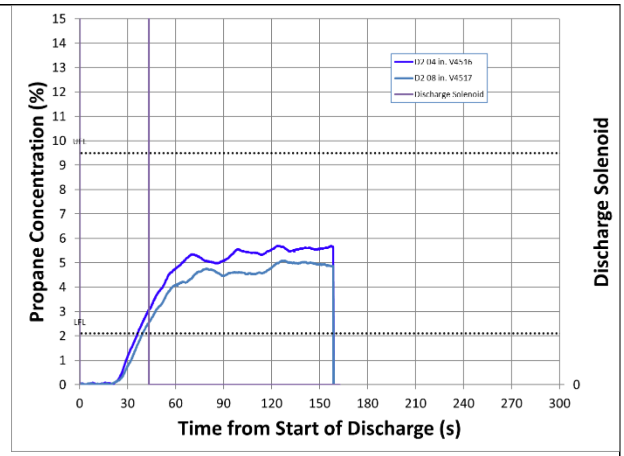
Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 153 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. At the end of data recording, concentrations at location B2 12-inch level and lower showed levels above the LFL of 2.1%. Levels showed signs of a slow decrease at the end of data recording. The sensors at location D2 4-inch and 8-inch levels showed a concentration above LFL. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.

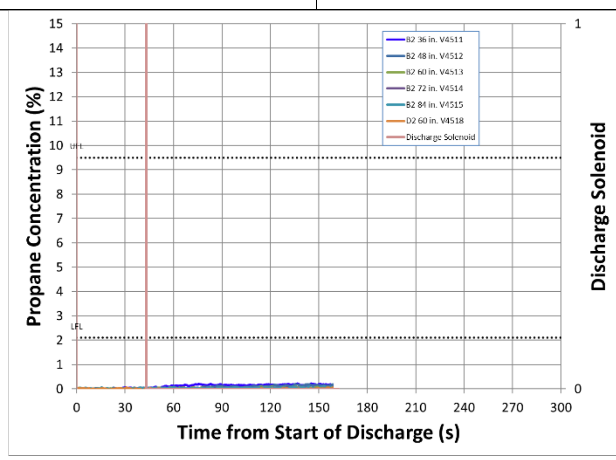
Immediately after completion of the discharge the concentration at location B2 2-, 4- and 6-inch levels was above the upper flammability limit (UFL) of 9.5%.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 4-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 153 – CP_13 Concentrations

Figure 154 shows the mass flow rate and total mass flow.

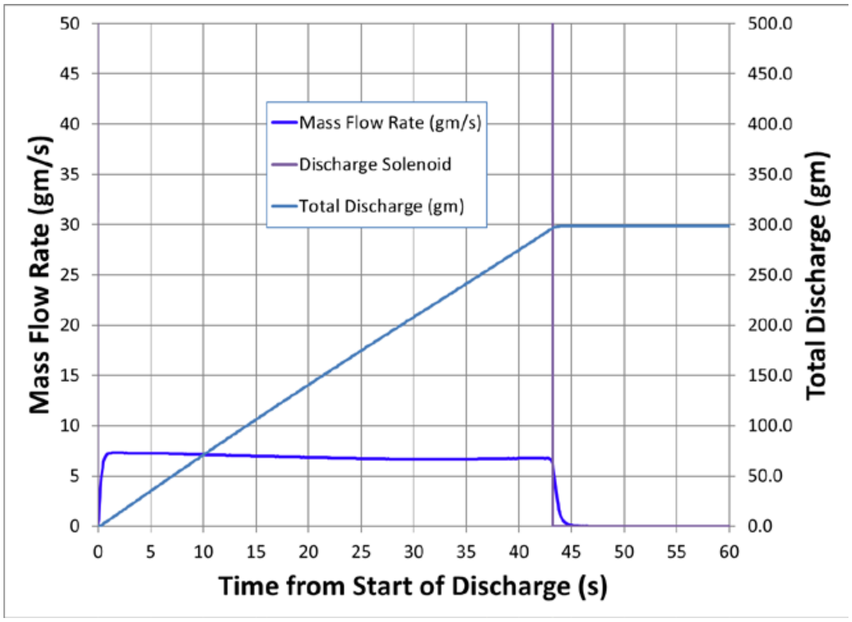


Figure 154 – CP_13 Mass Flow

Figure 155 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures. In this test, the pressurizer was not isolated until after data recording had completed.

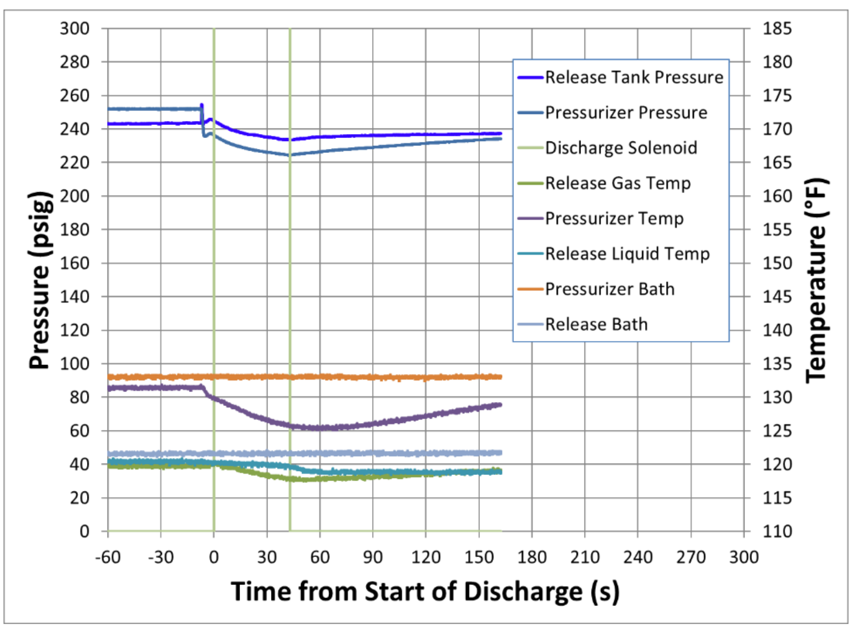


Figure 155 – CP_13 Pressurizer and Release Tank Pressure and Temperatures

Figure 156 shows the thermocouple response to potential liquid propane pooling on the floor in front of the discharge tube. Pool03 thermocouple detected the formation of a liquid pool at that location. The other three pool thermocouples did not detect liquid pooling. The videos taken during this test show droplets of liquid exiting the discharge tube.

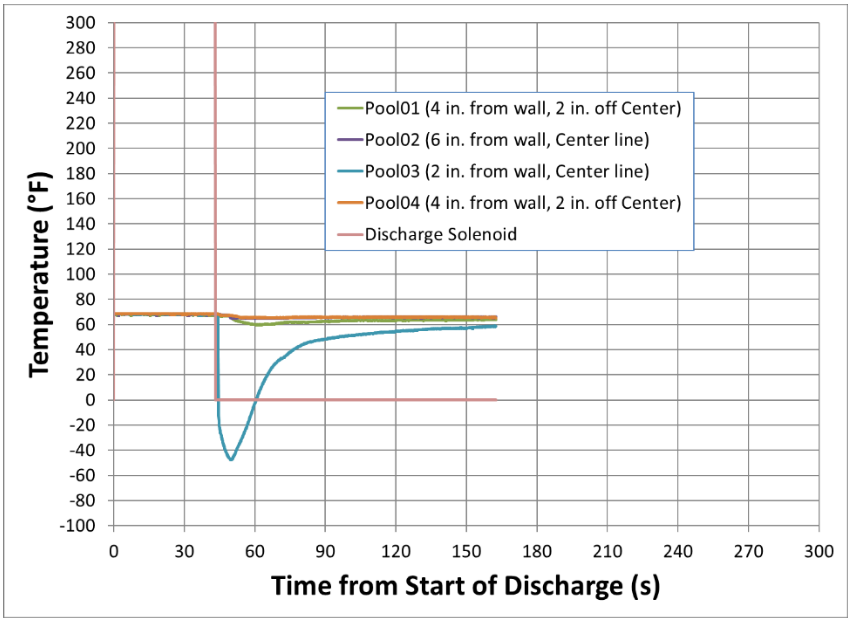


Figure 156 – CP_13 Liquid pooling at the floor

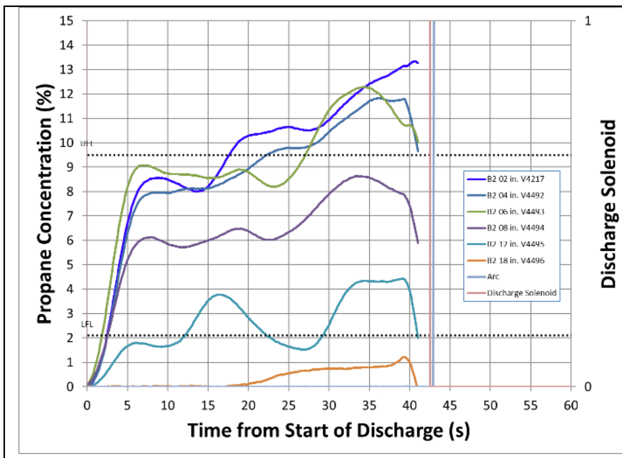
Test CP_14 (300 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_14 was performed with ignition sources and resulted in ignition at location B2 at the 12-inch level indicating that the 1-inch level was above the UFL for propane (9.5%). All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_13 showed concentration at the 2-inch level was close to the UFL for propane (9.5%). The propane-air mixture ignited at the 12-inch level with a blue (pre-mixed) flame which quickly expanded and changed to a diffusion flame. The propane-air mixture flaming lasted 4 seconds.

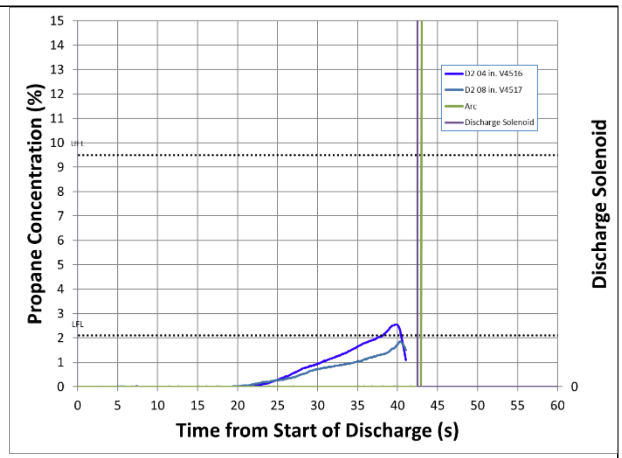
Table 36 – CP_14 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	300	44.1	6.8	0.2 m
Measured	299	42.4	7.0	

Figure 157 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration from the floor level to the 12-inch level.



Location B2 concentrations just prior to ignition



Location D2 concentrations just prior to ignition

Figure 157 – CP_14 Concentrations

Figure 158 compares the concentration and igniter tests (CP_13 and CP_14) concentrations at the 2-inch and 8-inch levels at location B2. The highest concentrations at discharge completion were at the 2-inch level.

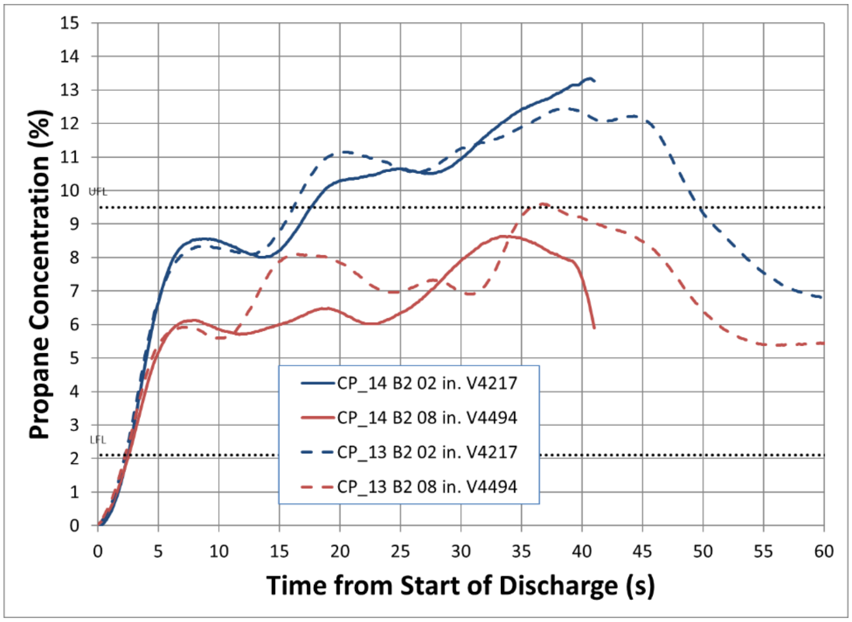


Figure 158 – CP_13 and CP_14 Concentration Comparison

Figure 159 shows the mass flow rate and total mass flow.

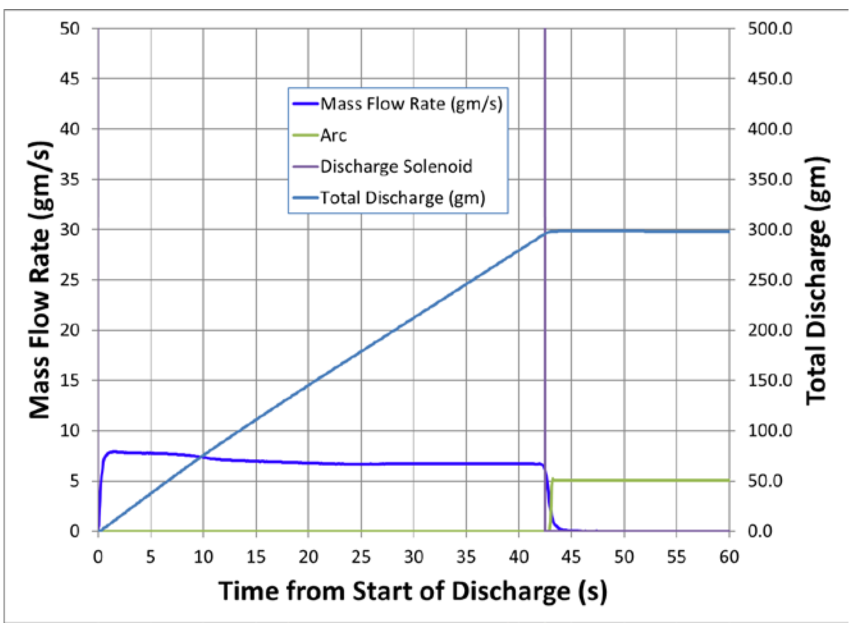


Figure 159 – CP_14 Mass Flow

Figure 160 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

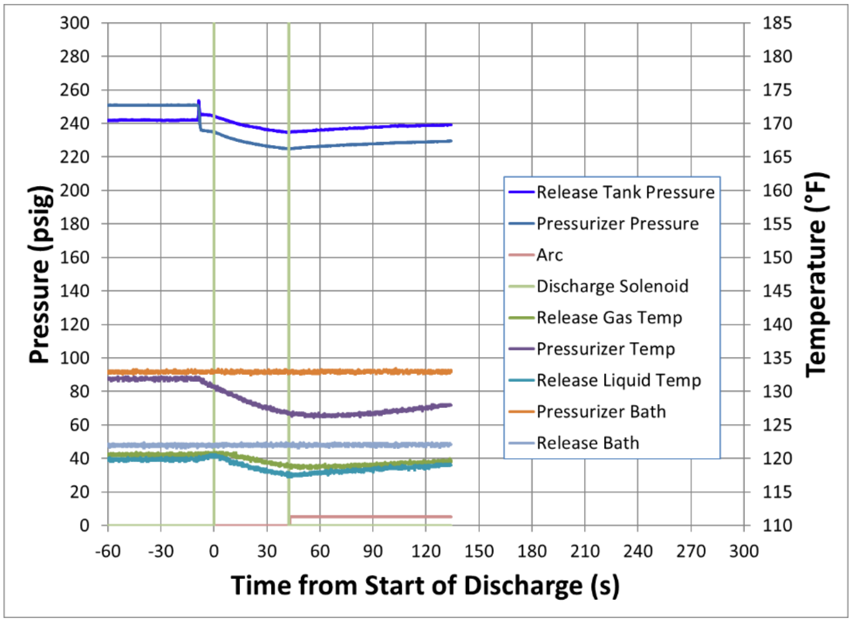


Figure 160 – CP_14 Pressurizer and Release Tank Pressure and Temperatures

Figure 161 shows the temperatures developed at the various locations following ignition.

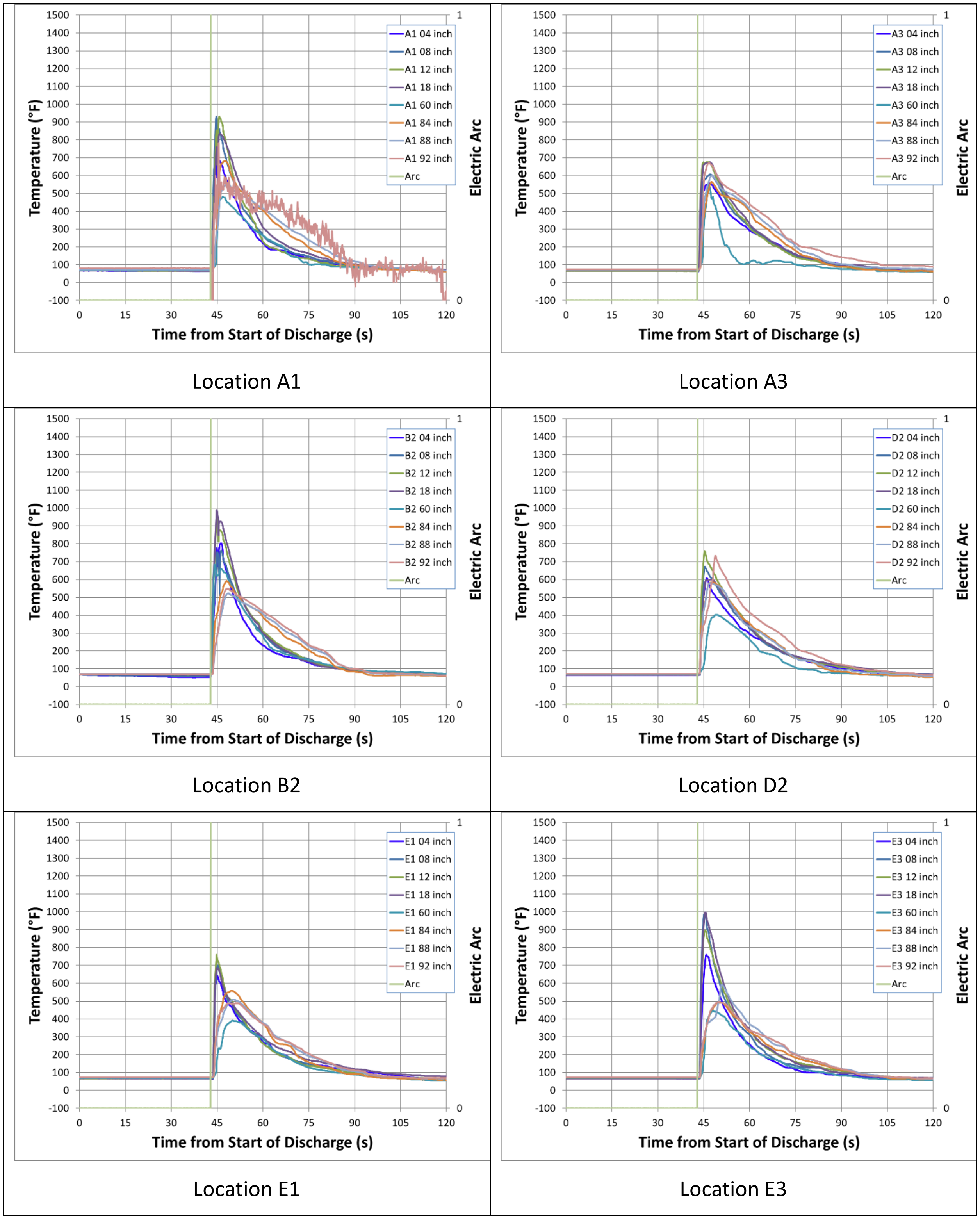


Figure 161 – CP_14 Temperatures at thermocouple trees

Notes to Figure 148:

- Location A1 92-inch level thermocouple was erratic. This thermocouple was replaced in later tests.
- Location D2 showed a delayed peak in temperature. This was due to bits of flaming cheesecloth that were burning near or on the thermocouple bead.
- All locations show a more rounded approach to peak temperatures at the 60-inch to ceiling levels due to the buoyancy of the gases ignited at the floor level.

Figure 162 shows the temperatures recorded by the pool thermocouples. Pool02 and Pool03 both showed indications of liquid propane at the bead. Both of these thermocouples were located on the centerline of the test room, just below the discharge tube (also on the room centerline).

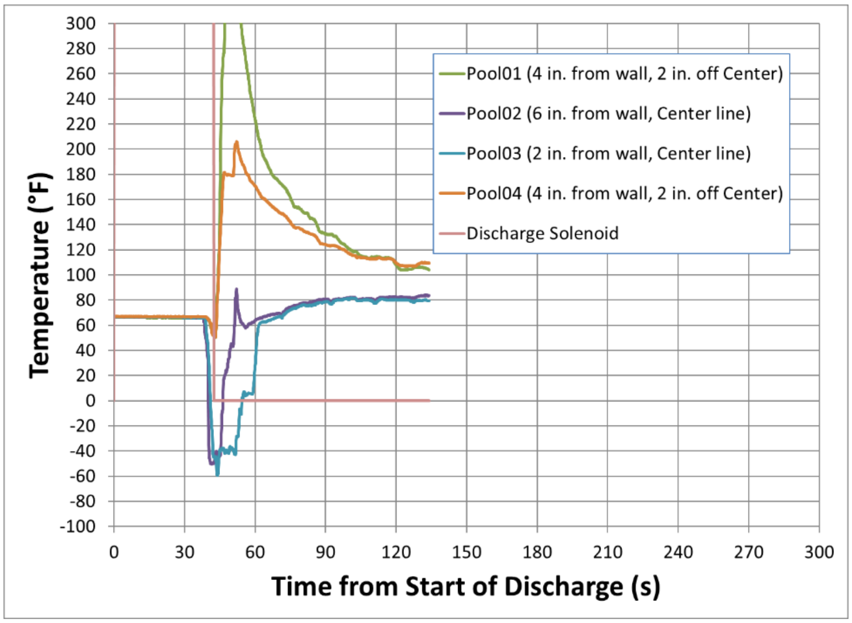


Figure 162 – CP_14 Liquid Propane Pool Temperatures

Figure 163 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 76 kW/m² exceeds the calibrated range of this heat flux sensor (0-50 kW/m²).

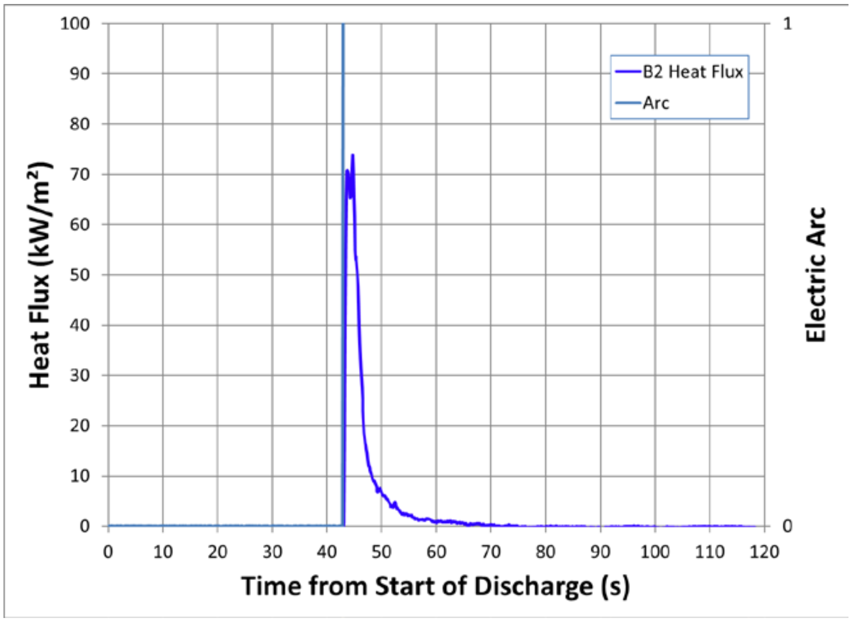
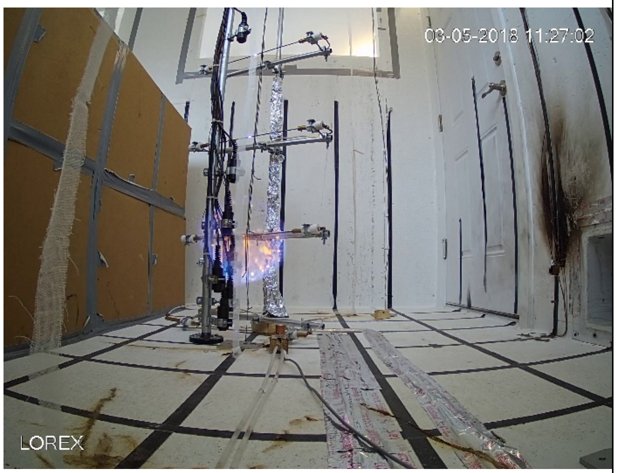


Figure 163 – CP_14 Heat Flux at Location B2, Floor Level

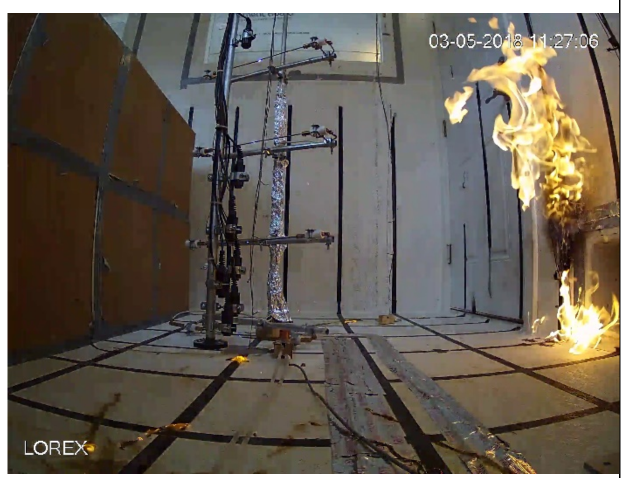
Selected frames from the videos are shown in Figure 164. Ignition first appeared as a pre-mixed (blue) flame at the 12-inch level. This flame transitioned to a diffusion flame. The flames continued to the opposite side of the obstruction to ignition the flammable layer at the floor level. Burning of these air mixtures stopped after 2 seconds. Continued flaming at the discharge due did not occur in this test either due to insufficient oxygen and an ignition source in close proximity.



Ignition at the 12-inch level

Estimated maximum extent of propane-air flaming.

Flaming extended around the obstruction to the flammable layer at floor level



Liquid Pool and Discharge Tube Flames

Figure 164 – CP_14: Frames of flaming from videos

At the time of ignition, all three deflagration vents burst with some flames extending out from the west side vents as shown in Figure 165. The last vent melted open due to hot gases.

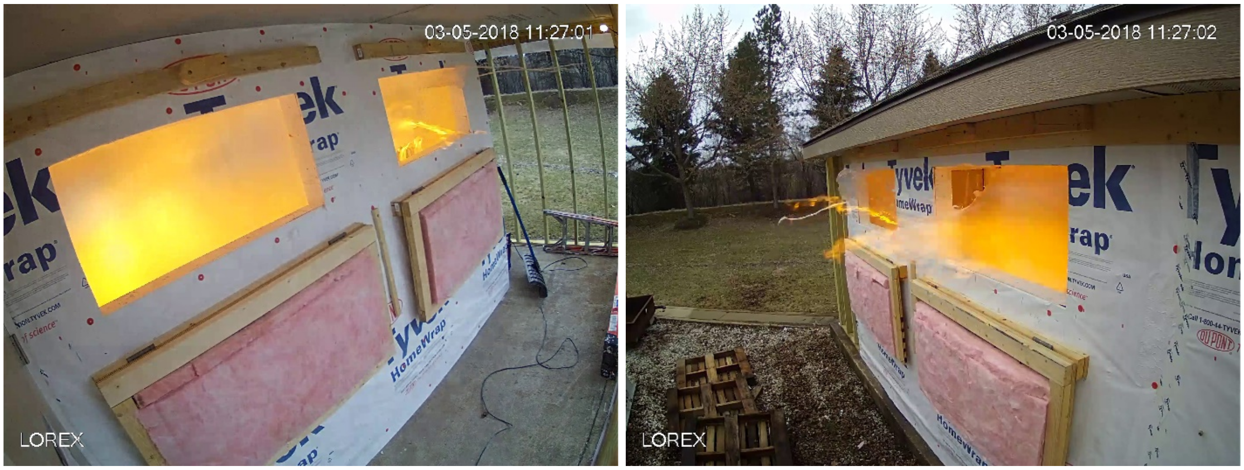


Figure 165 – CP_14 Flame extension through the west side vent

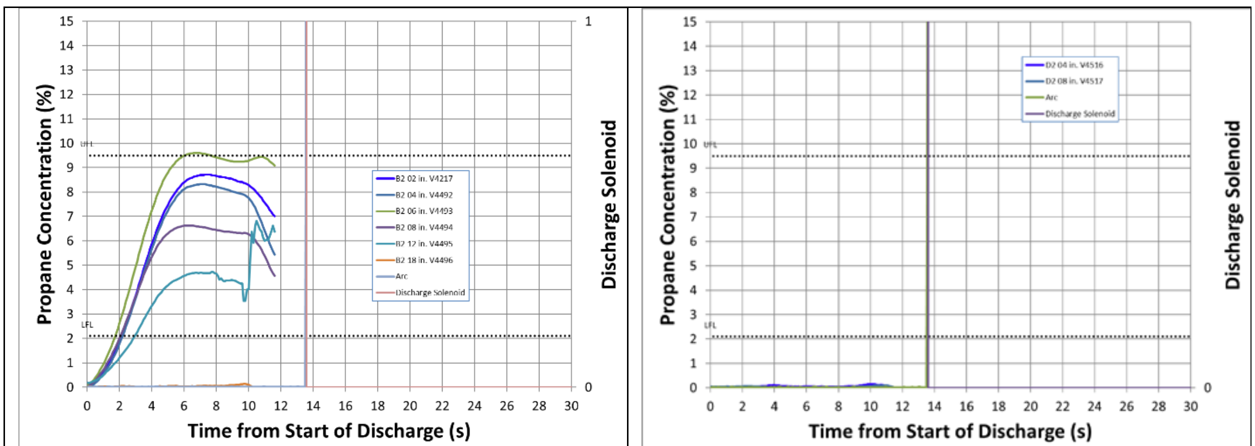
Test CP_15 (100 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_15 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_05 showed concentration at the 2-inch level was between the LFL and UFL.

Table 37 – CP_15 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	100	12.5	6.8	0.2 m
Measured	99	13.5	7.3	

Figure 166 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration from the floor to the 12-inch level. At the time of ignition concentrations at location D2 were nearly zero.



Location B2 concentrations just prior to ignition | Location D2 concentrations just prior to ignition

Figure 166 – CP_15 Concentrations

Figure 167 compares the concentration and igniter test(CP_05 and CP_15) concentrations at the 2-inch and 6-inch levels at location B2. The highest concentrations at discharge completion were at the 6-inch level which was nearly directly in front of the discharge tube (8-inch or 0.2 m).

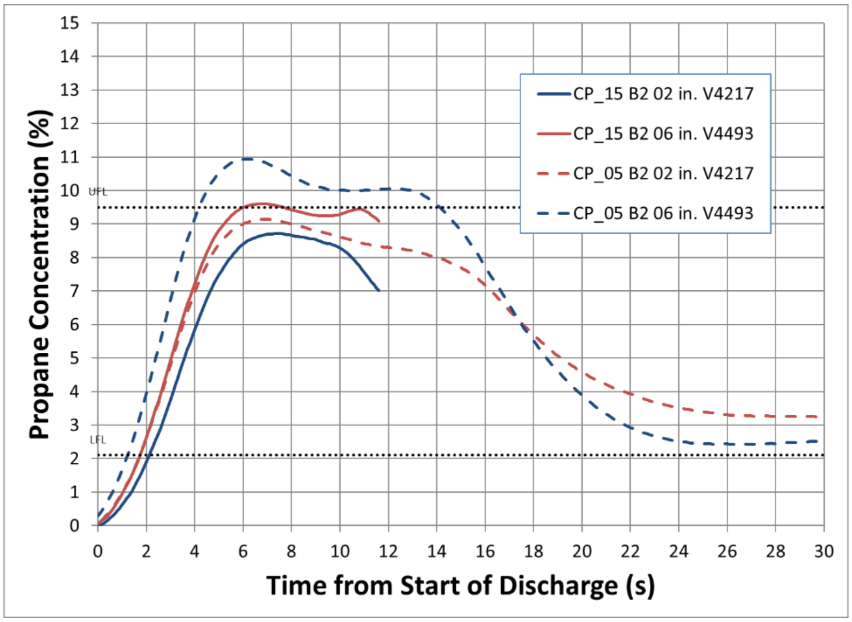


Figure 167 – CP_05 and CP_15 Concentration Comparison

Figure 168 shows the mass flow rate and total mass flow.

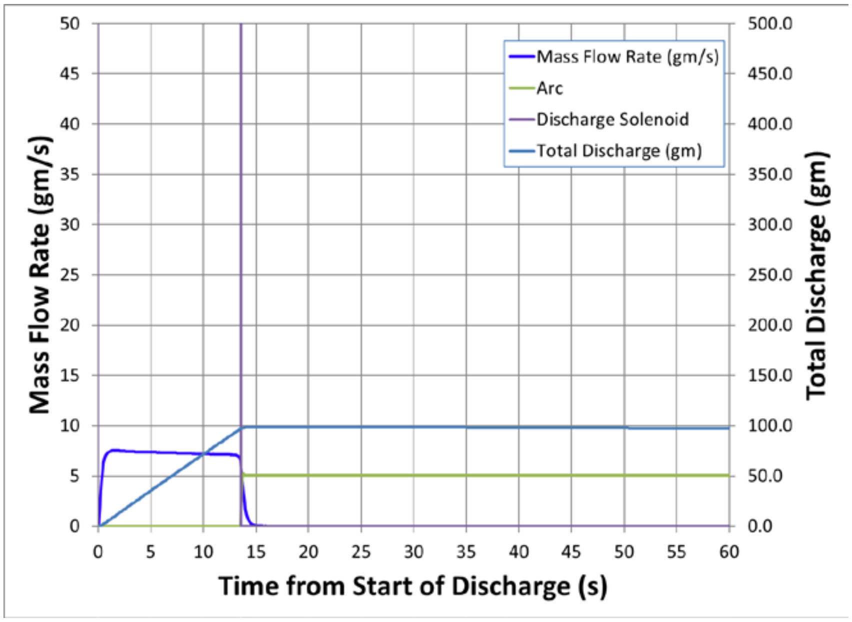


Figure 168 – CP_15 Mass Flow

Figure 109 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

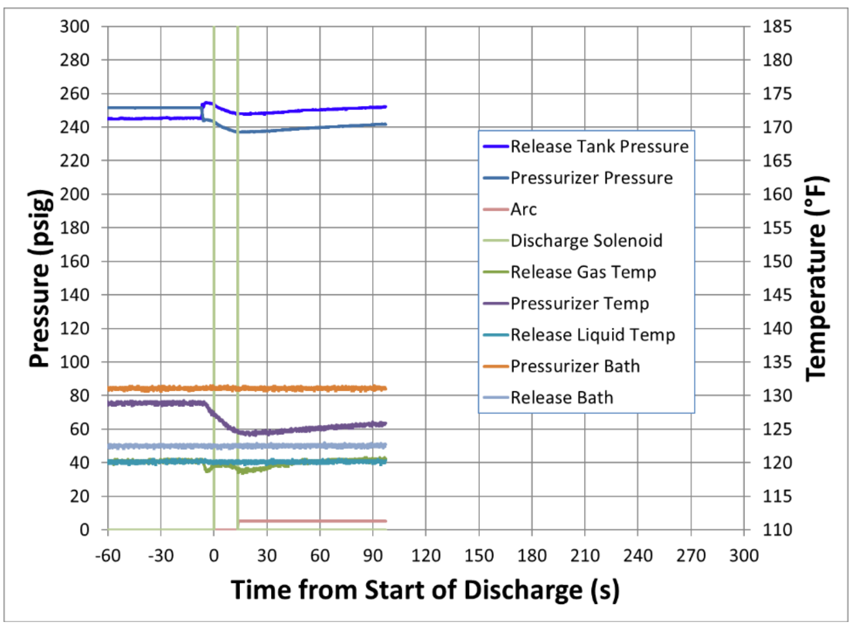


Figure 169 – CP_15 Pressurizer and Release Tank Pressure and Temperatures

Figure 170 shows the temperatures developed at the various locations following ignition.

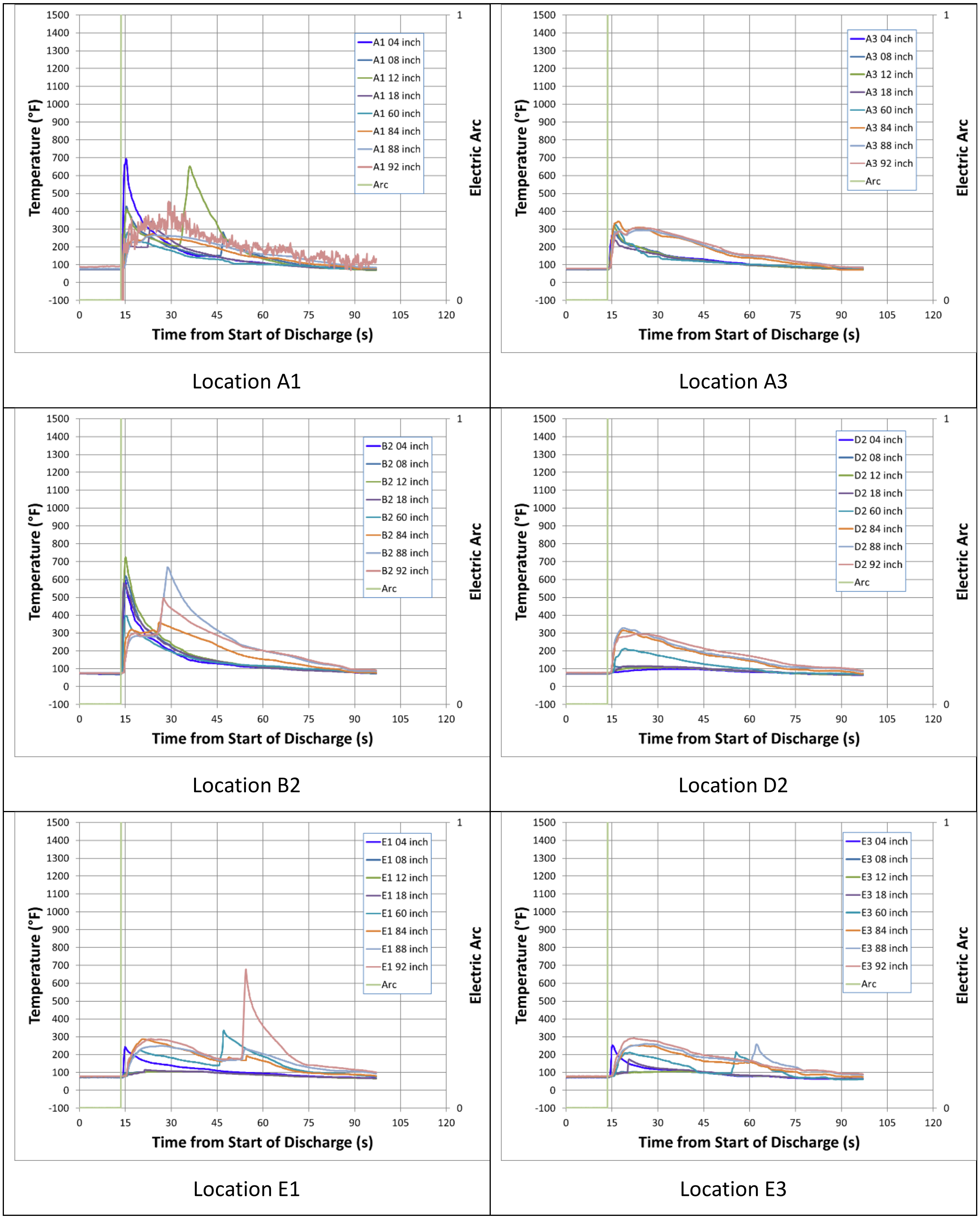


Figure 170 – CP_15 Temperatures at thermocouple trees

Notes to Figure 170:

- Location A1 92-inch level thermocouple was erratic. This thermocouple was replaced in later tests.
- Location E1 and E3 secondary temperature peaks were due to cheesecloth strips burning and attached to the thermocouple tree.

Figure 171 shows the temperatures recorded by the pool thermocouples. There was no indication of the formation of a pool of liquid propane.

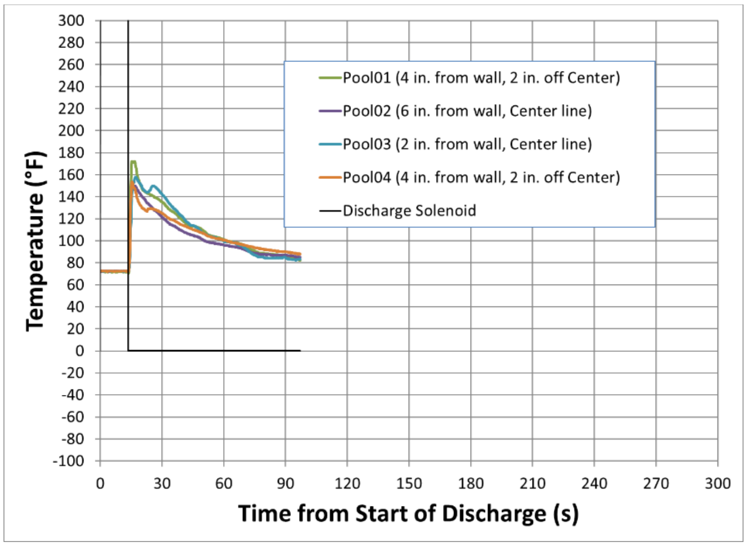


Figure 171 – CP_15 Liquid Propane Pool Temperatures

Figure 172 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 66 kW/m² exceeds the calibrated range of this heat flux sensor (0-50 kW/m²).

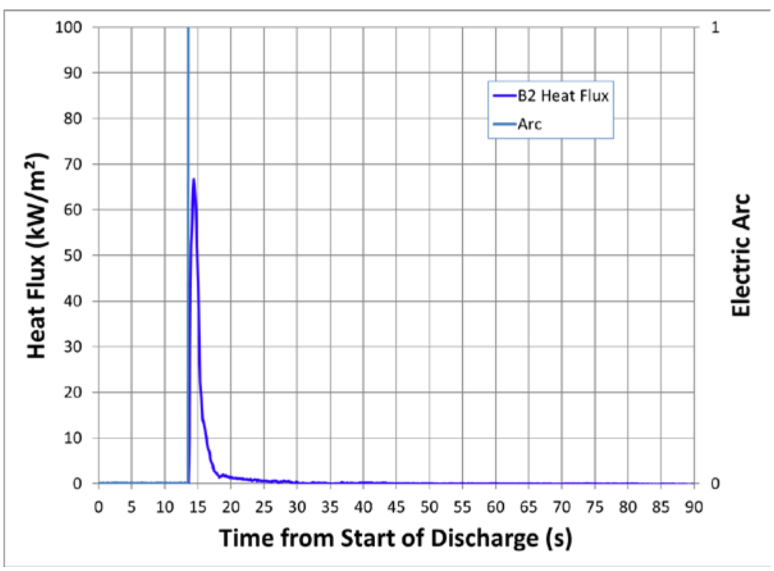
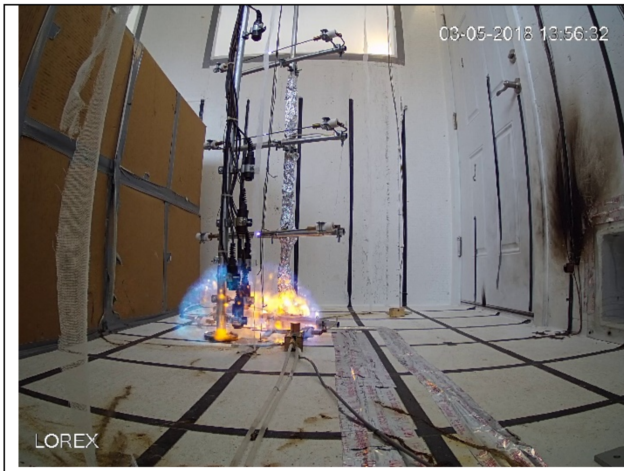


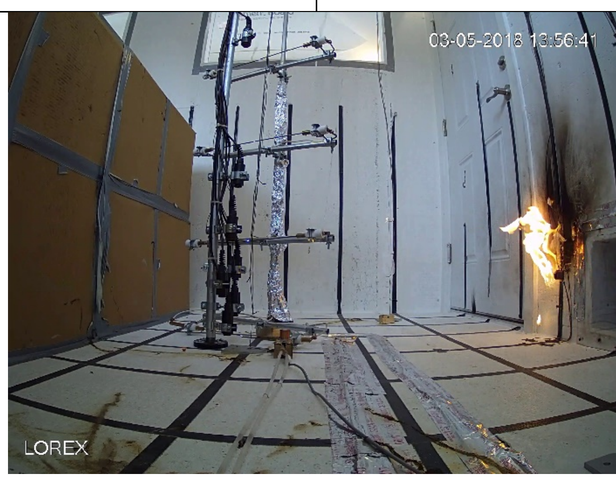
Figure 172 – CP_15 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 173. The ignition initially had the appearance of a pre-mixed flame, but quickly transitioned into a diffusion flame. Three deflagration vents burst at ignition time. The propane-air mixture flamed for 2 seconds. Remaining propane in the discharge tube continued to expand out of the tube and ignited for an additional 2 minutes.



Ignition at the 1-inch level

Estimated maximum extent of propane-air flaming.



Residual propane trapped in the discharge tube.

Figure 173 – CP_15: Frames of flaming from videos

Test CP_16 (350 grams; 6.8 g/s; 0.2 height)

Test CP_16 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_17. This test involved release of 350 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the 4-inch level and the 12-inch level. The 2-inch level concentration (10%) was above UFL (9.5%) at the end of data recording. This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

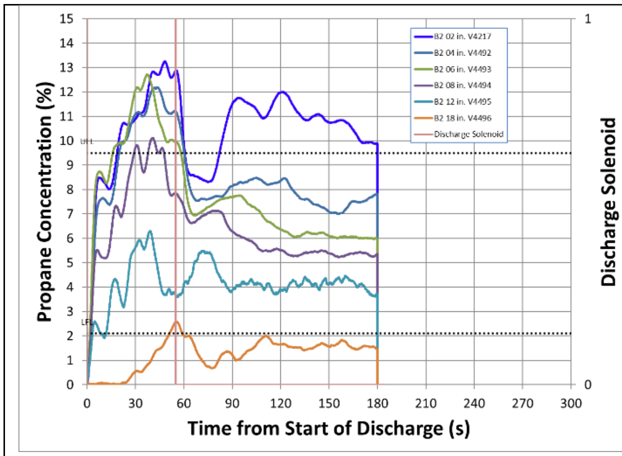
Table 38 – CP_16 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	350	51.5	6.8	0.2 m	0.89	Calculated if well Mixed in whole room
Measured	348	54.7	6.4		13.2 3.5	Location B2 2-inch Location D2 4-inch

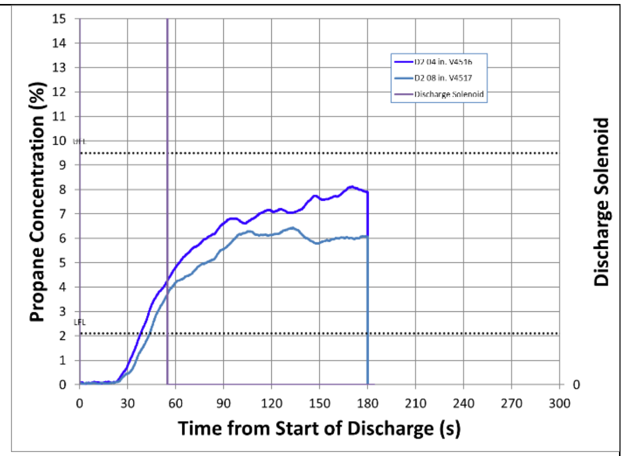
Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 174 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. At the end of data recording, concentrations at location B2 12-inch level and lower showed levels above the LFL of 2.1%. Levels showed signs of a slow decrease at the end of data recording. The sensors at location D2 4-inch and 8-inch levels showed a concentration above LFL. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.

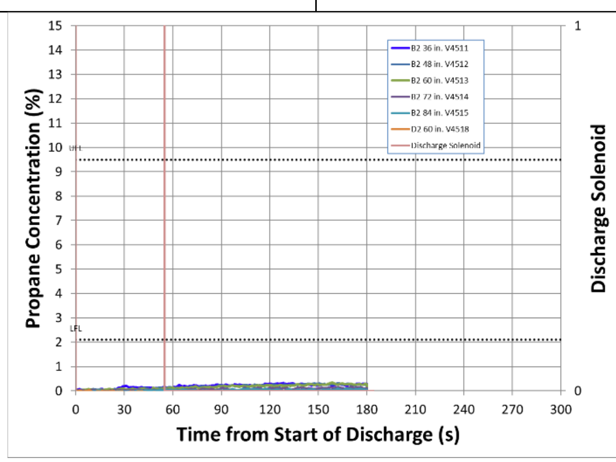
Immediately after completion of the discharge the concentration at location B2 2-, 4- and 6-inch levels was above the upper flammability limit (UFL) of 9.5%.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 4-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 174 – CP_16 Concentrations

Figure 175 shows the mass flow rate and total mass flow.

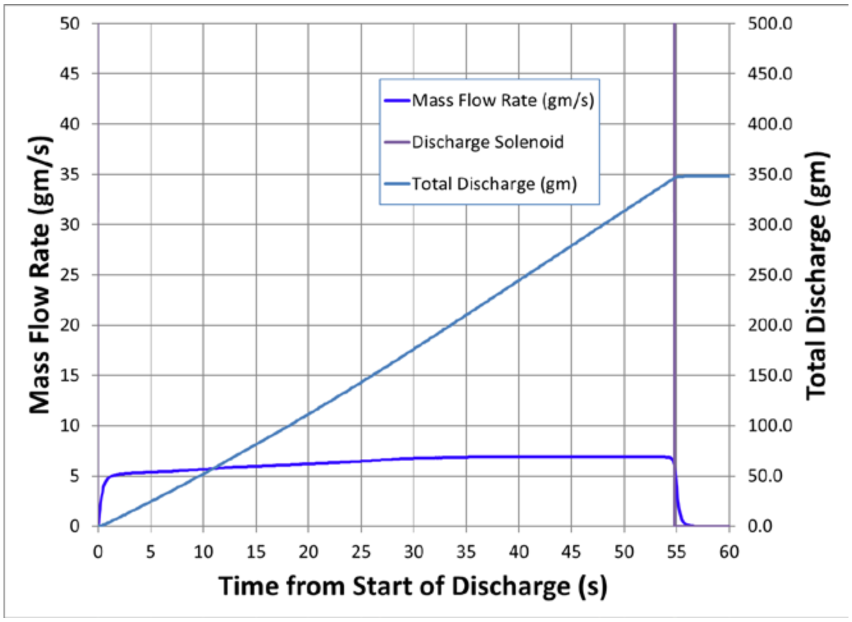


Figure 175 – CP_16 Mass Flow

Figure 176 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures. In this test, the pressurizer was not isolated until after data recording had completed.

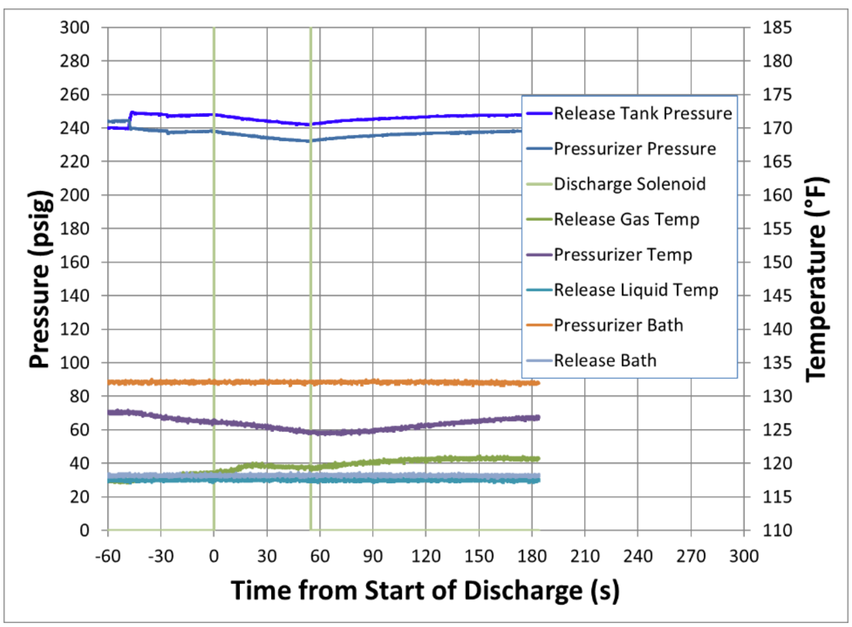


Figure 176 – CP_16 Pressurizer and Release Tank Pressure and Temperatures

Figure 177 shows the thermocouple response to potential liquid propane pooling on the floor in front of the discharge tube. All four thermocouples detected the formation of a liquid pool at those location. The videos taken during this test show droplets of liquid exiting the discharge tube.

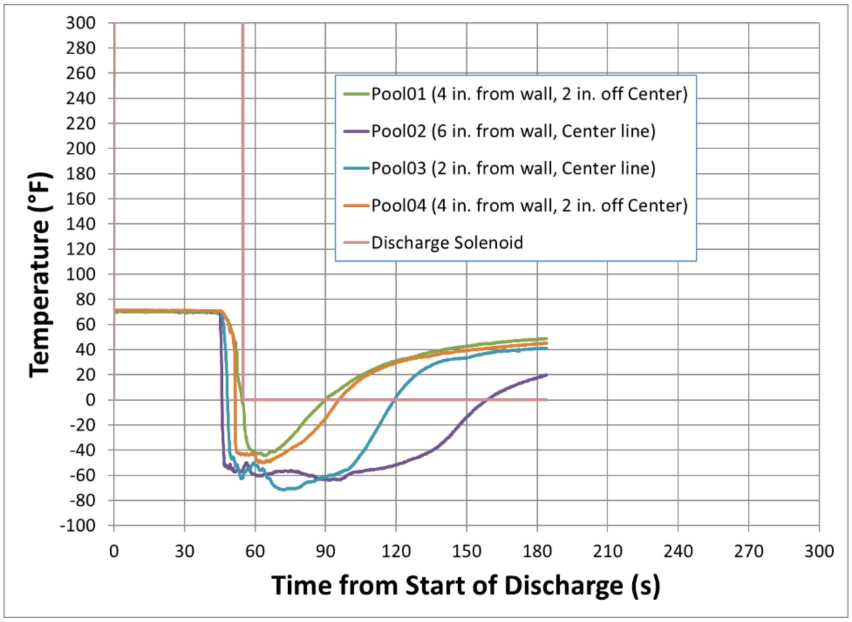


Figure 177 – CP_16 Liquid pooling at the floor

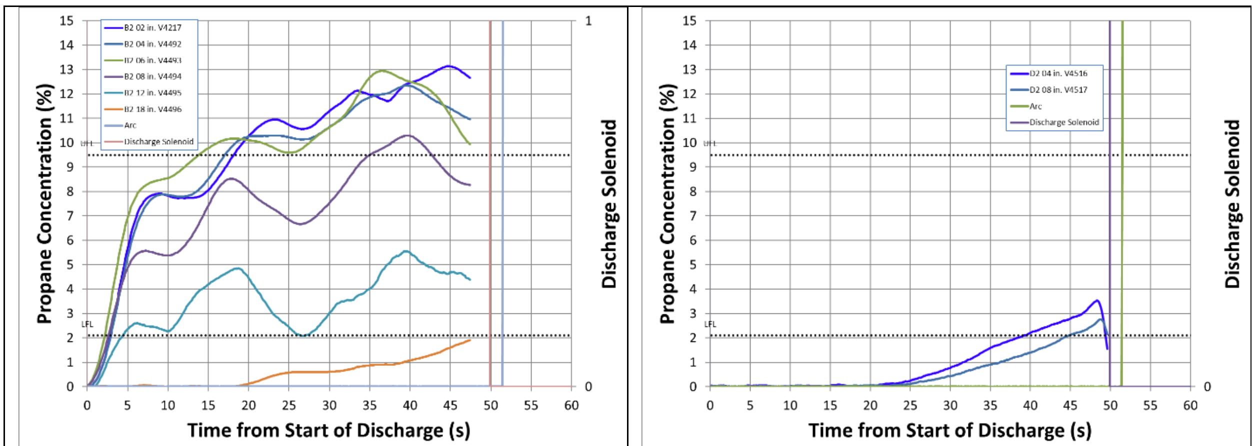
Test CP_17 (350 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_17 was performed with ignition sources and resulted in ignition at location B2 at the 12-inch level indicating that the 1-inch level was above the UFL for propane (9.5%). All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_16 showed concentration at the 2-inch level was close to the UFL for propane (9.5%). The propane-air mixture ignited at the 12-inch level with a blue (pre-mixed) flame which quickly expanded and changed to a diffusion flame. The propane-air mixture flaming lasted 5 seconds.

Table 39 – CP_17 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	350	51.5	6.8	0.2 m
Measured	353	49.8	7.1	

Figure 178 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration from the floor level to the 12-inch level.



Location B2 concentrations just prior to ignition

Location D2 concentrations just prior to ignition

Figure 178 – CP_17 Concentrations

Figure 179 compares the concentration and igniter tests (CP_16 and CP_17) concentrations at the 2-inch and 8-inch levels at location B2. The highest concentrations at discharge completion were at the 2-inch level.

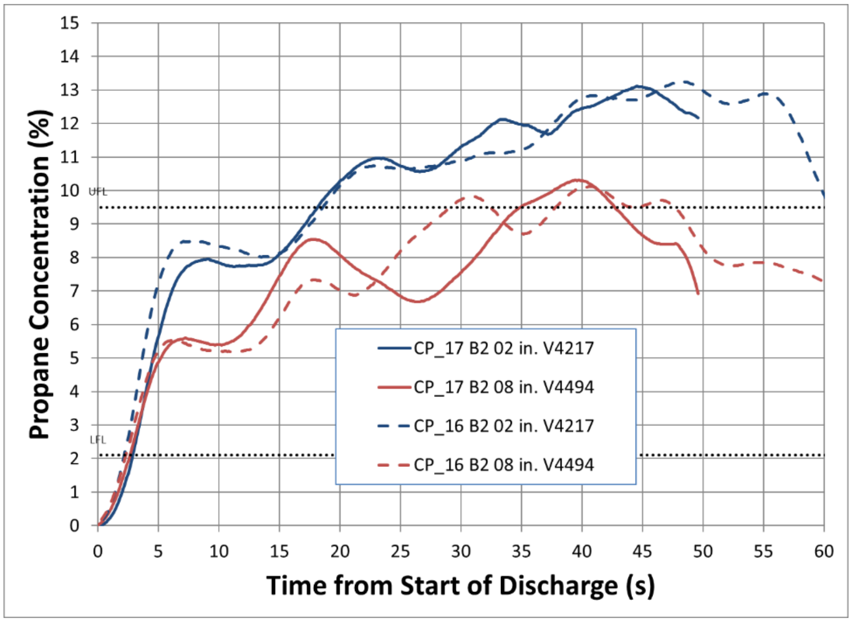


Figure 179 – CP_16 and CP_17 Concentration Comparison

Figure 180 shows the mass flow rate and total mass flow.

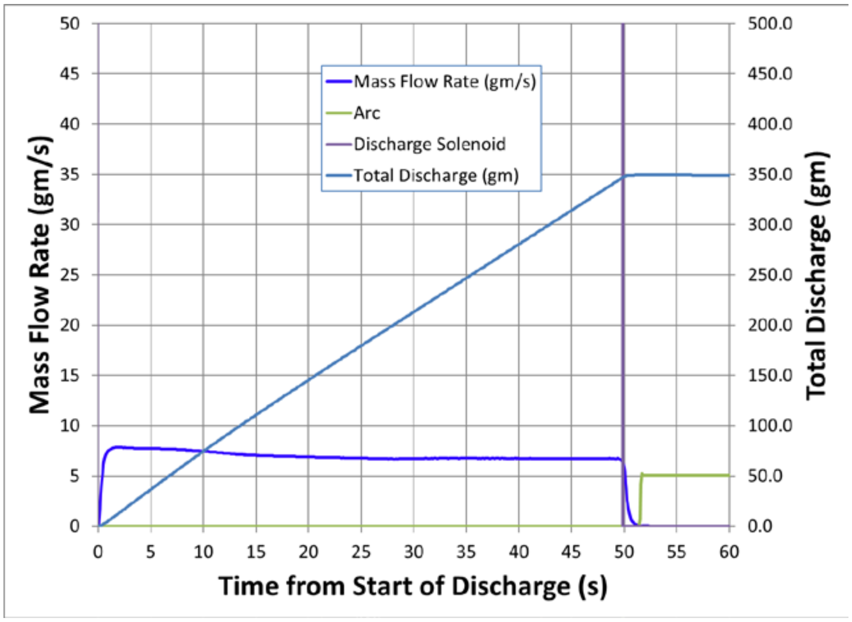


Figure 180 – CP_17 Mass Flow

Figure 181 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

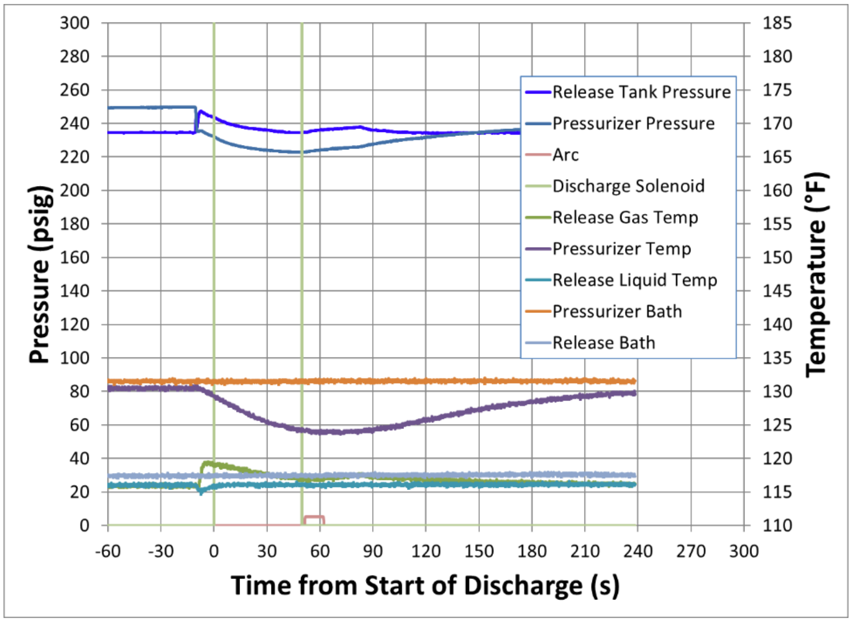


Figure 181 – CP_17 Pressurizer and Release Tank Pressure and Temperatures

Figure 182 shows the temperatures developed at the various locations following ignition.

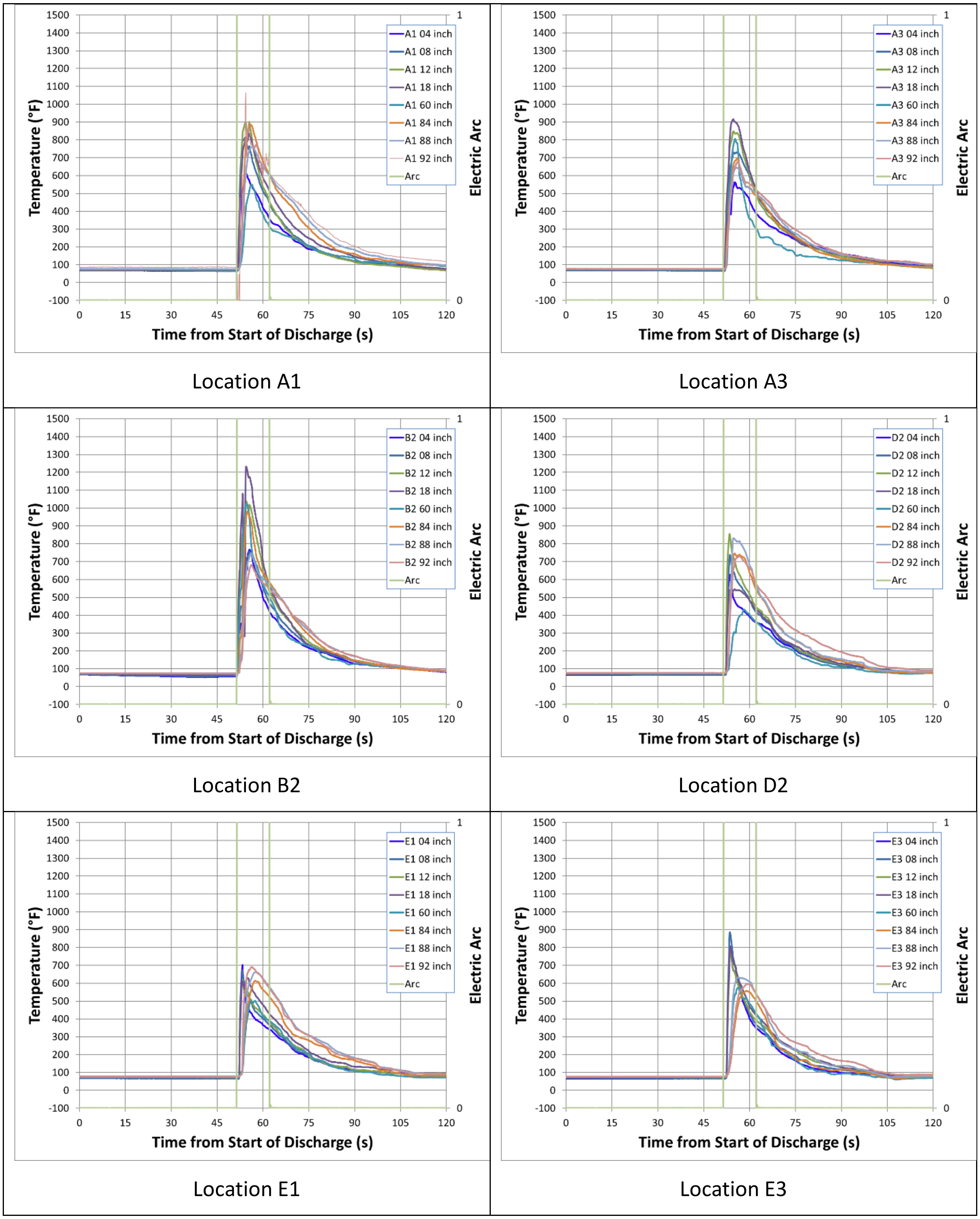


Figure 182 – CP_17 Temperatures at thermocouple trees

Notes to Figure 182:

- Location A1 92-inch level thermocouple was erratic. This thermocouple was replaced in later tests.
- All locations show a more rounded approach to peak temperatures at the 60-inch to ceiling levels due to the buoyancy of the gases ignited at the floor level.

Figure 183 shows the temperatures recorded by the pool thermocouples. Pool02 and Pool03 both showed indications of liquid propane at the bead. All four thermocouples detected the formation of a liquid pool at those location. The duration of this pool is shortened compared to the concentration test CP_16 (Figure 177) due to combustion and more rapid evaporation.

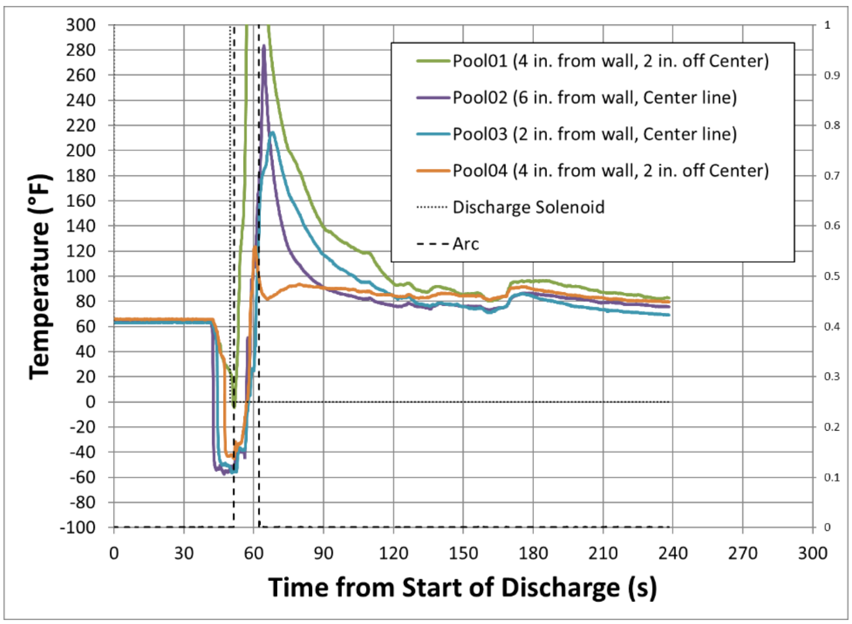


Figure 183 – CP_17 Liquid Propane Pool Temperatures

Figure 184 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 70 kW/m² exceeds the calibrated range of this heat flux sensor (0-50 kW/m²).

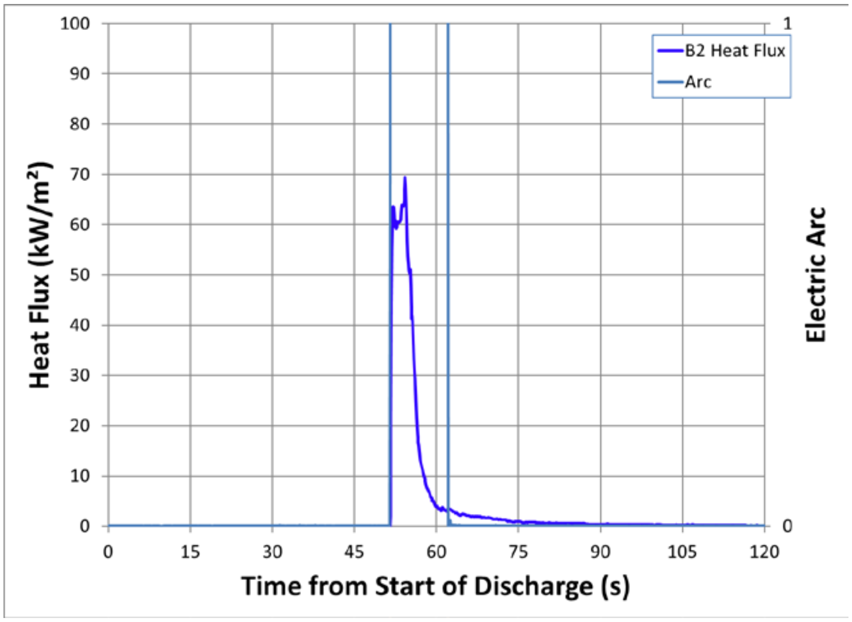
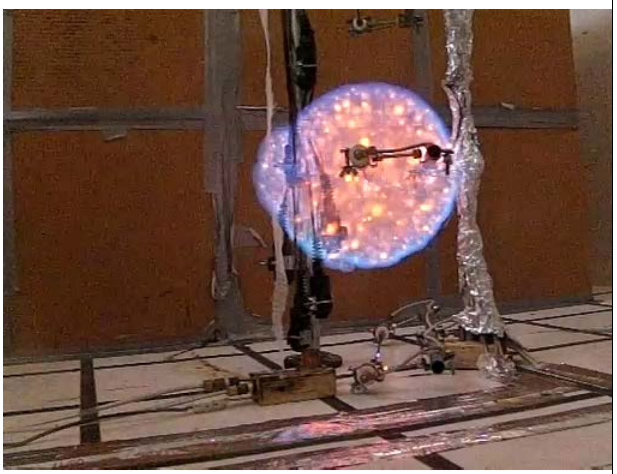


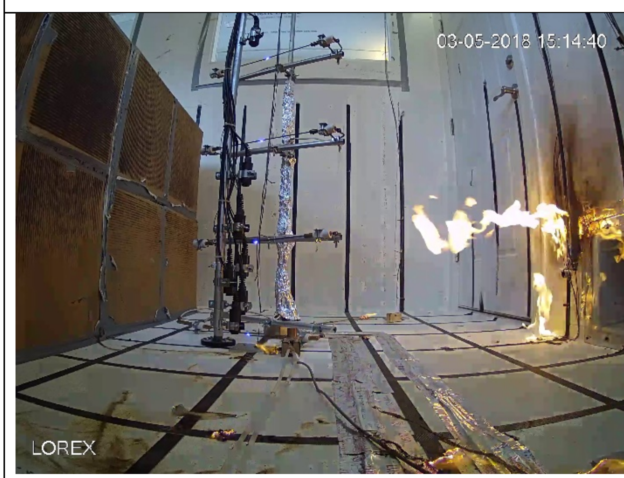
Figure 184 – CP_17 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 185. Ignition first appeared as a pre-mixed (blue) flame at the 12-inch level. This flame transitioned to a diffusion flame. The flames continued to the opposite side of the obstruction to ignition the flammable layer at the floor level. Burning of these air mixtures stopped after 2 seconds. Continued flaming at the discharge due did not occur in this test either due to insufficient oxygen and an ignition source in close proximity.

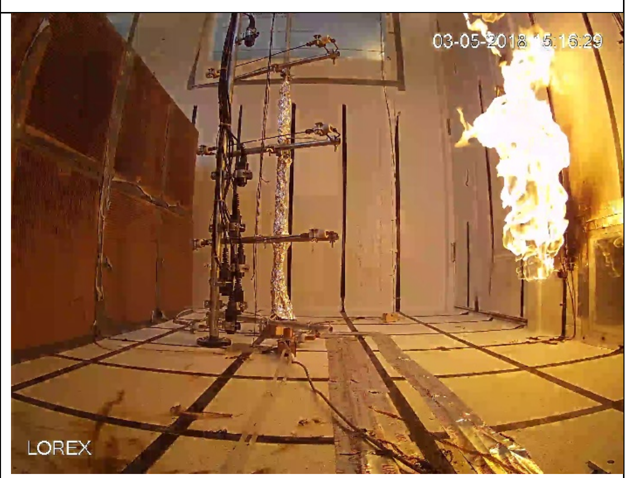


Ignition at the 12-inch level

Estimated maximum extent of propane-air flaming. Flaming extended around the obstruction to the flammable layer at floor level



Liquid Pool and Discharge Tube Flames



Flare from nitrogen purge of the discharge tube

Figure 185 – CP_17: Frames of flaming from videos

At the time of ignition, all three deflagration vents burst with some flames extending out from the east and west side vents as shown in Figure 186. The last vent melted open due to hot gases.

Figure 186 – CP_17 Flame extension through the west and east side vents

Test CP_18 (400 grams; 6.8 g/s; 0.2 height)

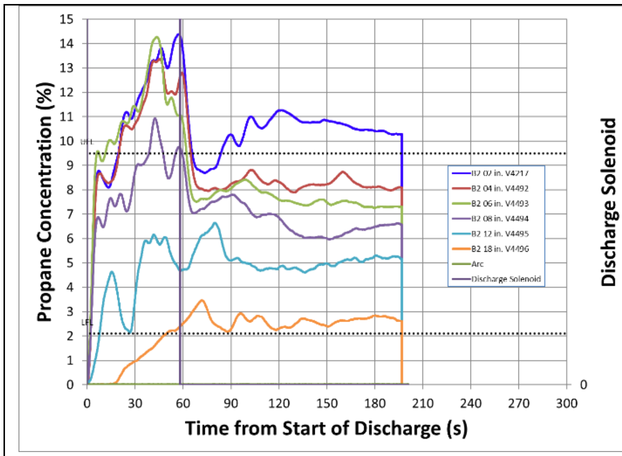
Test CP_18 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_19. This test involved release of 400 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and UFL (9.5%) was observed throughout the test room between the 4 and 12 inch level. The layer of gas at the 2-inch level was above the UFL (9.5%). This low-lying layer was beginning to show signs of diffusion within the room as indicated by increasing propane concentrations at the 36-inch level and higher.

Table 40 – CP_18 Summary

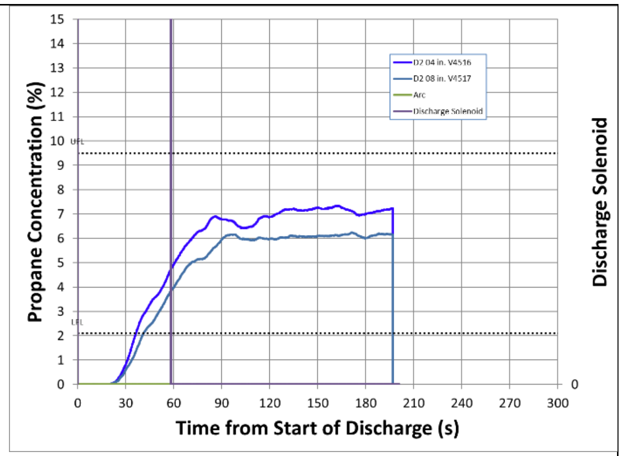
	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	400	58.8	6.8	0.2 m	1.1	Calculated if well Mixed in whole room
Measured	397	58.1	6.8		14.3 2.4	Location B 2-inch Location B 18-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

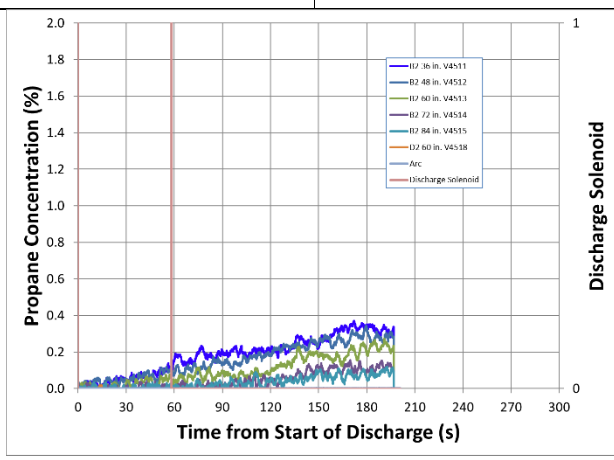
Figure 187 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. Sensors at the 18-inch level and lower showed concentrations above LFL of 2.1% to the end of data recording, but were slowly decreasing. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels. The 2-inch level is above the UFL



Deconvoluted concentrations measured at location D2, 2-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 187 – CP_18 Concentrations

Figure 188 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

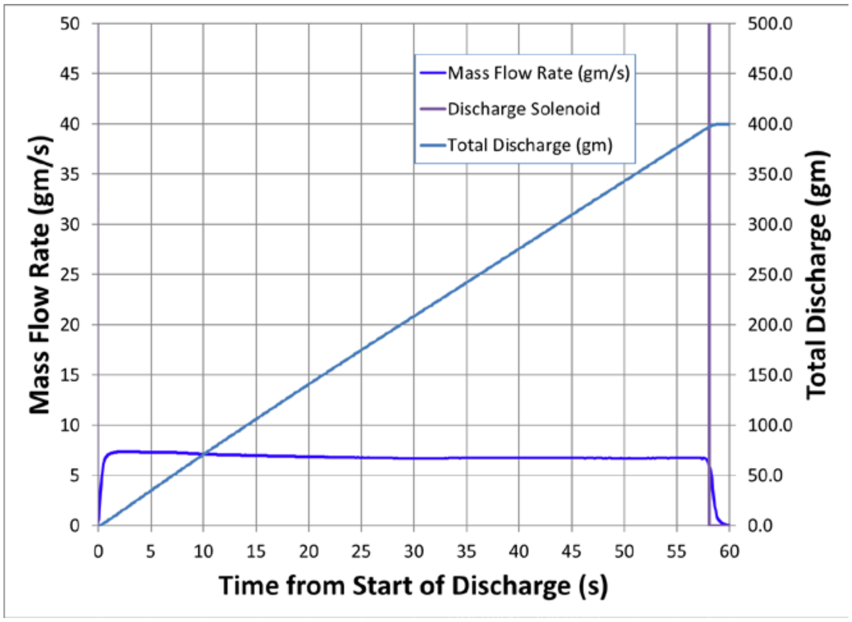


Figure 188 – CP_18 Mass Flow

Figure 189 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures. The pressurizer does not show this increase because the pressurizer was not isolated from the release tank until after data recording was completed.

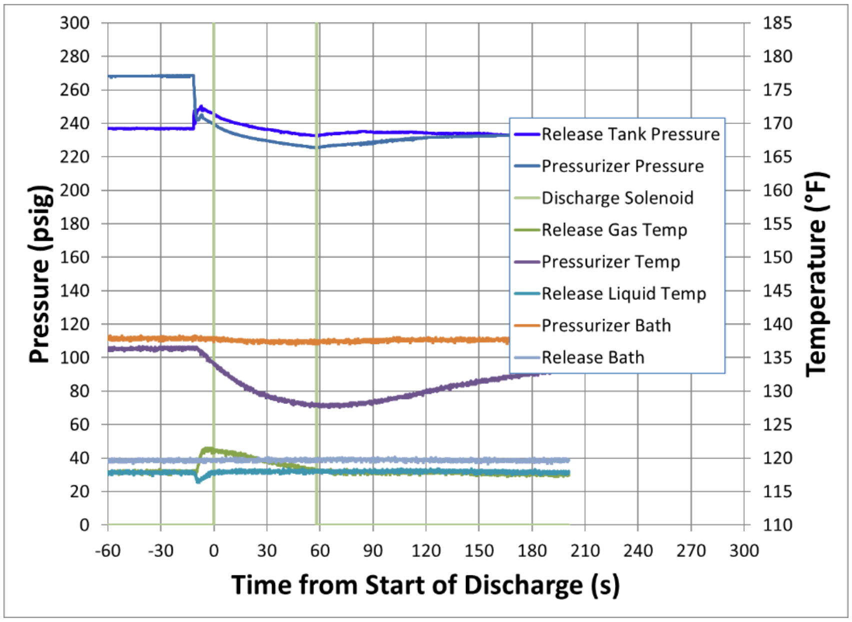


Figure 189 – CP_18 Pressurizer and Release Tank Pressure and Temperatures

Figure 190 shows the thermocouple response to liquid propane pooling on the floor in front of the discharge tube. The temperatures show that the pool evaporated with 60 to 90 seconds after the discharge valve closed.

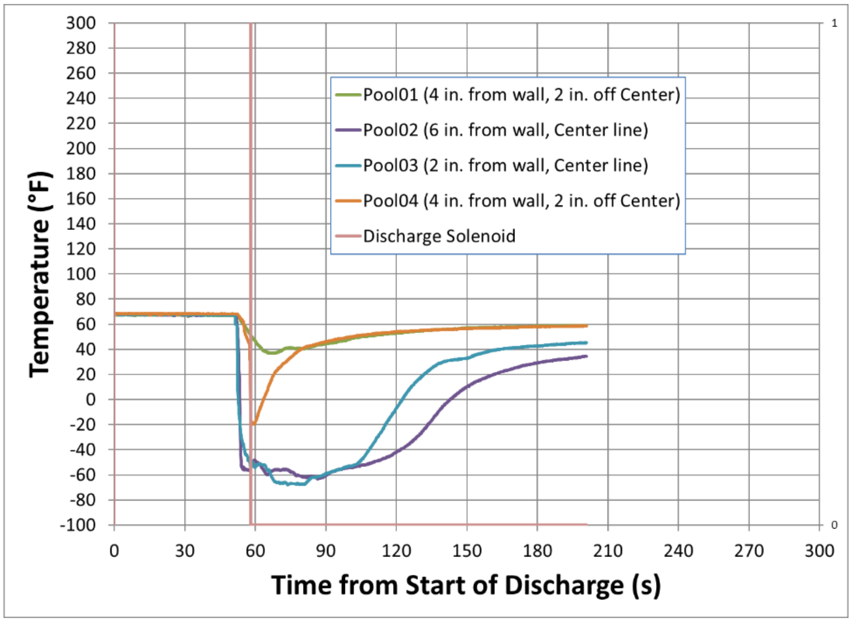


Figure 190 – Liquid pooling at the floor

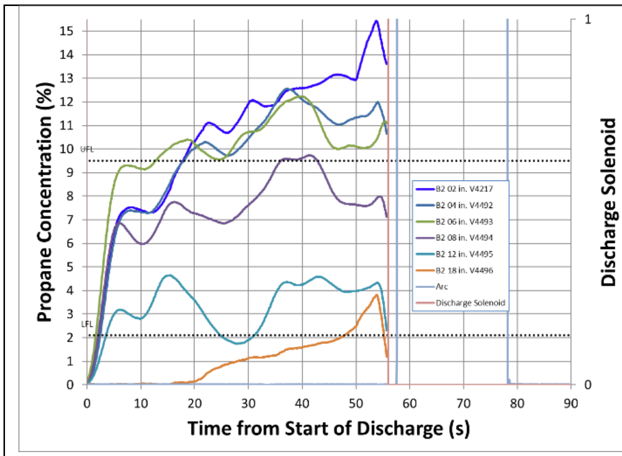
Test CP_19 (400 grams; 6.8 g/s; 0.2 height; with Igniters)

Test CP_19 was performed with ignition sources and resulted in ignition at location B2 at the 12-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_18 showed concentration at the 2-inch level was above the UFL and not ignitable. Concentrations at the 24- and 36-inch levels were lower than LFL.

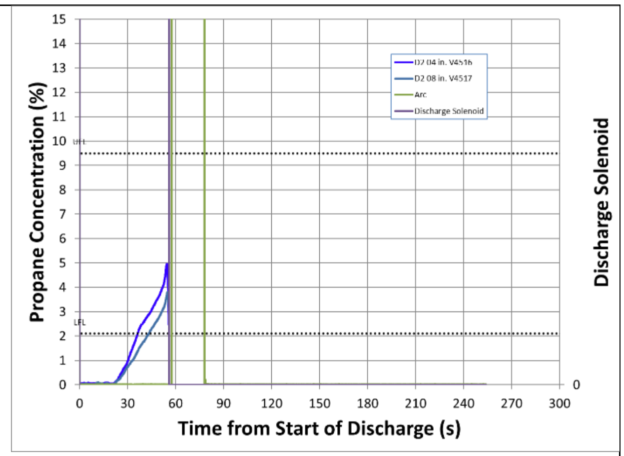
Table 41 – CP_19 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	400	58.8	6.8	0.2 m
Measured	397	56.0	7.1	

Figure 191 shows the deconvoluted concentrations measured up to the point up to a certain time. The combustion products would cause a false measure of propane concentration once there is igntion. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration at the 12-inch (approximately 4%) while the 2-inch level shows a concentration above the UFL of approximately 15%.



Location B2 concentrations just prior to ignition



Location D2 concentrations just prior to ignition

Figure 191 – CP_19 Concentrations

Figure 192 compares the pre-ignition and ignition test (CP_18 and CP_19) concentrations at the 1-inch and 12-inch levels at location B2 at locations A and B for the pre-test and ignition tests.

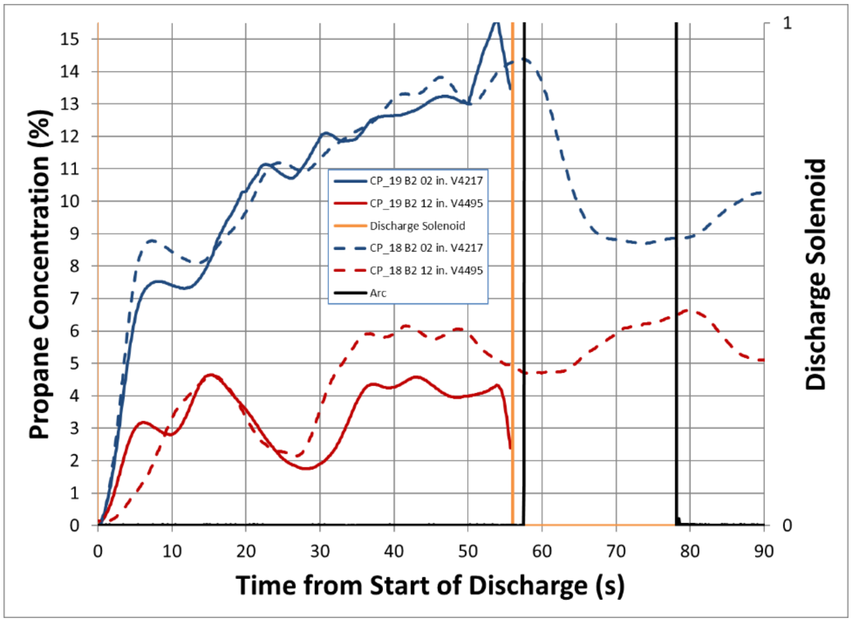


Figure 192 – CP_18 and CP_19 Deconvoluted Concentration Comparison

Figure 193 shows the mass flow rate and total mass flow.

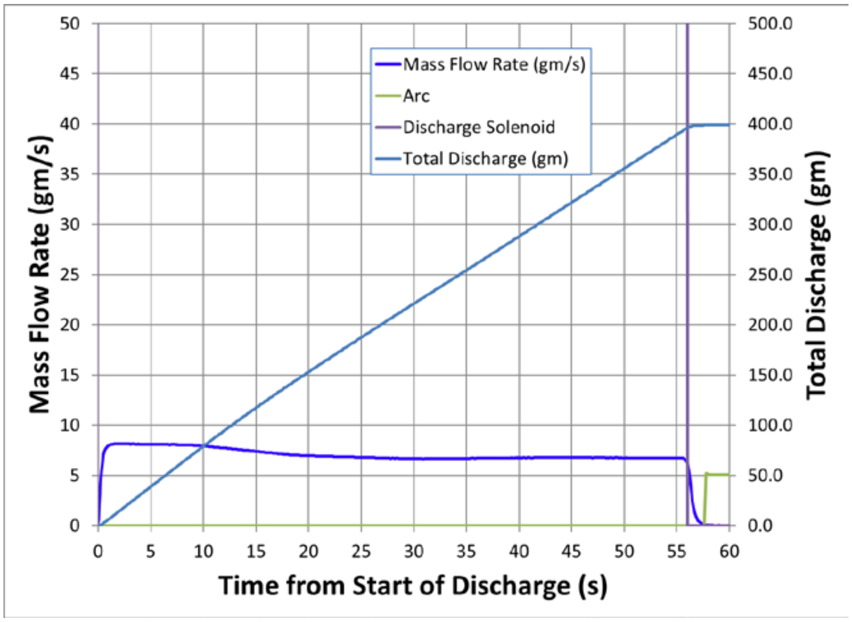


Figure 193 – CP_19 Mass Flow

Figure 194 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

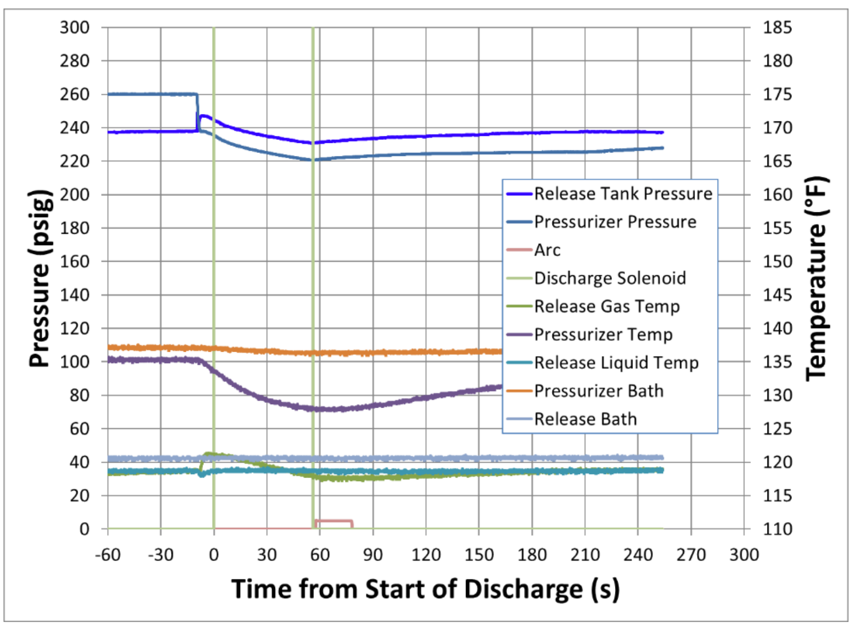


Figure 194 – CP_19 Pressurizer and Release Tank Pressure and Temperatures

Figure 195 shows the temperatures developed at the various locations following ignition.

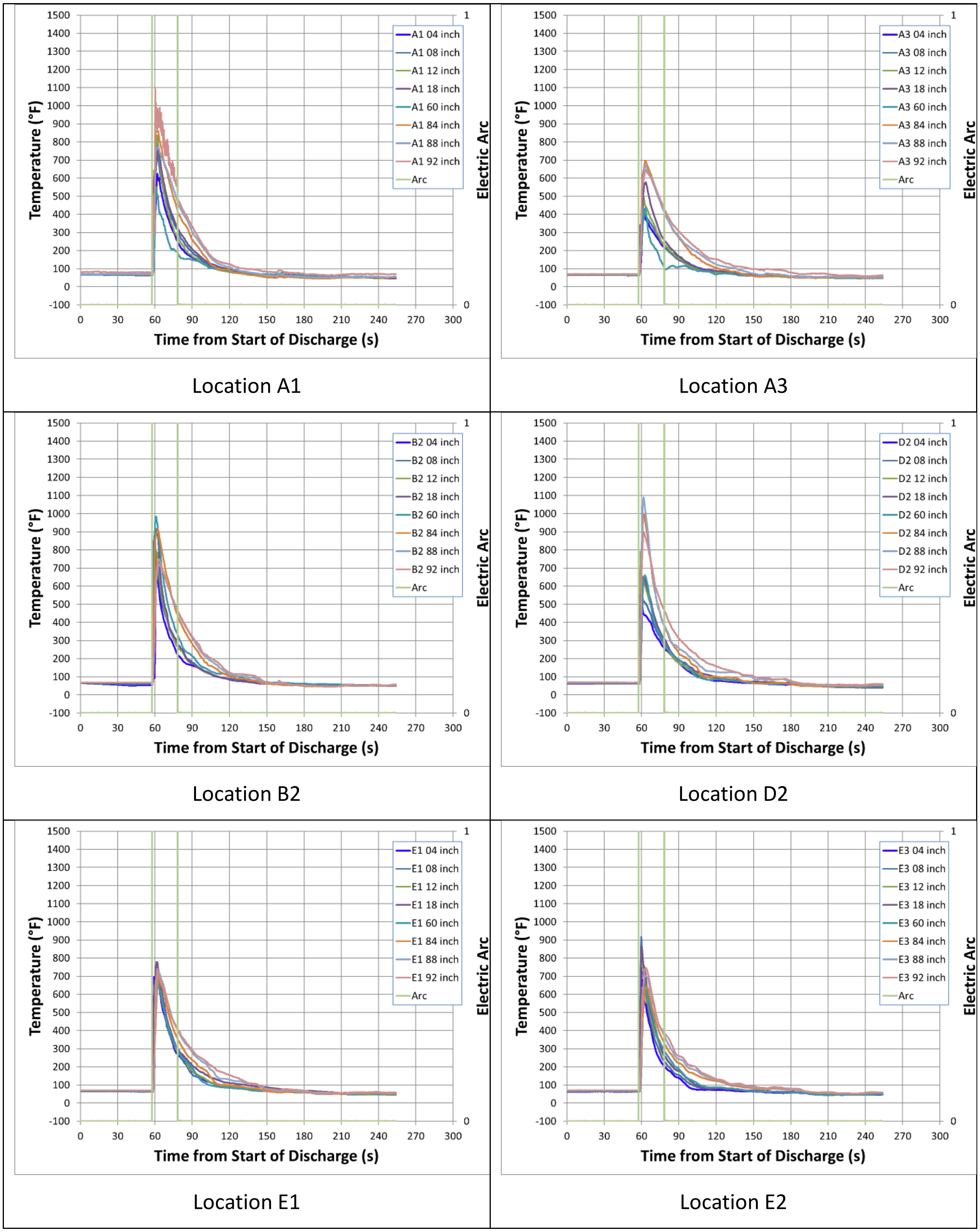


Figure 195 – CP_19 Temperatures at thermocouple trees

Figure 196 shows the temperatures recorded by the pool thermocouples. The data shows the formation of a pool of liquid propane that endured for some time after ignition occurred. Analysis of this data and the videos show that this pool persists until 7 to 10 seconds after the arc ignition.

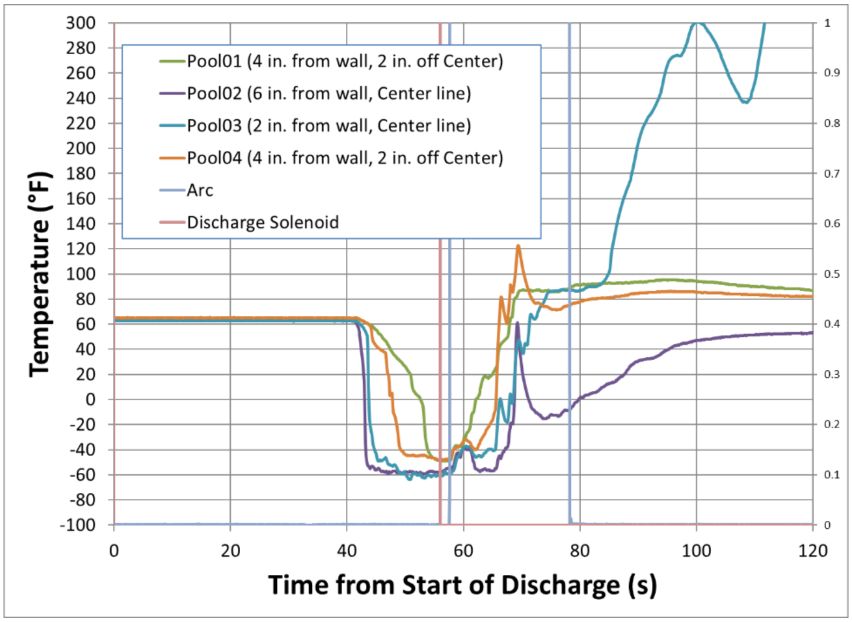


Figure 196 – CP_19 Liquid Propane Pool Temperatures

Figure 197 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 12-inch level.

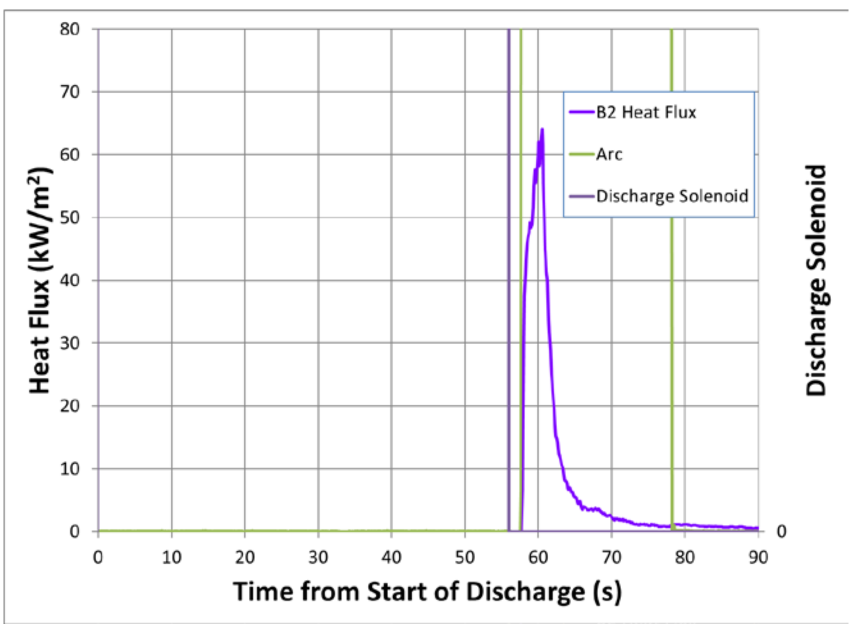
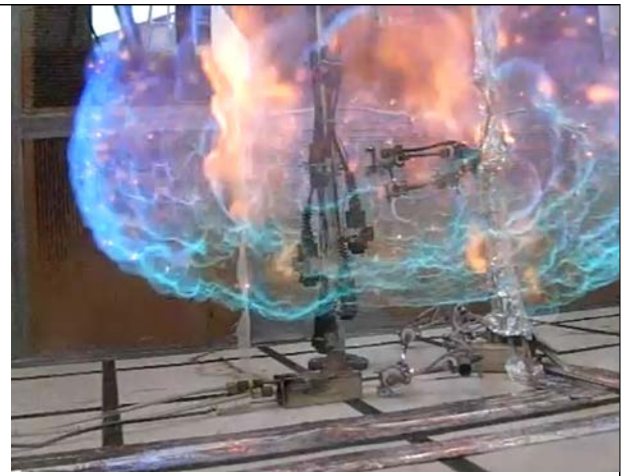


Figure 197 – CP_19 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 198. Burning started (A) as a spherical ball at the 12-inch level. As it spread in all directions, it flattened at the floor level (B) where concentrations were above the UFL. The fire wrapped around the obstruction (C) and continued to ignite the flammable layer at floor level until the entire floor area was ignited (D). Burning of these air mixtures stopped after 2 seconds. At the time of ignition, two deflagration vents burst while the other two melted open within 1 second due to the hot gases.

(C) Ignition at Location B2 12-inch Level



(D) Fireball flattens at a floor layer above UFL (approximately 0.1 seconds after ignition)

(E) Flames wrap around obstruction to ignite flammable concentrations at floor level

(F) Flames originating at the entire floor area

Figure 198 – CP_19: Frames of flaming from videos

Figure 199 shows that flaming continued at a liquid pool (A) of propane on the floor below the discharge tube after ignition of the air mixtures had stopped. The discharge tube still contained propane possibly in the liquid state that continued to discharge well after the discharge solenoid valve had closed (B). The discharge tube was purged with nitrogen 39 seconds after ignition to prevent damage to the facilities.

(A) Burning pool of liquid propane

(B) Propane flaming at discharge tube location

Figure 199 – CP_19: Pool burning and discharge tube flames

Test CP_20 (200 grams; 6.8 g/s; 1.8 height)

Test CP_20 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_21. This test involved release of 200 grams of propane through a 25 mm tube located at 1.8 m on the center of the short wall of the test room. The mass discharge rate was planned for 6.8 g/s, while the measured value was 7.1 g/s.

The videos of this test show this discharge behaved as a slow jet. The stream was moving along the length of the room, but also dropping, staying high in the test room throughout the entire length until it collided with the opposite wall and began sinking to the floor level. The data show that the highest concentrations of propane occurred on the side of the obstruction opposite the discharge location.

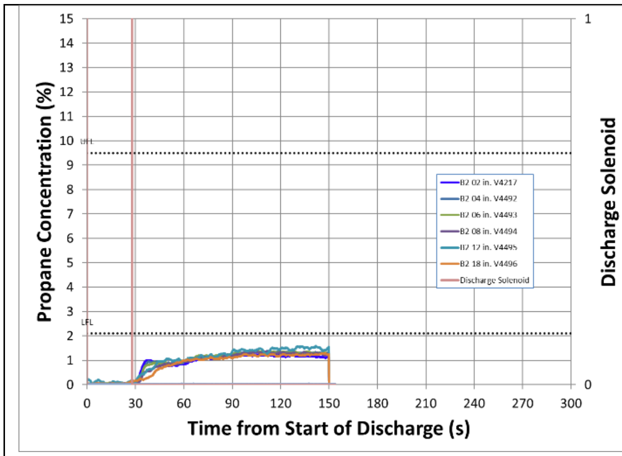
Table 42 – CP_20 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at Discharge Completion (%)	
Planned	200	29.4	6.8	1.8 m	0.6	Calculated if well Mixed in whole room
Measured	199	28.0	7.1		1.6 9.0	Location D 4-inch Location B 72-inch

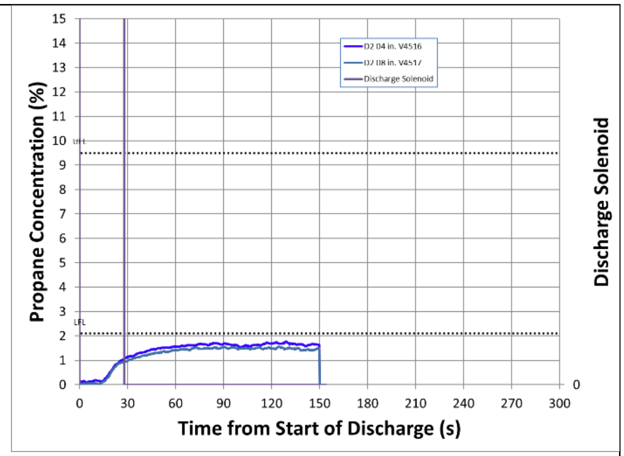
Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 200 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. Location B2 was on the discharge tube side of the obstruction and showed an increase in concentration higher than the well-mixed value of approximately 0.6%. Location D2 sensors at the 2- and 8-inch levels showed a similar increase above the well-mixed value. This data shows that the discharge stream was insufficient to stir the whole room to equal concentrations at the end of data recording.

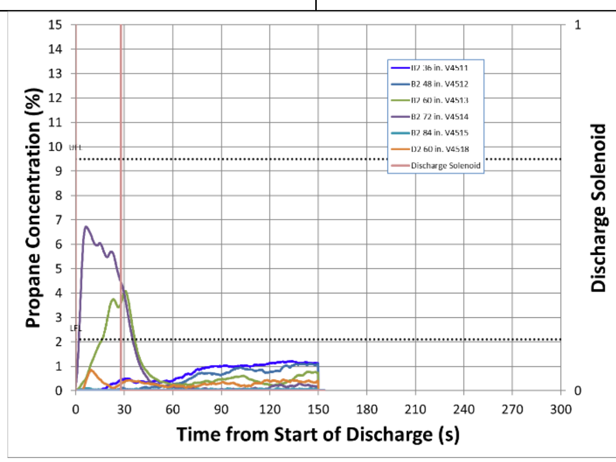
Of the higher elevation sensors, location B2 72-inch (1.8 m) level showed the highest concentration, 4.5%, immediately after completion of the discharge. This sensor was directly in the path of the discharge located at 1.8 m on the wall. Location B2 60-inch (1.5 m) showed a concentration of 3.8% immediately after completion of the discharge. The sensors at location D2 did not show increases above the LFL value of 2.1%. The sensor at location B2 84-inch level showed a final value of 0.1% a further indication that the discharge rate was insufficient to stir the whole contents of the test room.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 2-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 200 – CP_20 Concentrations

There was no evidence of liquid propane pools at the floor level. Mist during the discharge was also not observed.

Figure 201 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

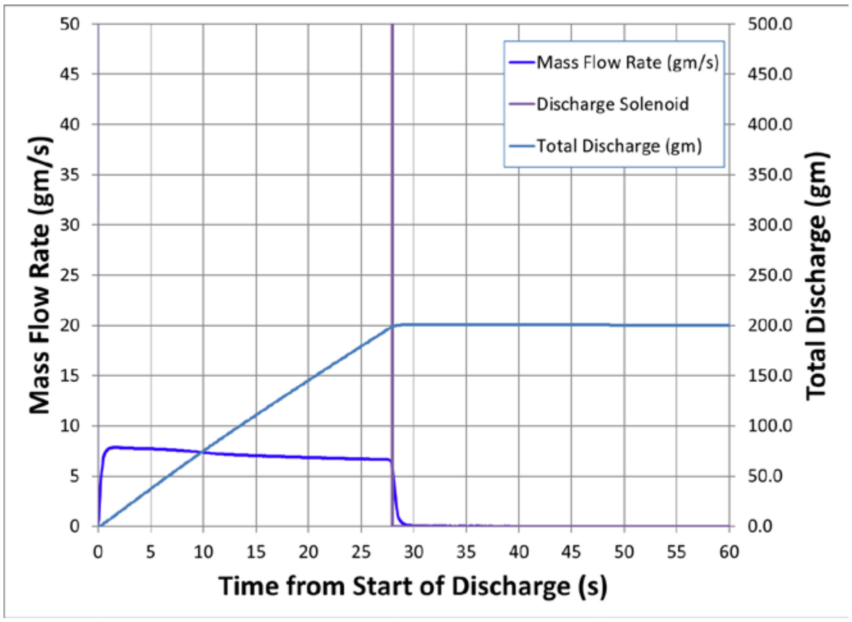


Figure 201 – CP_20 Mass Flow

Figure 202 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

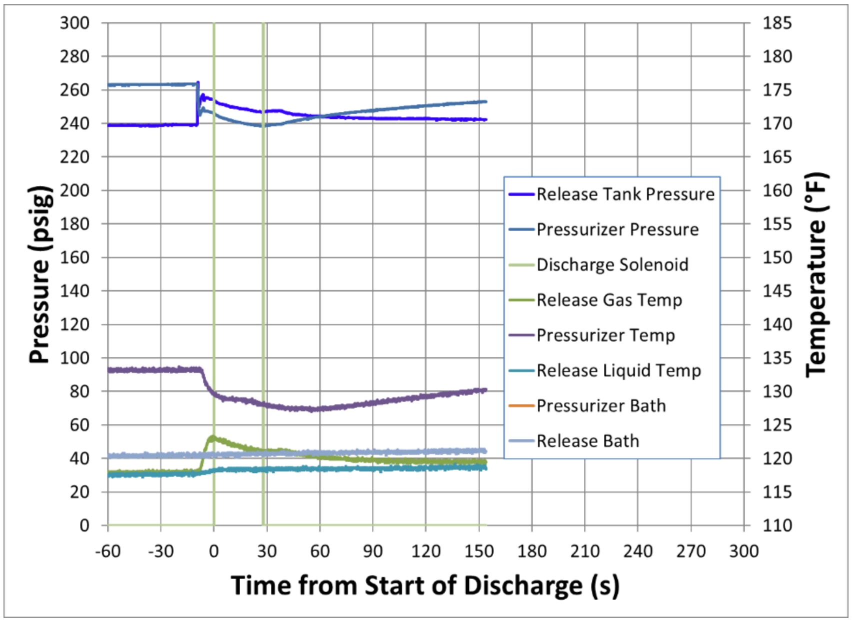


Figure 202 – CP_20 Pressurizer and Release Tank Pressure and Temperatures

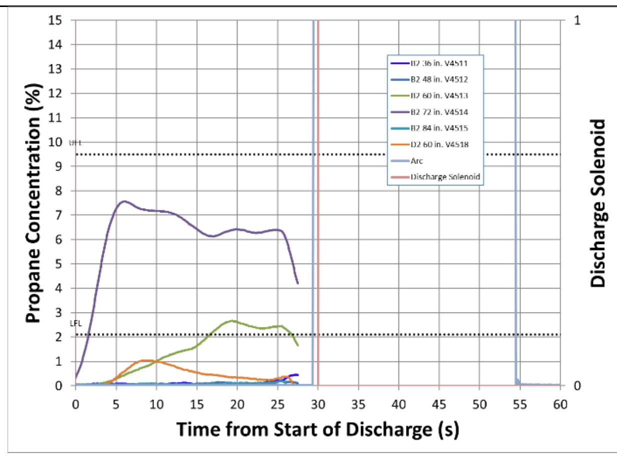
Test CP_21 (200 grams; 6.8 g/s; 1.8 height; with Igniters)

Test CP_21 was performed with ignition sources and resulted in ignition at location B2 at the 72-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 72-inch levels).

Table 43 – CP_21 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	200	29.4	6.8	1.8 m
Measured	196	29.4	6.7	

Figure 203 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentrations location B2 72-inch level. Concentrations at other locations were all less than LFL.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 203 – CP_21 Concentrations

Figure 204 compares the pre-ignition and ignition test (CP_20 and CP_21) concentrations at B2 72-inch and D2 60-inch levels for the pre-ignition and ignition tests.

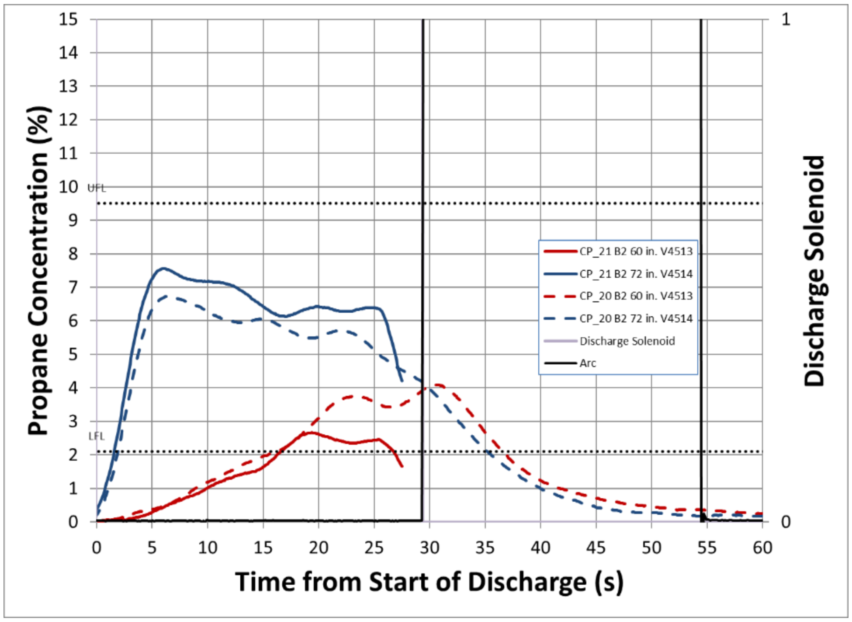


Figure 204 – CP_20 and CP_21 Concentration Comparison

There was no evidence of liquid propane pools at the floor level. Mist during the discharge was also not observed.

Figure 205 shows the mass flow rate and total mass flow.

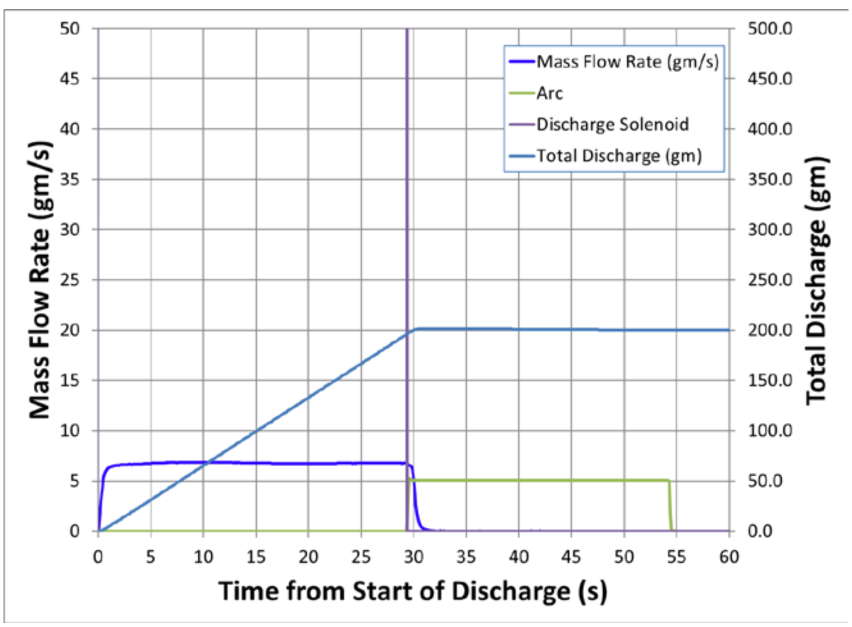


Figure 205 – CP_21 Mass Flow

Figure 206 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The pressurizer pressure transmitter had failed prior to this test and was replaced before the continuing the test schedule. Additionally, the pressurizer tank was not placed in line with the release tank due to a procedure oversight.

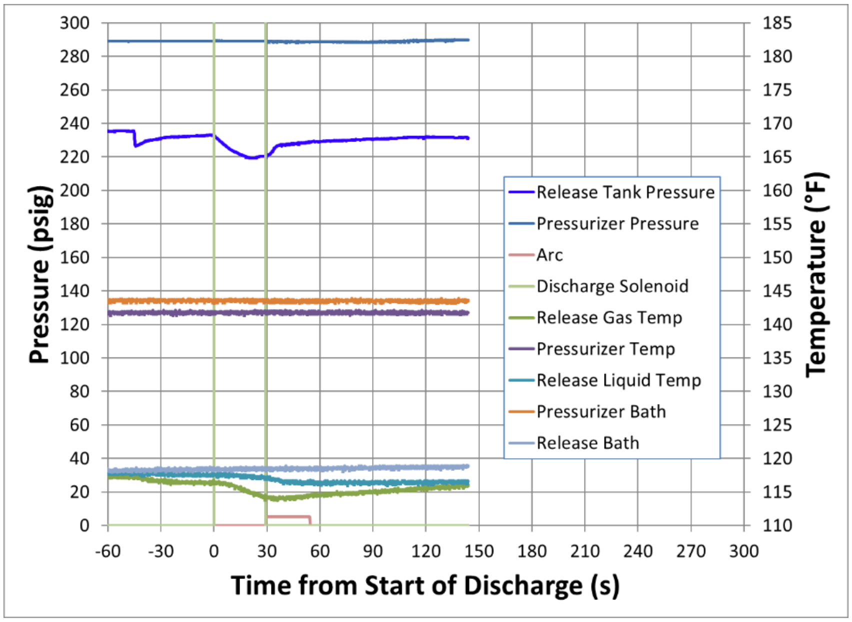


Figure 206 – CP_21 Pressurizer and Release Tank Pressure and Temperatures

Figure 207 shows the temperatures developed at the various locations following ignition.

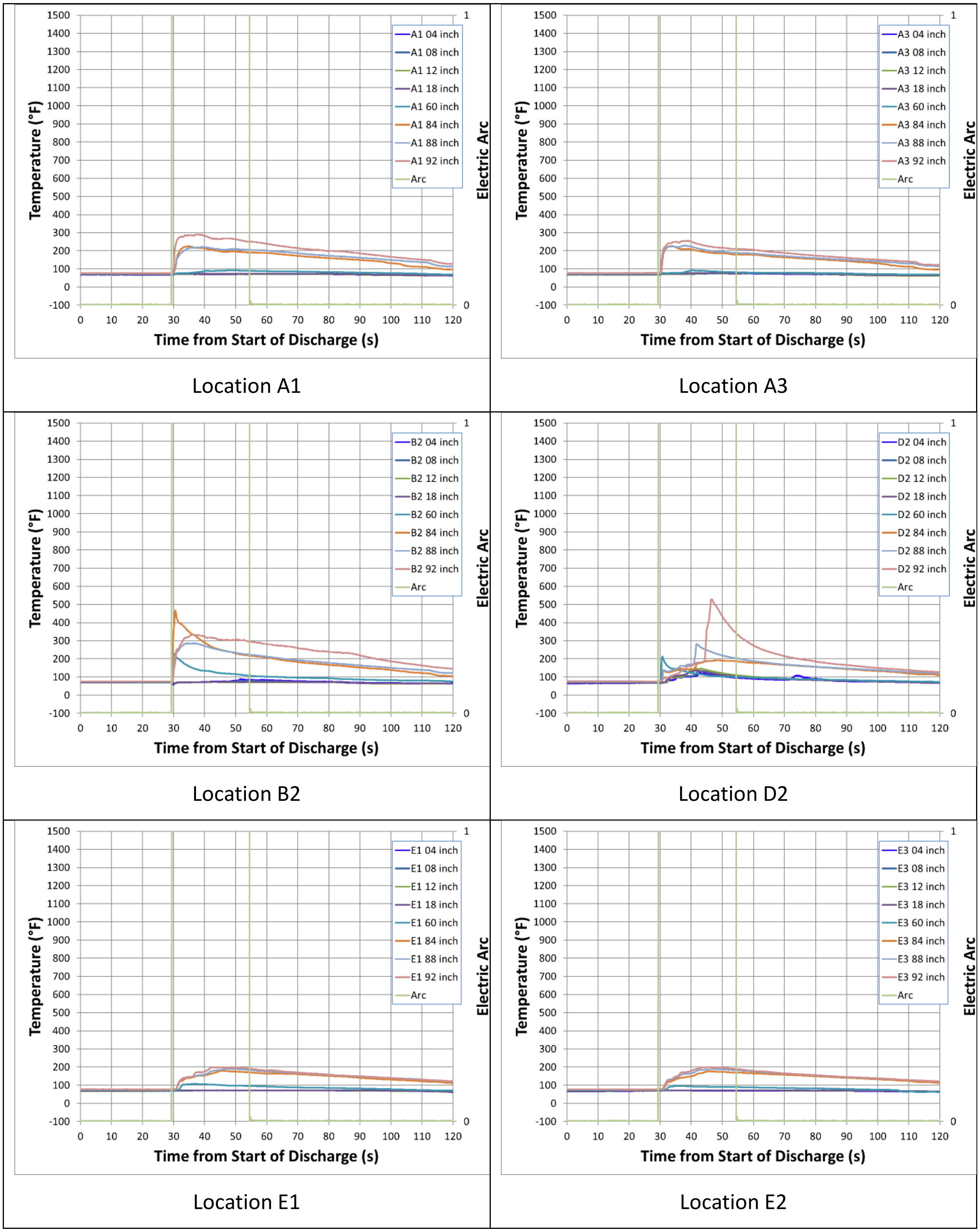


Figure 207 – CP_21 Temperatures at thermocouple trees

The sharp initial peaks after the 30 second mark at location B2 and D2 is due to ignition of the flammable mixture in that area. The sharp peaks after 40 seconds at location D2 are due to burning strips of cheesecloth near the thermocouples. All other locations show a slower increase to their maximum temperatures due to buoyancy and circulation of the hot gases.

Figure 208 shows the temperatures measured at the 18-inch level. There was a small increase in temperature other than the location D2 explained above. The other thermocouples below the 18-inch level show similarly small increases.

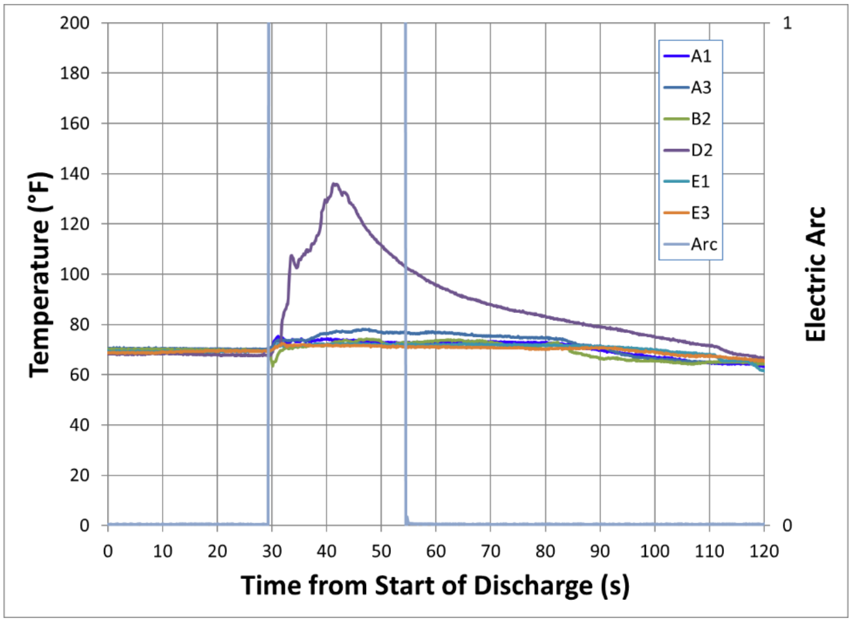


Figure 208 – CP_21 Thermocouples at the 18-inch level

Figure 209 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 72-inch level.

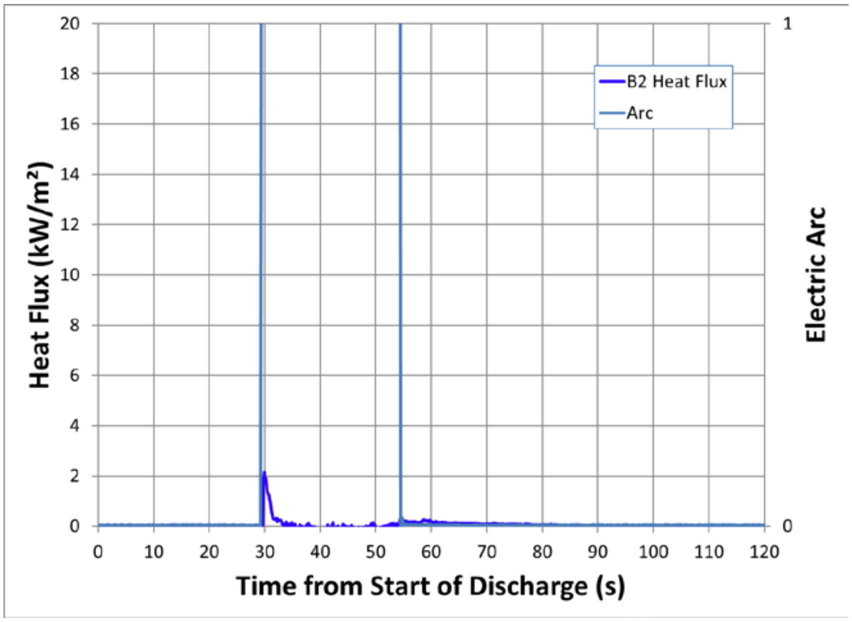


Figure 209 – CP_21 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in. (A) and (B) show ignition of a cone of flammable mixture extending from Location B2 72-inch level down to the far side of the obstruction. (C) shows ignition the remaining and expanding gas from the discharge tube. At 0.6 seconds after ignition (D) show a faint blue flame extending from the top of the obstruction to the floor. Burning of these air mixtures stopped after 0.6 seconds. One deflagration vent burst and another partially opened. The other two deflagration vents remained intact.

(A) 0.06 seconds after ignition at Location B2 72-inch Level.

(B) 0.2 seconds after ignition

(C) 0.5 seconds after. Arc ignites slow speed expansion of propane from the discharge tube.

(D) 0.6 seconds after ignition. Flames reach to the floor side of the obstruction opposite the discharge tube.

Figure 210 – CP_21: Frames of flaming from videos

Figure 211 shows that some propane remained in the discharge tube after the closure of the discharge solenoid. This gas slowly expanded and continued to flame for 50 seconds after ignition. The flames were manually suppressed after 1 minute to protect sensor wiring.

Flames continued at the discharge tube for one minute after ignition until manually extinguished.

Figure 211 – CP_21: Continued flaming from expanding propane in the discharge tube

Test CP_22 (400 grams; 40 g/s; 1.8 height)

Test CP_22 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_26. This test involved release of 400 grams of propane through a 25 mm tube located at 1.8 m on the center of the short wall of the test room. The mass discharge rate was planned for 40 g/s, while the measured value was 44.1 g/s.

The videos of this test show this discharge behaved as a jet staying high in the test room throughout the entire length until it collided with the opposite wall and began sinking to the floor level. The data show that the highest concentrations of propane at floor level occurred on the side of the obstruction opposite the discharge location.

Table 44 – CP_22 Summary

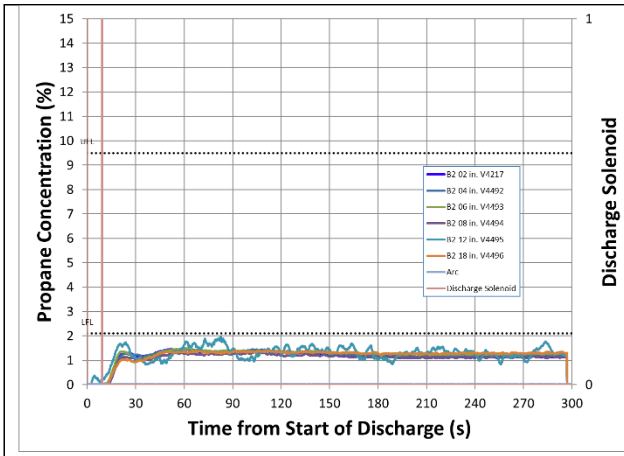
<table>
<tr><th></th><th>Discharge Amount (g)</th><th>Duration of Discharge (Seconds)</th><th>Discharge Rate (g/s)</th><th>Leak Location</th><th colspan="2">Concentration at Discharge Completion (%)</th></tr>
<tr><td>Planned</td><td>400</td><td>10.0</td><td>40</td><td rowspan="2">1.8 m</td><td>1.1</td><td>Calculated if well Mixed in whole room</td></tr>
<tr><td>Measured</td><td>401</td><td>9.2</td><td>44.1</td><td>1.6
9.0</td><td>Location D 4-inch
Location B 72-inch</td></tr>
</table>

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

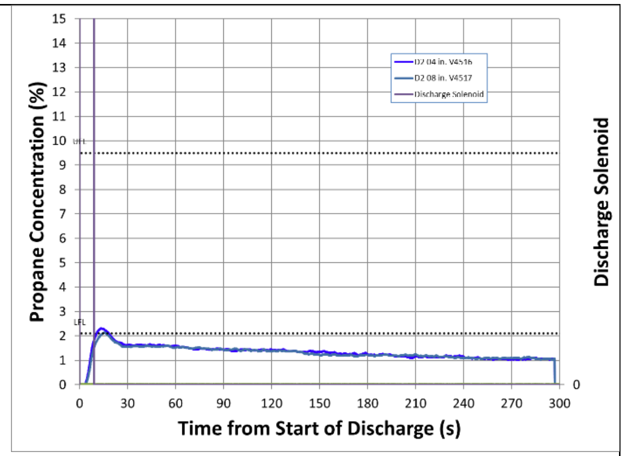
Figure 212 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. Location B2 was on the discharge tube side of the obstruction and showed an increase in concentration to the well-mixed value of approximately 1.1%. Location D2 sensors at the 2- and 8-inch levels showed and increase above the LFL immediately after completion of the discharge. These values declined to the same well-mixed value at the end of data recording.

Of the higher elevation sensors, location B2 72-inch (1.8 m) level showed the highest concentration, 9.0%, immediately after completion of the discharge. This sensor was directly in the path of the discharge located at 1.8 m on the wall. Location D2 60-inch (1.5 m) (opposite side of the obstruction) showed a concentration of 3.8% immediately after completion of the discharge.

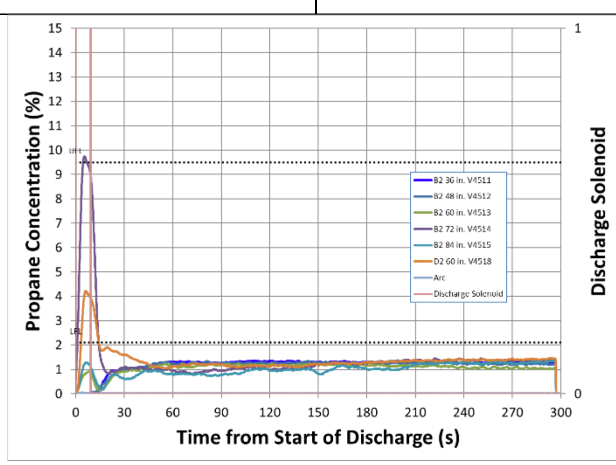
All sensors recorded values close to the well-mixed value of 1.1% at the end of data recording. This data indicates the action of near-complete stirring of the room by the jet discharge. The range of last recorded concentrations was 1.0 to 1.4% and the average was 1.2%.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 2-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 212 – CP_22 Concentrations

There was no evidence of liquid propane pools at the floor level. There was evidence of a mist during some stages of the discharge, but the videos show this mist quickly dispersing into the vapor state.

Figure 213 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

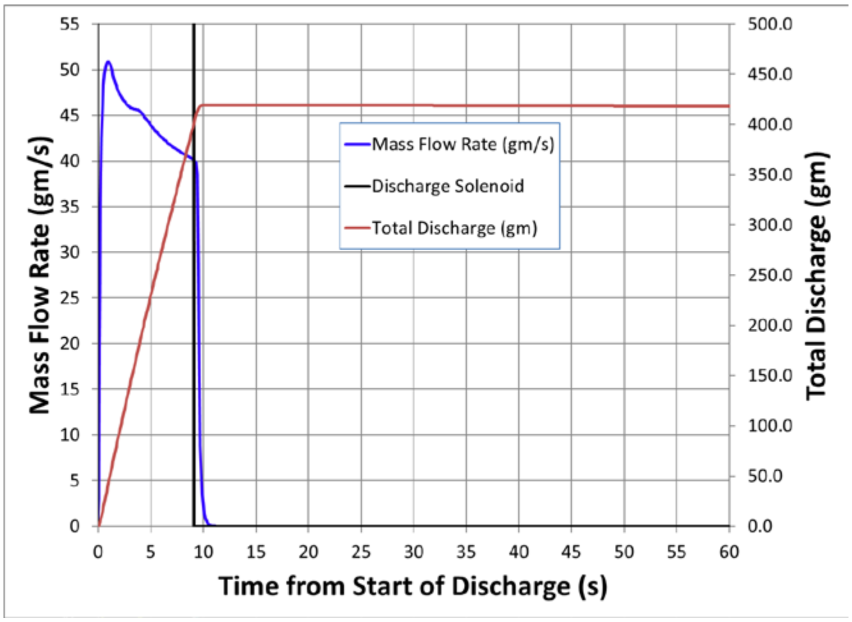


Figure 213 – CP_22 Mass Flow

Figure 214 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

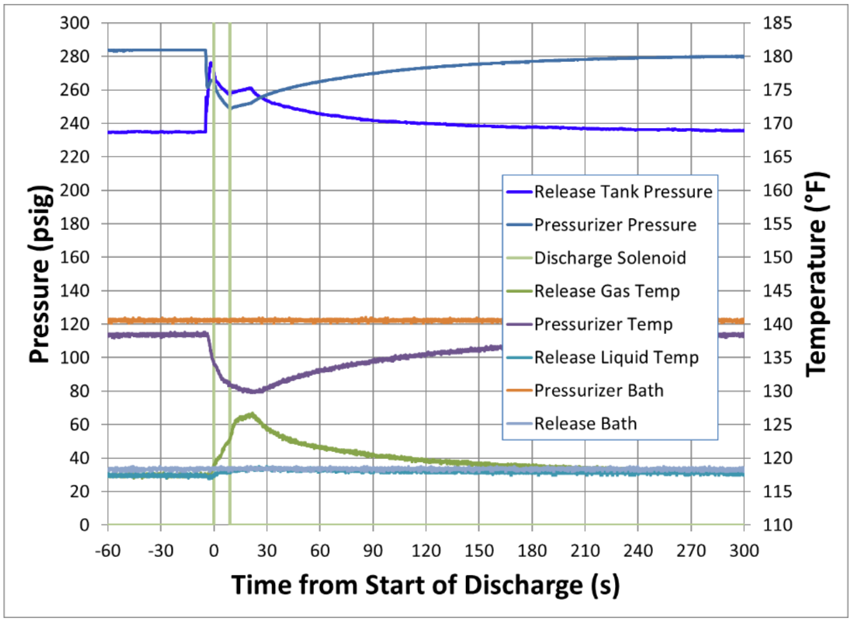


Figure 214 – CP_22 Pressurizer and Release Tank Pressure and Temperatures

Test CP_23 (400 grams; 40 g/s; 1.8 height; with Igniters)

Test CP_23 was performed with ignition sources and resulted in ignition at location B2 at the 72-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 72-inch levels). This test was repeated in test CP_26 because these test results showed the arc igniter was not located in the volume with the highest concentrations. In test CP_26, the igniter at the 72 -inch level was moved to be much closer to the center of the jet of gas from the discharge tube.

Table 45 – CP_23 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	400	10.0	40	1.8 m
Measured	417	9.5	44	

Figure 215 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentrations location B2 72-inch and D2 60-inch level. Concentrations at other locations were all less than LFL.

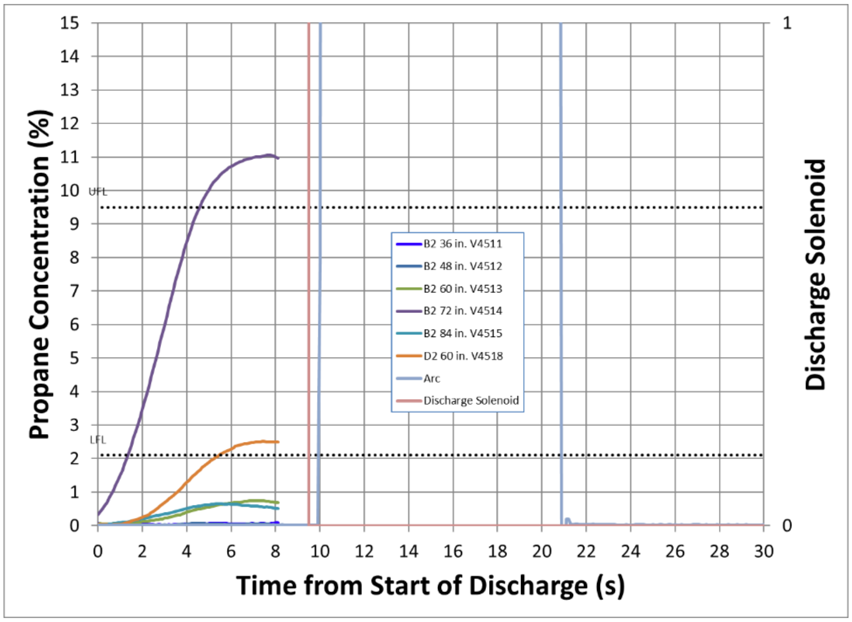


Figure 215 – CP_23 Concentrations

Figure 216 compares the concentration and igniter test(CP_22 and CP_23) concentrations at B2 72-inch and D2 60-inch levels for the pre-ignition and ignition tests.

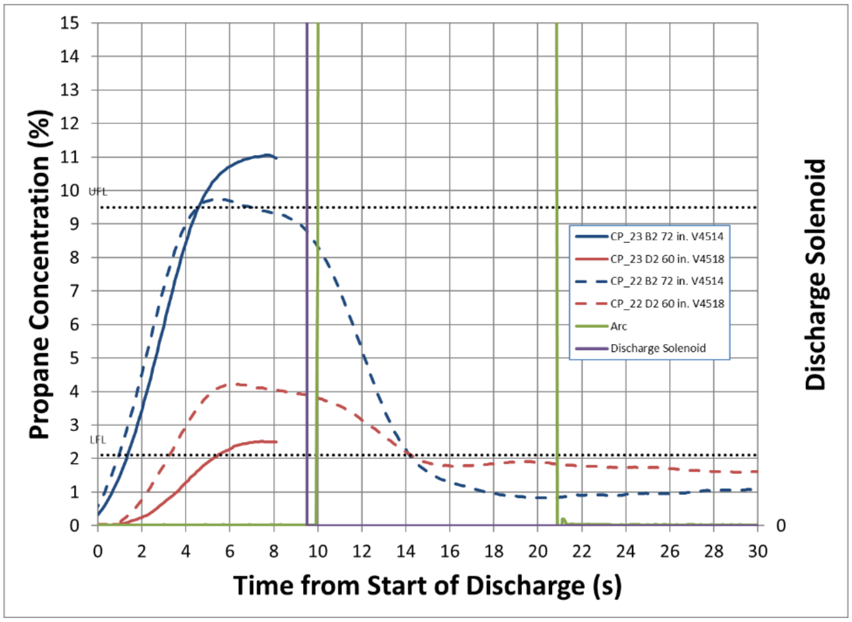


Figure 216 – CP_22 and CP_23 Concentration Comparison

There was no evidence of liquid propane pools at the floor level. There was evidence of a mist during some stages of the discharge, but the videos show this mist quickly dispersing into the vapor state.

Figure 217 shows the mass flow rate and total mass flow.

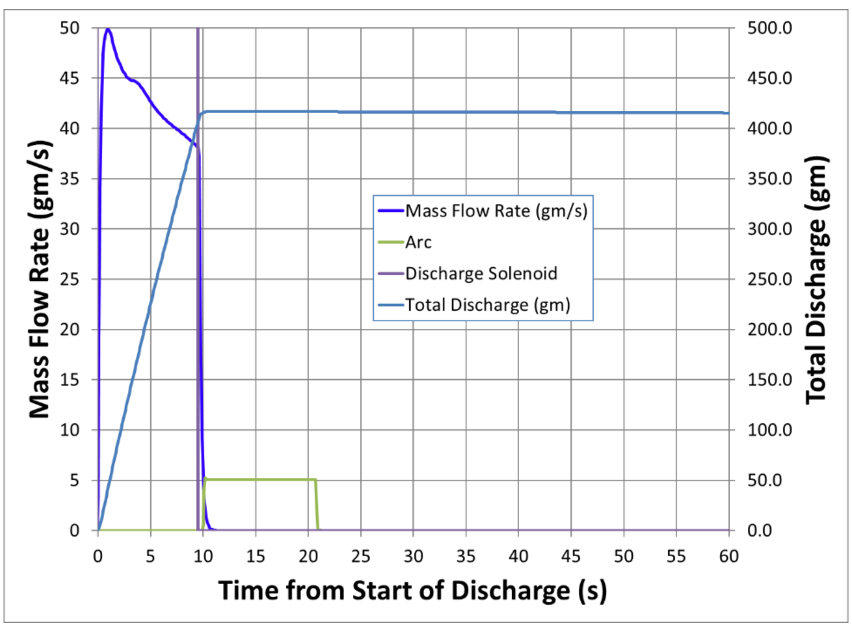


Figure 217 – CP_23 Mass Flow

Figure 218 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

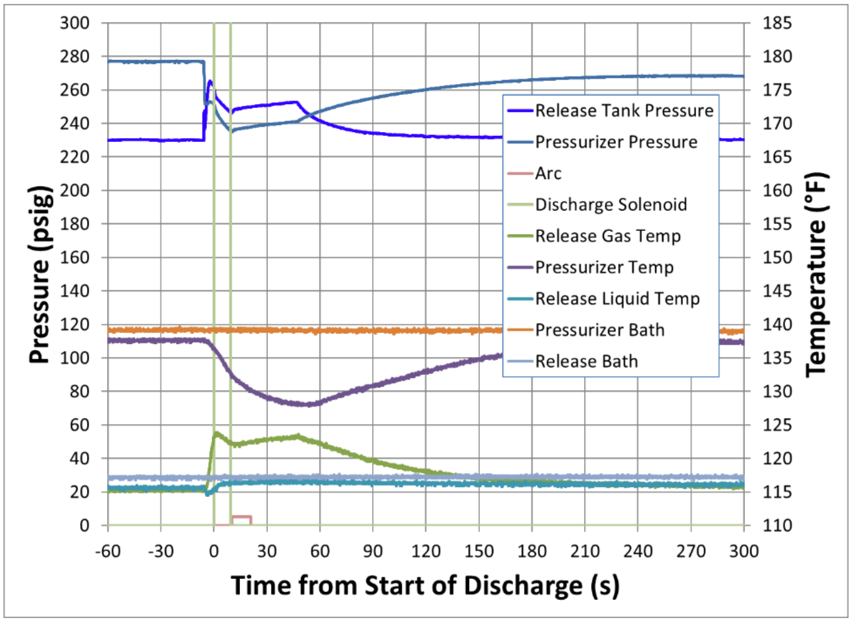


Figure 218 – CP_23 Pressurizer and Release Tank Pressure and Temperatures

Figure 219 shows the temperatures developed at the various locations following ignition.

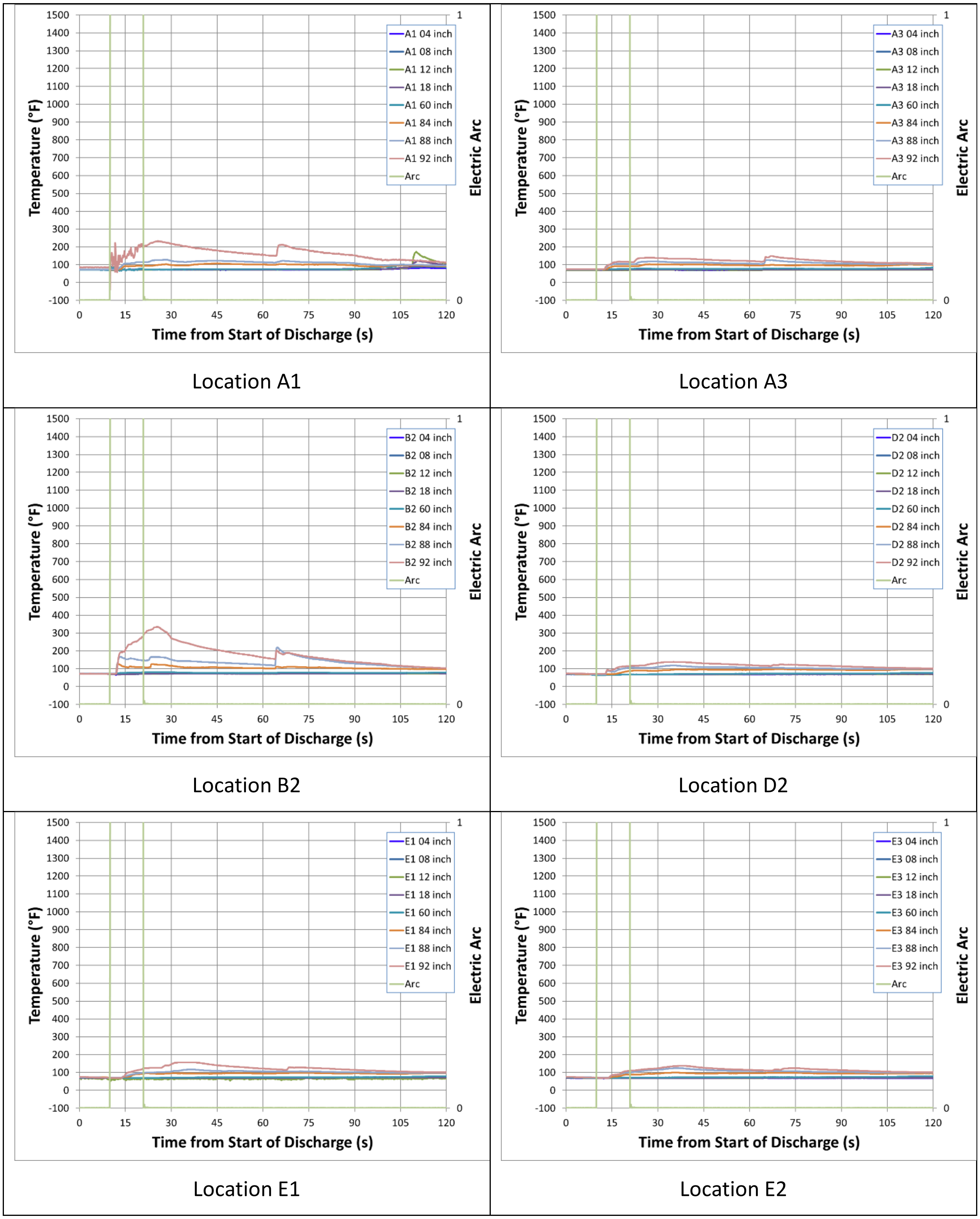


Figure 219 – CP_23 Temperatures at thermocouple trees

Notes to Figure 219:

- The first peak in temperature at 25 seconds was due to the ignition of the propane-air mixture
- The second peak at 65 seconds was due to a flare from purging the discharge tube with nitrogen
- The last peak at location A2 (110 seconds) was due to a fallen piece of cheesecloth ignited by the flare following the nitrogen purge.

Figure 220 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 72-inch level. The increase in heat flux between at 65 seconds was due to the flare at the discharge tube resulting from the nitrogen purge.

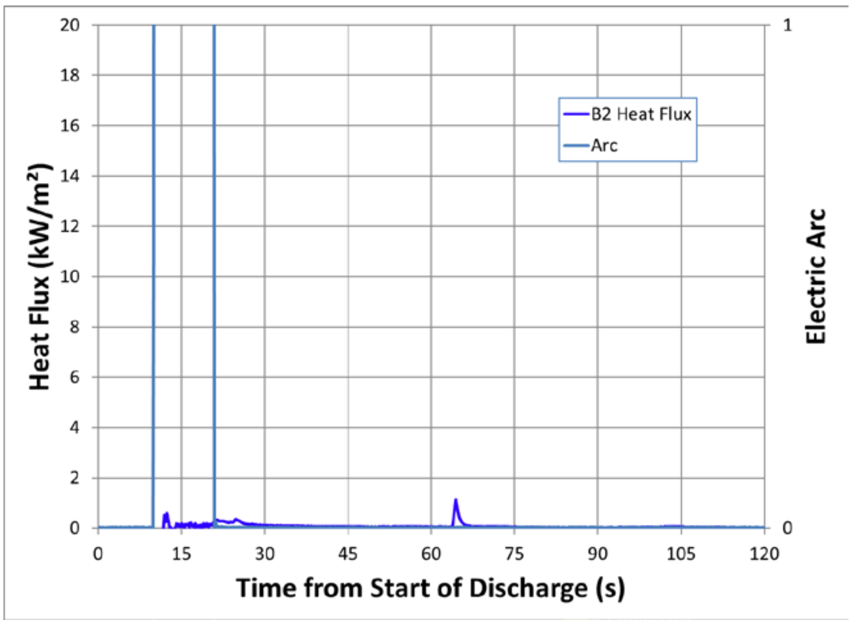
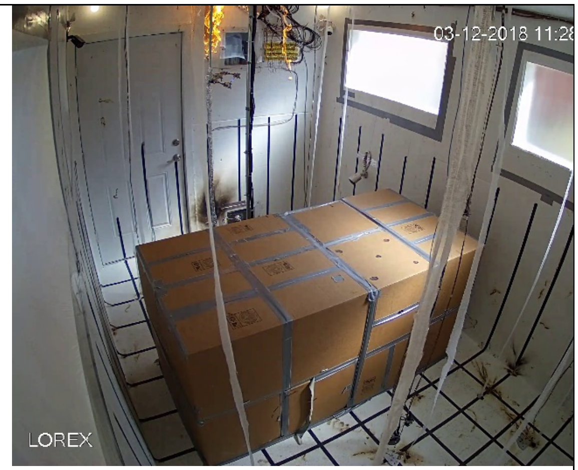


Figure 220 – CP_23 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 221. Ignition was barely visible in the camera view, but resulted in ignition of two cheesecloth strips and ignited the remaining propane expanding from the discharge tube. The tube was purged with nitrogen resulting in a brief flare at 55 seconds after the arcs were energized. There was no bursting or melting of the deflagration vents in this test.

Ignition (barely visible blue flame at the arc location)



Ignition of two cheesecloth strips.

Nitrogen purge of discharge tube

Figure 221 – CP_23: Frames of flaming from videos

Test CP_24 (400 grams; 40 g/s; 0.2 height)

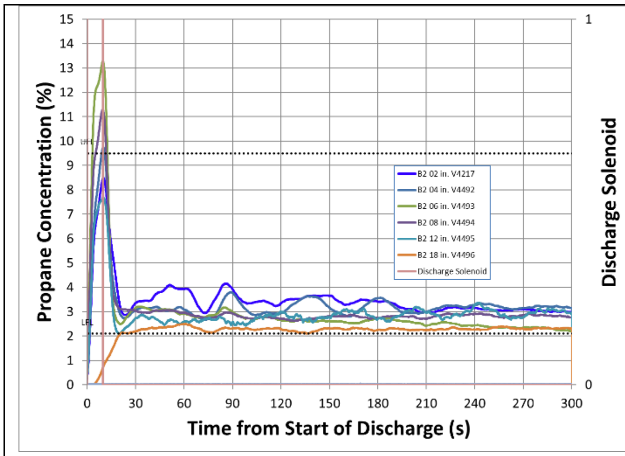
Test CP_24 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is CP_25. This test involved release of 400 grams of propane through a 25 mm tube located at 0.2 m on the center of the short wall of the test room. The key parameters and results of this test are summarized in the following table. At the end of data recording an ignitable volume between the LFL (2.1%) and 3% was observed throughout the test room between the 2 and 18 inch level. Sensors at the 36-inch level and higher reported concentrations between 0.5 and 1.0%. This gradient in concentrations showed that the discharge jet and its impact on the obstruction was insufficient to completely stir the contents of the room.

Table 46 – CP_24 Summary

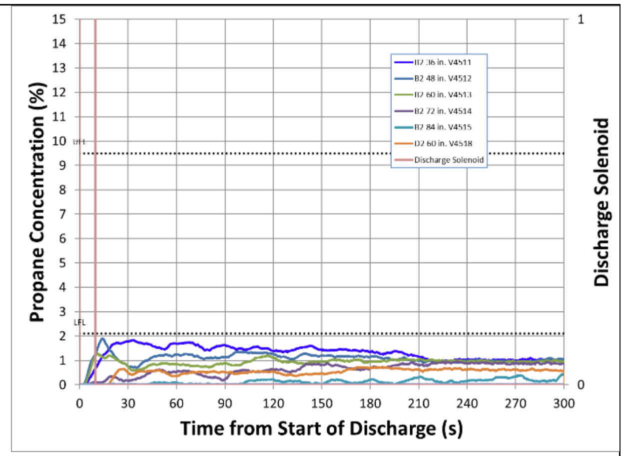
<table>
<tr><th></th><th>Discharge Amount
(g)</th><th>Duration of Discharge
(Seconds)</th><th>Discharge Rate
(g/s)</th><th>Leak Location</th><th colspan="2">Concentration at Discharge Completion
(%)</th></tr>
<tr><td>Planned</td><td>400</td><td>10.0</td><td>40</td><td rowspan="2">0.2 m</td><td>1.1</td><td>Calculated if well Mixed in whole room</td></tr>
<tr><td>Measured</td><td>391</td><td>9.9</td><td>39.5</td><td>13.3
7.7</td><td>Location B 6-inch
Location B 12-inch</td></tr>
</table>

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

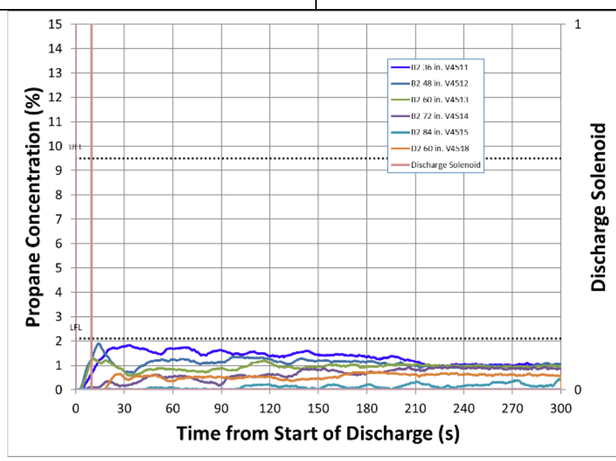
Figure 222 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations B2 and D2. Sensors at the 18-inch level and lower showed concentrations above LFL of 2.1% to the end of data recording, but were slowly decreasing. Sensors between the 36-inch level and ceiling were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.



Deconvoluted concentrations measured at location B2 between 2-inch and 18-inch levels.



Deconvoluted concentrations measured at location D2, 2-inch and 8-inch levels.



Deconvoluated concentrations at locations B2 and D2 at 36-inch height and higher.

Figure 222 – CP_24 Concentrations

Figure 223 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

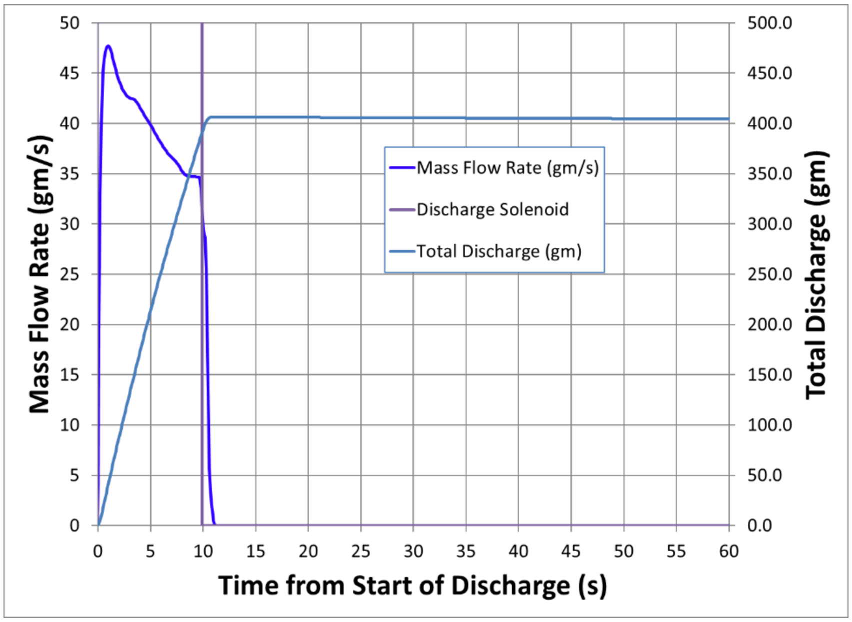


Figure 223 – CP_24 Mass Flow

Figure 224 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

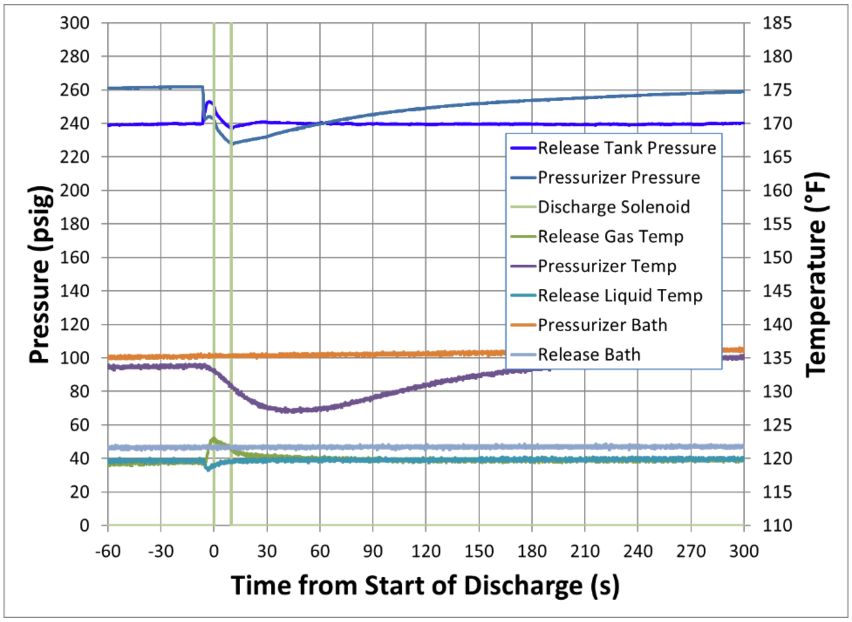


Figure 224 – CP_24 Pressurizer and Release Tank Pressure and Temperatures

Figure 225 shows the thermocouple response to liquid propane pooling on the floor in front of the discharge tube. The temperatures show that the pool evaporated with 60 to 90 seconds after the discharge valve closed.

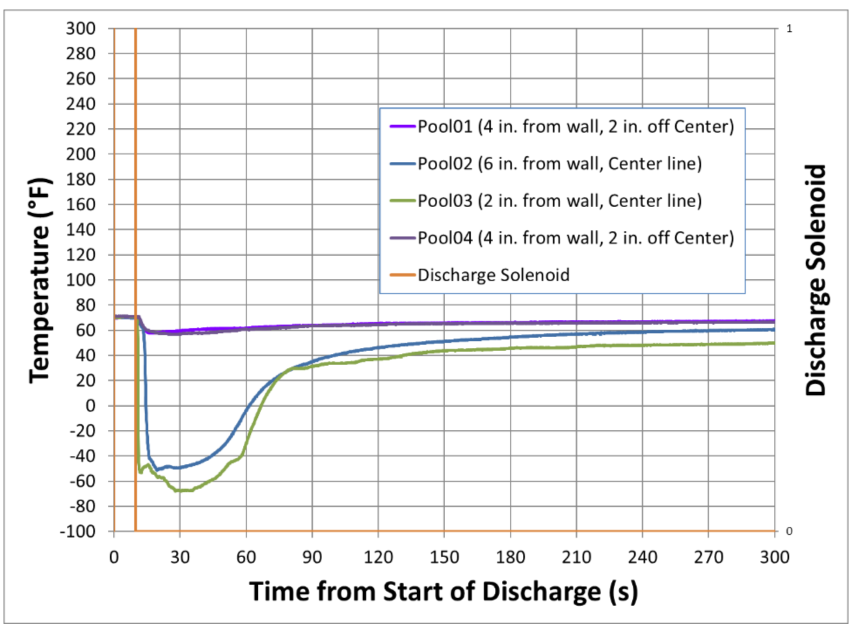


Figure 225 – Liquid pooling at the floor

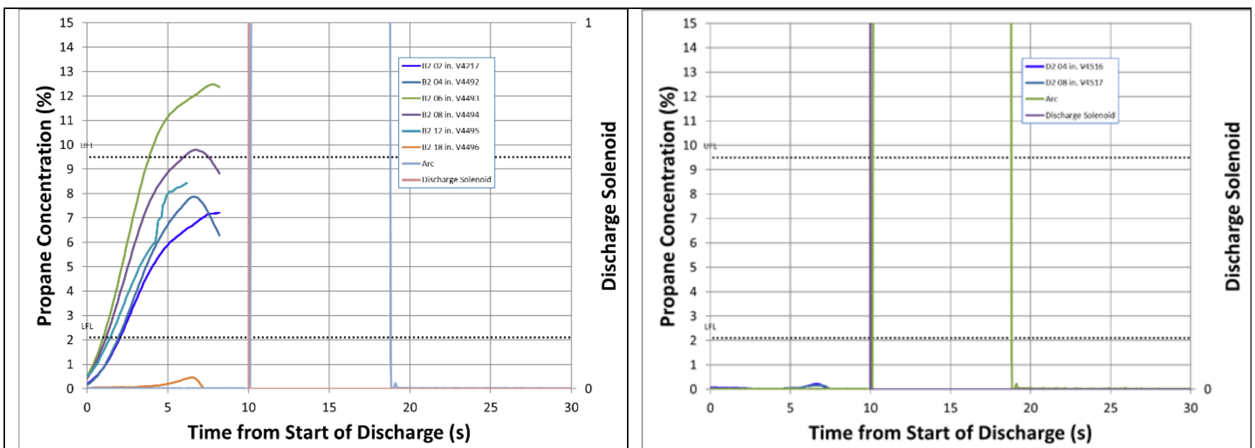
Test CP_25 (400 grams; 40 g/s; 0.2 height; with Igniters)

Test CP_25 was performed with ignition sources and resulted in ignition at location B2 at the 1-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 36-inch levels). Pre-ignition test data from CP_24 showed concentration at the 2-inch level was between the LFL and UFL. Elevations higher than the 2-inch level were near or above the UFL. The videos show that resulting flames were yellow in color due to diffusion flaming. This confirms the higher concentrations at ignition time. Blue flames are expected when a pre-mixed concentration is ignited.

Table 47 – CP_25 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	400	10.0	40.0	0.2 m
Measured	402	9.9	40.6	

Figure 226 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentration at the 2-inch and 4-inch levels.



Location B2 concentrations just prior to ignition

Location D2 concentrations just prior to ignition

Figure 226 – CP_25 Concentrations

Figure 227 compares the pre-ignition and ignition test (CP_24 and CP_25) concentrations at the 2- , 4- and 6-inch levels at location B2. The highest concentrations at discharge completion were at the 6-inch level which was nearly directly in front of the discharge tube (8-inch or 0.2 m). The lowest concentration was at the 2-inch level from the pre-ignition test was at 8.5% which is just below the UFL of 9.5%.

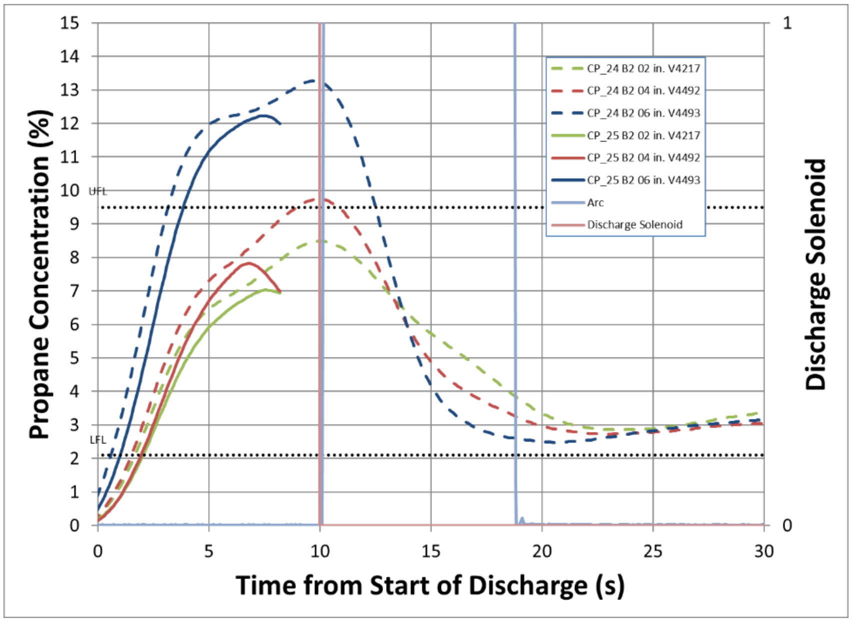


Figure 227 – CP_24 and CP_25 Concentration Comparison

Figure 228 shows the mass flow rate and total mass flow.

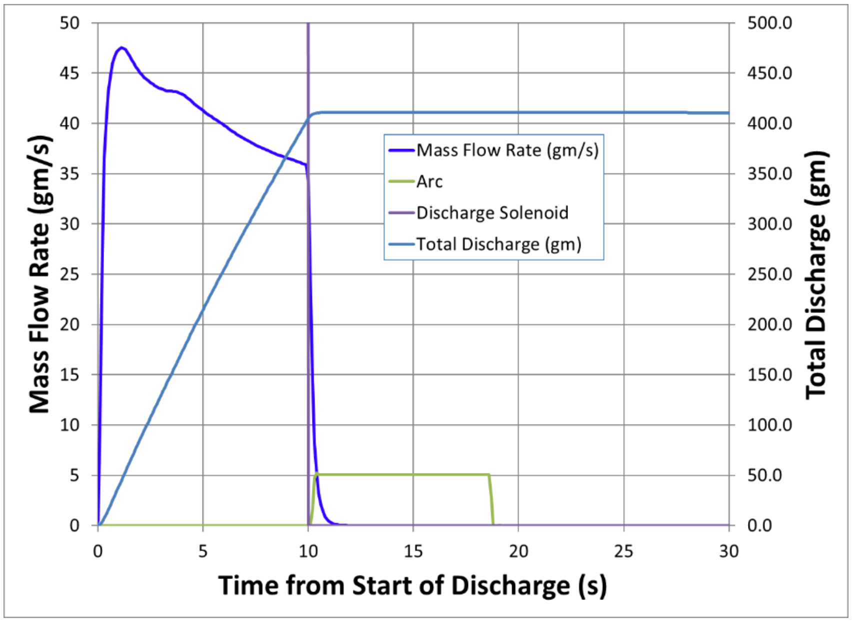


Figure 228 – CP_25 Mass Flow

Figure 229 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

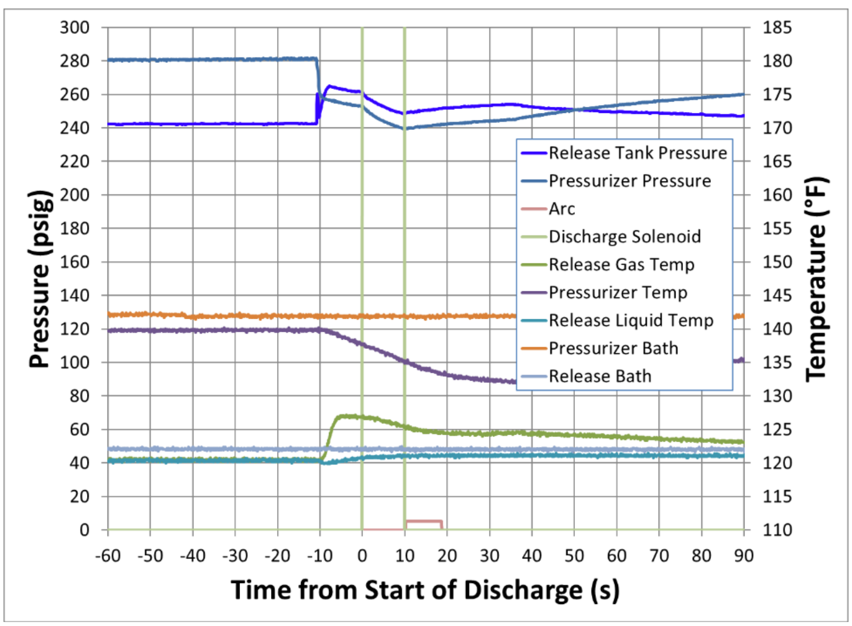


Figure 229 – CP_25 Pressurizer and Release Tank Pressure and Temperatures

Figure 230 shows the temperatures developed at the various locations following ignition.

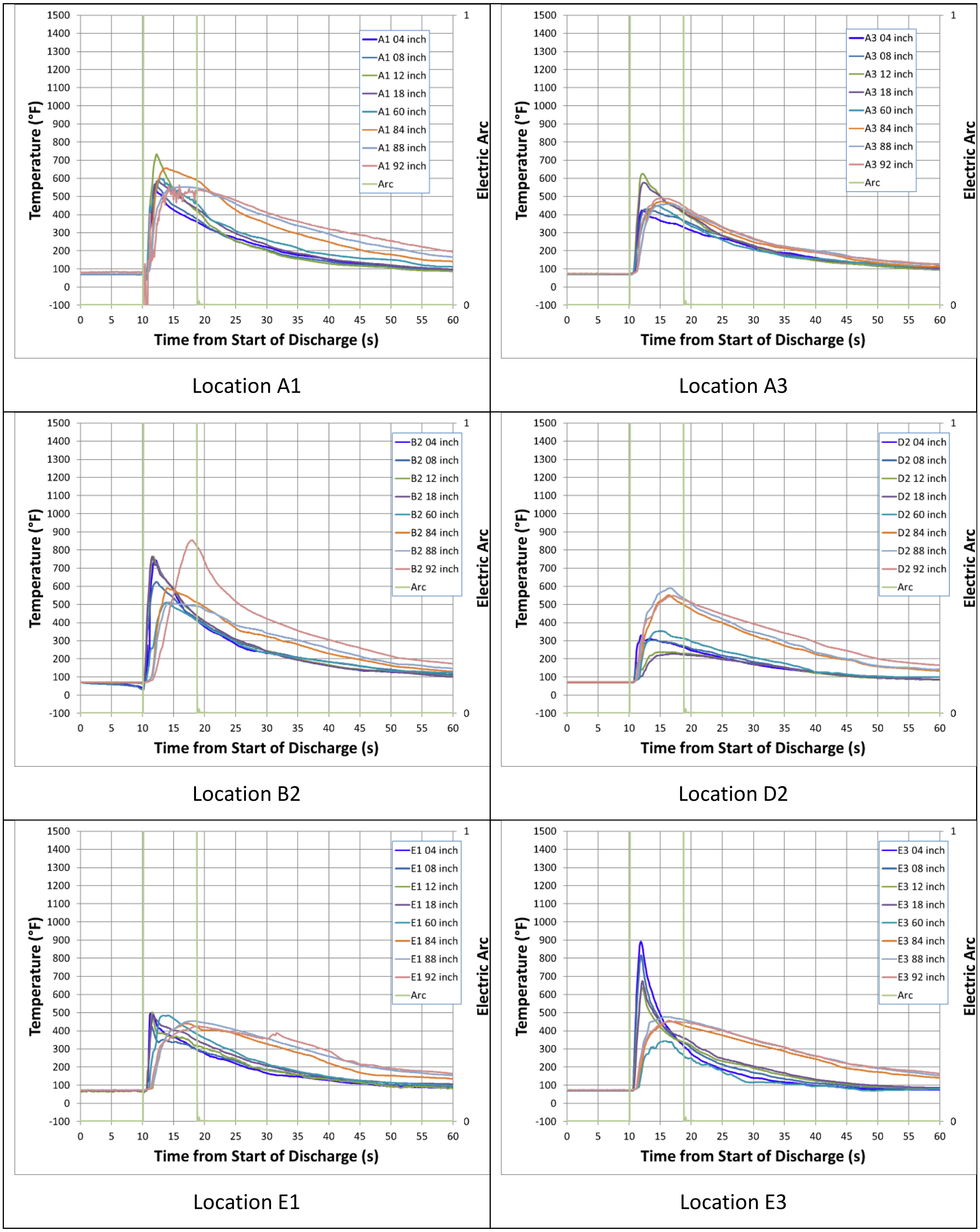


Figure 230 – CP_25 Temperatures at thermocouple trees

Notes to Figure 230:

- Location A1 92-inch level is erratic coinciding with the period that the electric arcs were energized.
- Location B2 show a drop in temperatures at the 4- and 8-inch level due to the impact of the refrigerant mist on those two thermocouples.
- Location B2 92-inch level shows a delayed peak caused by the continued flaming from residual propane expanding from the discharge tube.
- Location E3 4- to 18-levels show the highest temperatures even though ignition started on the opposite side of the obstruction. The video shows that the flames become attached to this thermocouple tree and sustained flaming for a longer period of time than the other locations.
- All locations show a more rounded approach to peak temperatures at the 60-inch to ceiling levels due to the buoyancy of the gases ignited at the floor level.

Figure 231 shows the temperatures recorded by the pool thermocouples. The data shows the formation of a pool of liquid propane that endured for some time after ignition occurred. Analysis of this data and the videos show that this pool lasted until 7 to 10 seconds after the arc ignition.

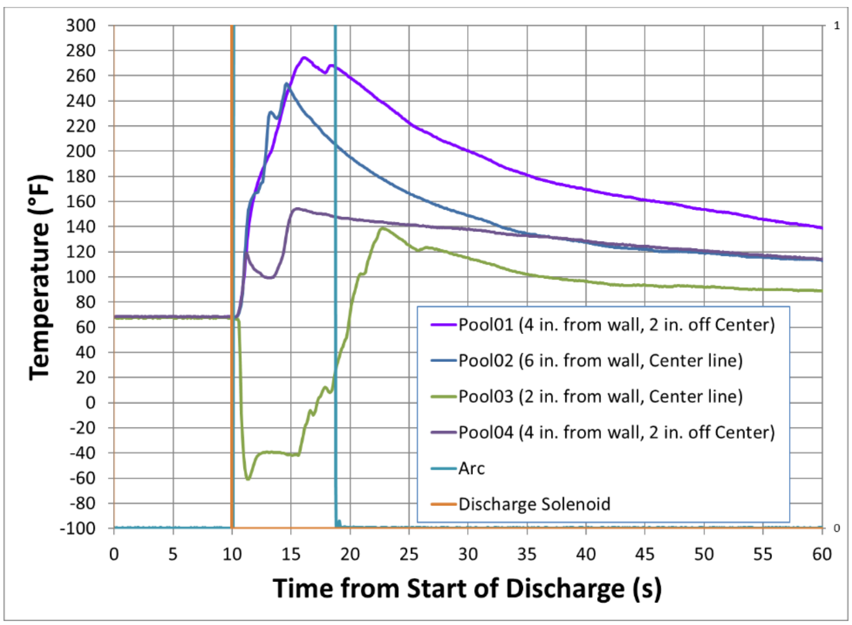


Figure 231 – CP_25 Liquid Propane Pool Temperatures

Figure 232 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 1-inch level. The value of 85 kW/m² exceeds the calibrated range of this heat flux sensor (0-50 kW/m²).

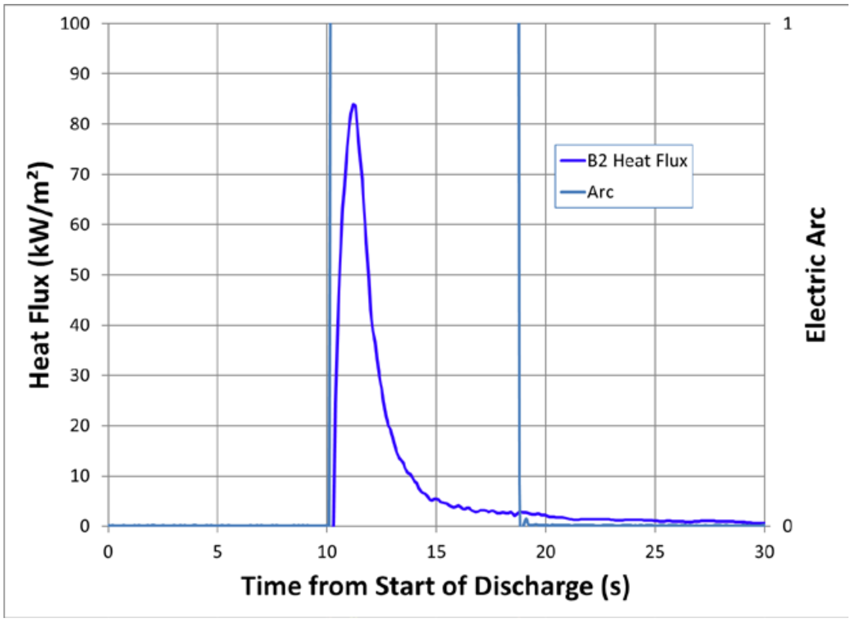
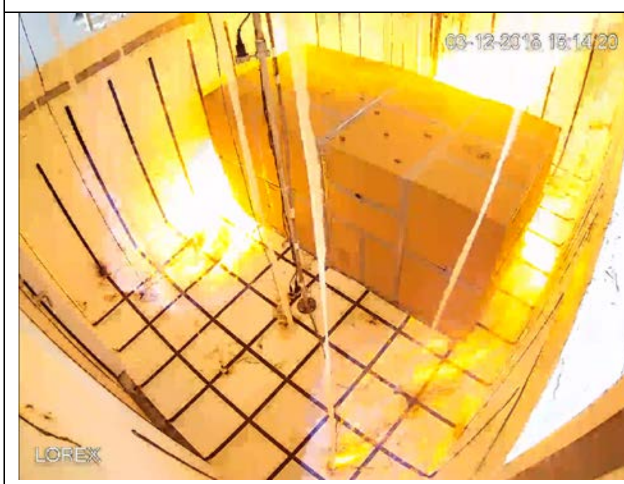


Figure 232 – CP_25 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 233. Burning started (A) as a spherical ball at the 12-inch level. As it spread in all directions, it flattened at the floor level (B) where concentrations were above the UFL. The fire wrapped around the obstruction (C) and continued to ignite the flammable layer at floor level until the entire floor area was ignited (D). Burning of these air mixtures stopped after 2 seconds.

(A) Propane mist impacting thermocouples at the 4- and 8-inch levels

(B) Ignition at Location B2 1-inch Level. Diffusion flame is yellow with small portion of pre-mixed flaming.



(C) Fireball attaches to the thermocouple tree at location E3 resulting in higher temperatures.

(D) Pool fire at floor level and fire at the discharge tube from residual propane in the line.

Figure 233 – CP_25: Frames of flaming from videos

At the time of ignition, all four deflagration vents burst with some flames extending out from the vents as shown in Figure 234.

(A) East side deflagration vents

(B) West side deflagration vents.

Figure 234 – CP_25 Deflagration Vents Bursting with Flame Extension

Test CP_26 (400 grams; 40 g/s; 1.8 height; with Igniters)

Test CP_26 was performed with ignition sources and resulted in ignition at location B2 at the 72-inch level. All four arcs were energized at the same time (1-, 12-, 24-, and 72-inch levels).

Table 48 – CP_26 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	400	10.0	40	1.8 m
Measured	400	9.1	43.6	

Figure 235 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time so the data has been chopped 2 seconds before the electric arc time to delete the combustion gases effect on the oxygen sensors. The figure shows an ignitable concentrations location B2 72-inch and D2 60-inch level. Concentrations at other locations were all less than LFL.

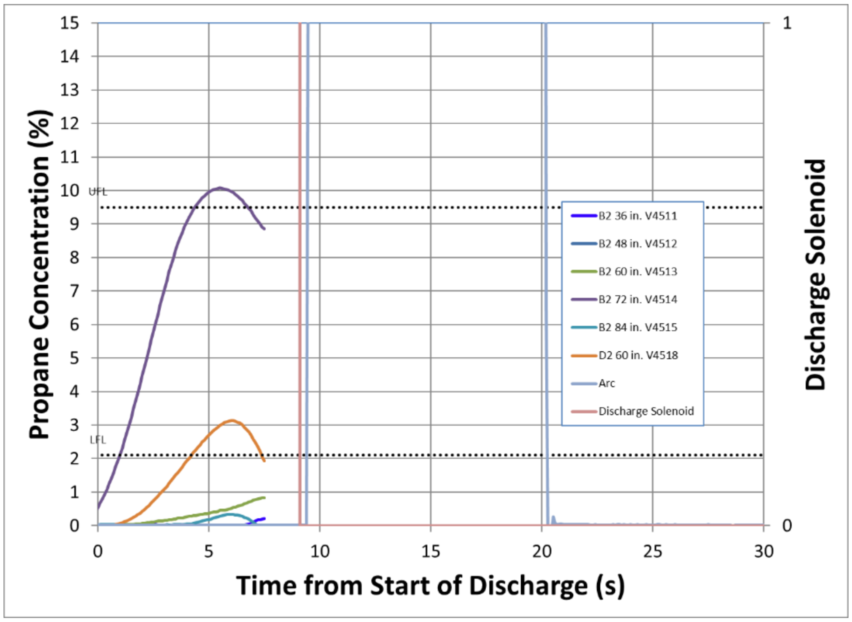


Figure 235 – CP_26 Concentrations

Figure 236 compares the pre-ignition and ignition test (CP_22 and CP_26) concentrations at B2 72-inch and D2 60-inch levels for the pre-ignition and ignition tests.

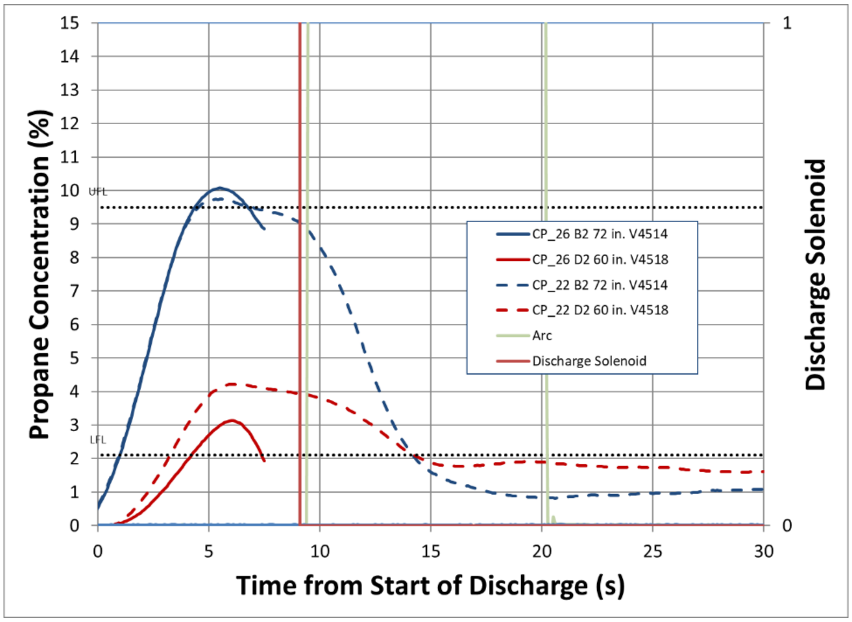


Figure 236 – CP_22 and CP_26 Concentration Comparison

There was no evidence of liquid propane pools at the floor level. There was evidence of a mist during some stages of the discharge, but the videos show this mist quickly dispersing into the vapor state.

Figure 237 shows the mass flow rate and total mass flow.

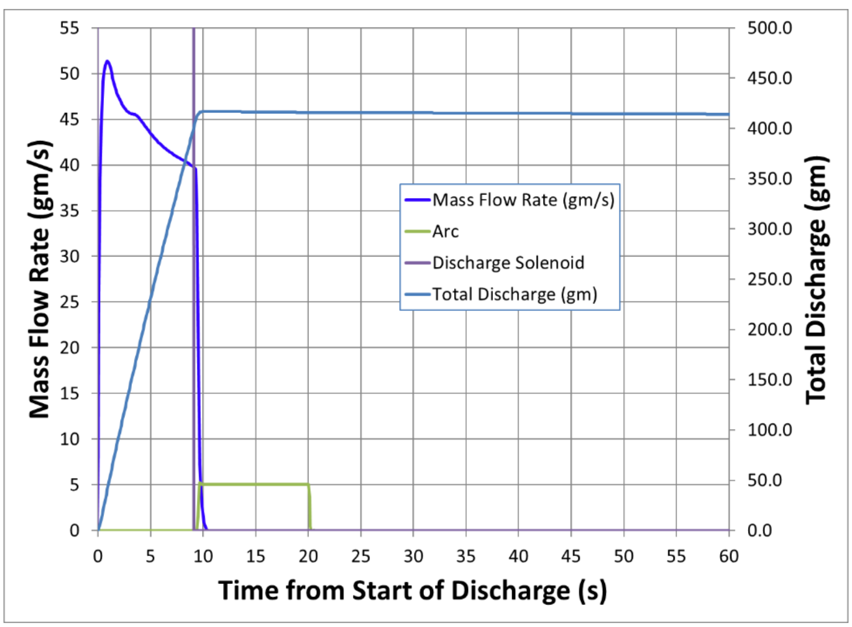


Figure 237 – CP_26 Mass Flow

Figure 238 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

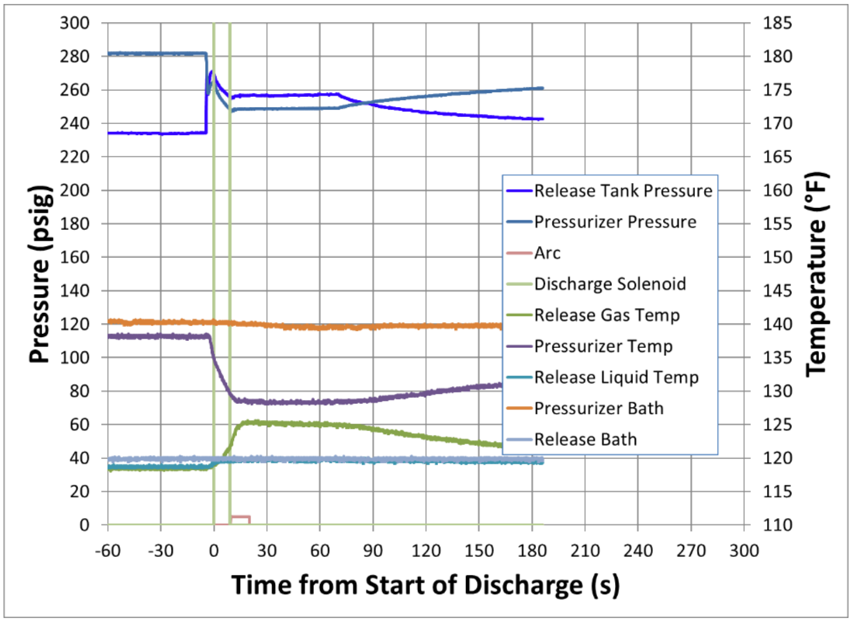


Figure 238 – CP_26 Pressurizer and Release Tank Pressure and Temperatures

Figure 239 shows the temperatures developed at the various locations following ignition.

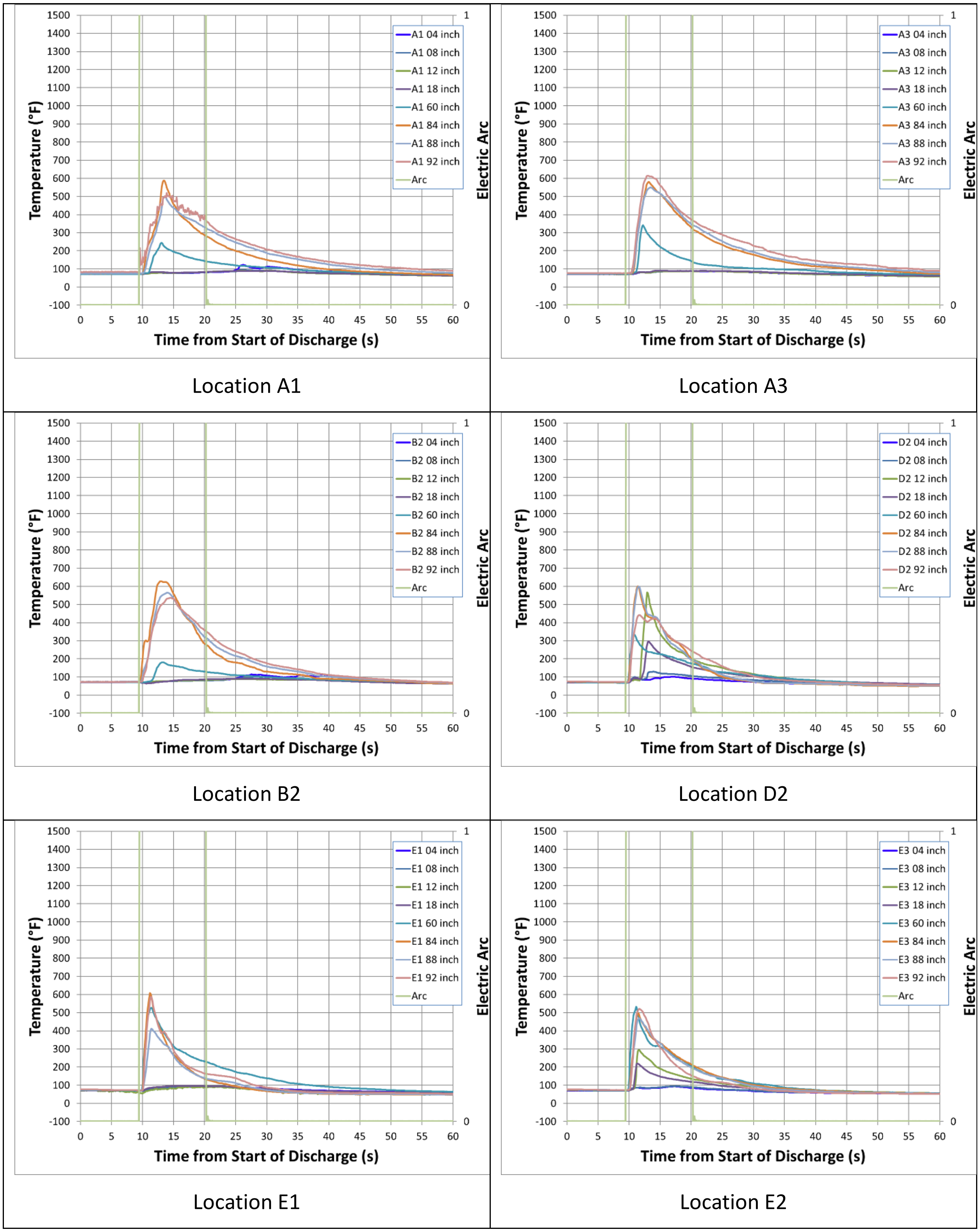


Figure 239 – CP_26 Temperatures at thermocouple trees

In general, the highest temperatures shown in Figure 239 occur at the 60-inch level and the ceiling. Those thermocouples at the 36-inch level and below show very small increases with the exception of locations D2 and E3. The temperatures at 12- and 18-inch levels at locations D2 and E3 increase with a slight delay due to the close proximity of burning strips of cheesecloth.

Figure 240 shows the heat flux measured at floor level at Location B2. This location is directly below the point of ignition at the 72-inch level. The increase in heat flux between 20 and 30 seconds was due to fallen pieces of burning cheesecloth that landed near the heat flux gauge.

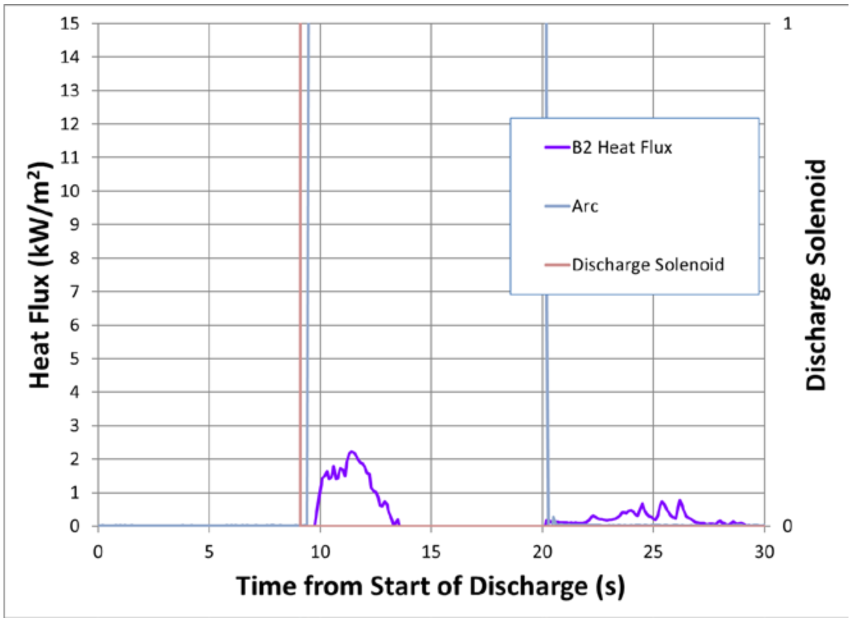


Figure 240 – CP_26 Heat Flux at Location B2, Floor Level

Selected frames from the videos are shown in Figure 241. Burning of these air mixtures stopped after 0.6 seconds. Three deflagration vents burst and the other melted 2 seconds later due to the hot gases.

(A) 0.05 seconds after ignition at Location B2 72-inch Level

(B) 0.22 seconds after ignition just before deflagration vents burst

(C) 0.6 seconds after ignition ignition of flammable mixture stops. A barely visible small arc of blue flame is visible between the door handle and the floor. Cheesecloth strips ignited.

Figure 241 – CP_26: Frames of flaming from videos

Appendix B PTAC Test Data and Summary

This appendix summarizes the tests with the PTAC unit.

The table below summarizes all tests with the PTAC unit. The sections that follow describe each test in detail.

Temperatures are color coded according to the following legend:

Range
< 0°F
0 – 105 °F
105 – 400 °F
400°F and higher

Table 49 – PTAC Tests

										Raw Video														
Test Code	Date	Purpose	Fan State	Planned Discharge (g)	Planned Discharge Rate (g/s)	Measured Mass (g)	Measured Rate (g/s)	Discharge Location (m)	Discharge Opening	Discharge Start HH:MM:SS	Discharge Stop HH:MM:SS	Electric Arc	Max Pressure (mmHg)	Max Temp (°F)	Max Temp Location	Max Ceiling Temp (°F)	Number of Vents Burst /Melted	Arc Delay Time (s)	Result	Location	Conc. @+ 5s (%)	Location	Decon. @+ 5 (%)	Analysis File
PTAC_01	03-Apr-2018	Concentrations	Off	325	21.4	322	19.9	0.6	1/4 OD											A 01 in.	4.4	B 01 in.	5.4	PTAC_01_2018-04-03-1455 Analysis.xlsx
PTAC_02	03-Apr-2018	Concentrations	Off	217	21.4	213	20.3	0.6	1/4 OD											A 01 in.	3.4	B 01 in.	5.8	PTAC_02_2018-04-03-1535 Analysis.xlsx
PTAC_03	03-Apr-2018	Concentrations	Off	114	21.4	110	20.0	0.6	1/4 OD											A 01 in.	2.1	A 01 in.	3.5	PTAC_03_2018-04-03-1609 Analysis.xlsx
PTAC_04	03-Apr-2018	Concentrations	Off	325	21.4	321	21.9	0.6	1/4 OD											A 01 in.	5.5	A 01 in.	5.7	PTAC_04_2018-04-03-1700 Analysis.xlsx
PTAC_05	04-Apr-2018	Concentrations	On	325	21.4	322	20.1	0.6	1/4 OD											A 01 in.	5.0	A 01 in.	4.3	PTAC_05_2018-04-04-1512 Analysis.xlsx
PTAC_06	04-Apr-2018	Concentrations	On	217	21.4	207	19.0	0.6	1/4 OD											A 01 in.	3.9	A 01 in.	3.9	PTAC_06_2018-04-04-1545 Analysis.xlsx
PTAC_07	04-Apr-2018	Concentrations	On	114	21.4	110	19.2	0.6	1/4 OD	NA: No video recorded			NA: Igniters not used							A 01 in.	2.4	A 01 in.	3.0	PTAC_07_2018-04-04-1616 Analysis.xlsx
PTAC_08	05-Apr-2018	Concentrations	Off	217	21.4	212	18.4	0.6	1/4 OD											A 01 in.	5.1	A 01 in.	3.8	PTAC_08_2018-04-05-1035 Analysis.xlsx
PTAC_09	05-Apr-2018	Concentrations	Off	114	21.4	111	20.8	0.6	1/4 OD											A 01 in.	3.2	A 01 in.	4.4	PTAC_09_2018-04-05-1103 Analysis.xlsx
PTAC_10	05-Apr-2018	Concentrations	On	325	21.4	322	24.8	0.6	1/4 OD											A 12 in.	6.0	A 01 in.	4.3	PTAC_10_2018-04-05-1407 Analysis.xlsx
PTAC_11	05-Apr-2018	Concentrations	+7s	325	21.4	323	21.4	0.6	1/4 OD											A 01 in.	6.0	A 01 in.	5.3	PTAC_11_2018-04-05-1434 Analysis.xlsx
PTAC_12	05-Apr-2018	Concentrations	+7s	217	21.4	213	21.1	0.6	1/4 OD											A 01 in.	5.3	A 01 in.	4.7	PTAC_12_2018-04-05-1504 Analysis.xlsx
PTAC_13	05-Apr-2018	Concentrations	+7s	114	21.4	111	20.5	0.6	1/4 OD											A 12 in.	3.5	A 01 in.	3.5	PTAC_13_2018-04-05-1532 Analysis.xlsx
PTAC_14	09-Apr-2018	With Igniters	+5s	217	21.4	214	18.3	0.6	1/4 OD	14:11:04	14:11:16	14:11:21	0.4	866	C-08	420	3/3	4.3	Ignition					PTAC_14_2018-04-09-1408 Analysis.xlsx
PTAC_15	17-Apr-2018	With Igniters	+5s	114	21.4	111	20.9	0.6	1/4 OD	09:49:22	09:49:27	09:49:28	0.2	993	C-08	531	4/1	0.9	Ignition	NA: Ignition Event				PTAC_15_2018-04-17-0945 Analysis.xlsx
PTAC_16	17-Apr-2018	With Igniters	+5s	114	21.4	110	20.4	0.6	1/4 OD	13:07:51	13:07:57	13:08:03	0.3	699	C-08	210		5.7	Ignition					PTAC_16_2018-04-17-1304 Analysis.xlsx
PTAC_17	18-Apr-2018	With Igniters	+5s	217	21.4	215	20.4	0.6	1/4 OD	08:52:15	08:52:25	08:52:31	0.2	722	B-60	243	3/1	5.7	Ignition					PTAC_17_2018-04-18-0845 Analysis.xlsx

Notes:

- The times recorded for the raw video are from the date/time stamp (time portion only) in the video.
- Temperatures are recorded in the cases where ignition occurred.
- Propane concentrations are recorded in cases where the igniters were not used.
- Refer to the main body of the report for the description of sensor locations.

Videos for each test are stored separately. The correspondence of channel number to camera view is as follows:

Video Channels	Usage
1	NorthEast Upper Corner
2	NorthWest Upper Corner
3	NorthEast Floor Corner
4	SouthWest Upper Corner
6	East Side Vents
7	West Side Vents
8	NorthEast Floor IR Camera
9	Test Marquee and Clock
13	NorthWest Upper Hi Def Camera

High speed camera videos are stored in the same folder for each test. High speed cameras were used where ignition was expected. The following table matches the test number with the high-speed camera video:

High Speed Cameras		
Test	**Floor Level**	**High Level**
PTAC_14	CIMG3346.MOV	CIMG3347.MOV
PTAC_15	CIMG3348.MOV	CIMG3348 (2).MOV
PTAC_16	CIMG3349.MOV	CIMG3348.MOV
PTAC_17	CIMG3350.MOV	CIMG3350 (2).MOV

Test PTAC_01 (325 grams; Fan Off)

Test PTAC_01 was performed without ignition sources to measure propane concentrations. This test involved release at the right side (when viewed from the front) of the evaporator coil. The key parameters and results of this test are summarized in the following table. At the end of data recording a propane-air mixture above the LFL had accumulated at floor level.

Table 50 – PTAC_01 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	325	15.2	21.4	Right side of Evaporator Coil	0.14	Calculated if well Mixed in whole room
Measured	322	11.5	19.9		5.0 5.4	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 242 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 1.4% to 3.0% at the one-inch level showing the existence of a stratified layer of a propane-air mixture above the LFL.

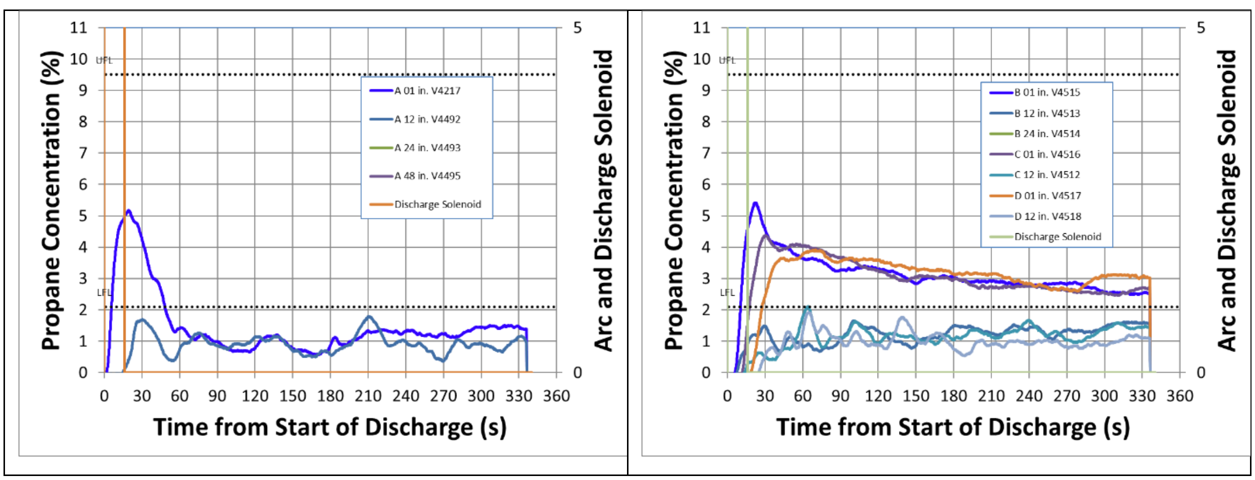


Figure 242 – PTAC_01 Concentrations

Figure 243 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. There was no indication of concentration above zero in the measurement located above the unit.

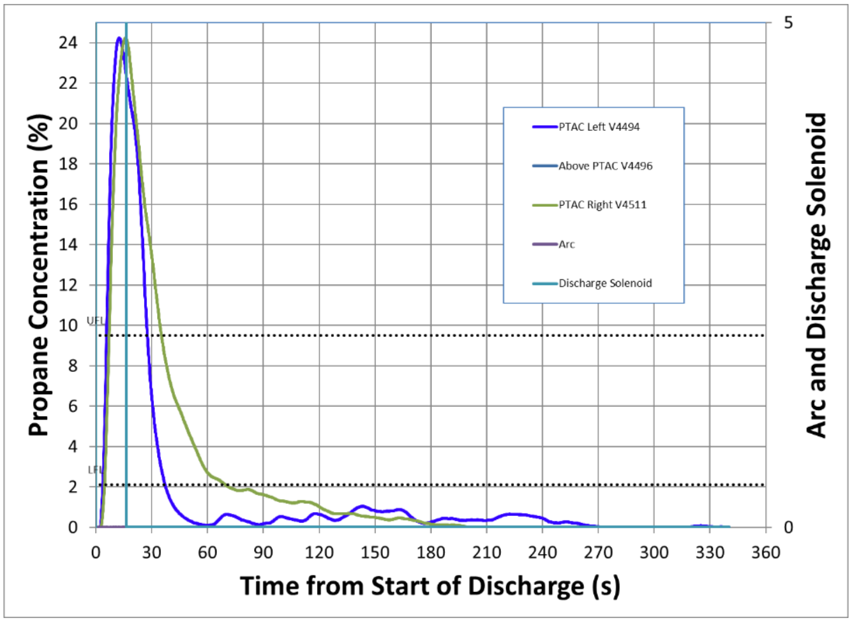


Figure 243 – PTAC_01 Concentrations near PTAC

Figure 244 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

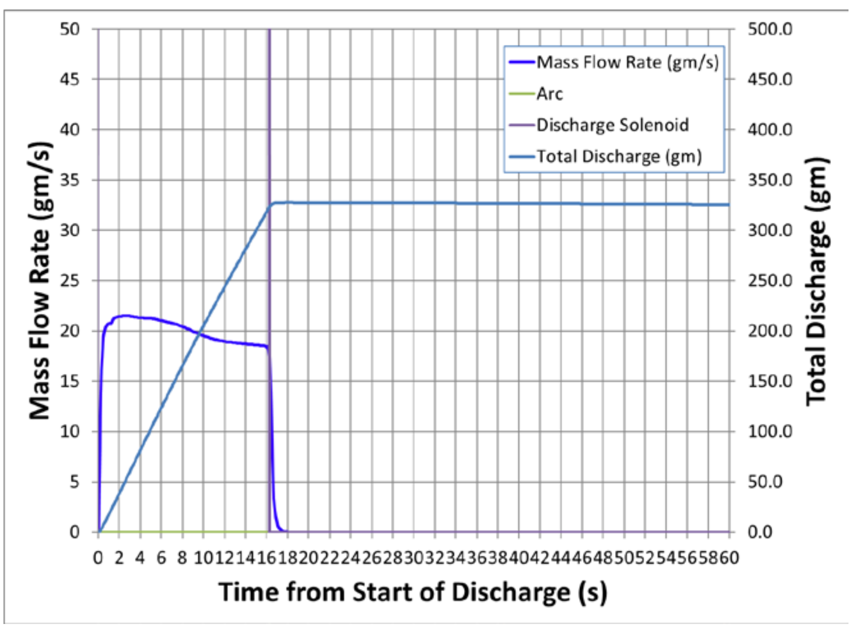


Figure 244 – PTAC_01 Mass Flow

Figure 245 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

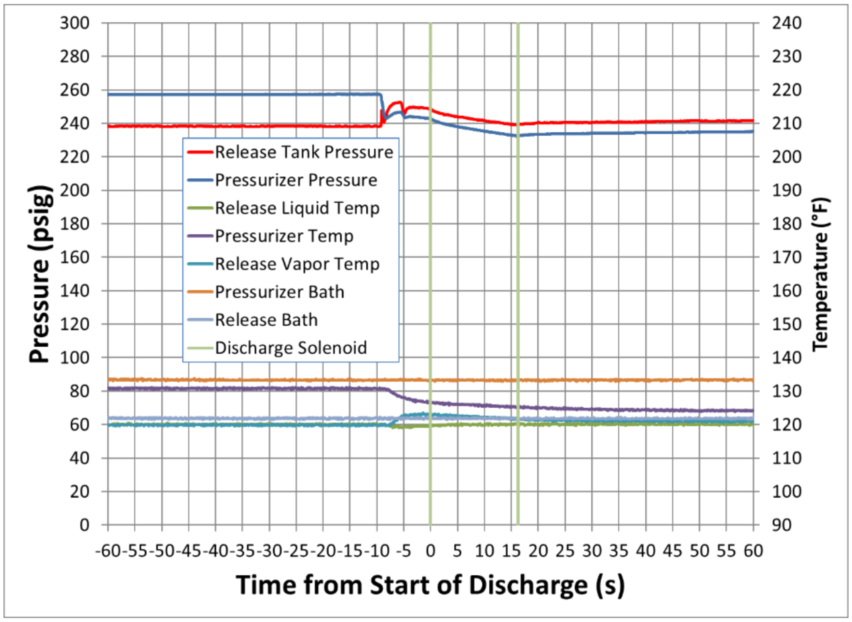


Figure 245 – PTAC_01 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_02 (217 grams; Fan Off)

Test PTAC_02 was performed without ignition sources to measure propane concentrations. This test involved release at the right side (when viewed from the front) of the evaporator coil. The key parameters and results of this test are summarized in the following table. At the end of data recording a propane-air mixture above the LFL had accumulated at floor level.

Table 51 – PTAC_02 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	217	10.1	21.4	Right side of Evaporator Coil	0.26	Calculated if well Mixed in whole room
Measured	213	10.6	20.3		4.1	Location A 1-inch
					5.8	Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 246 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 2.5% to 3.0% at the one-inch level showing the existence of a stratified layer of a propane-air mixture above the LFL.

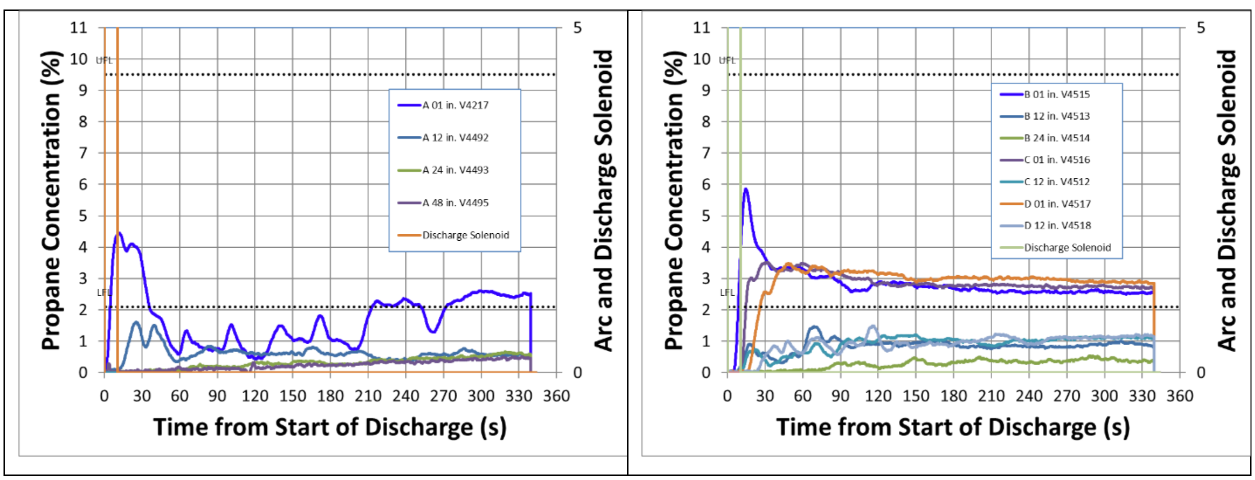


Figure 246 – PTAC_02 Concentrations

Figure 247 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. There was no indications of concentration above zero in the measurement located above the unit.

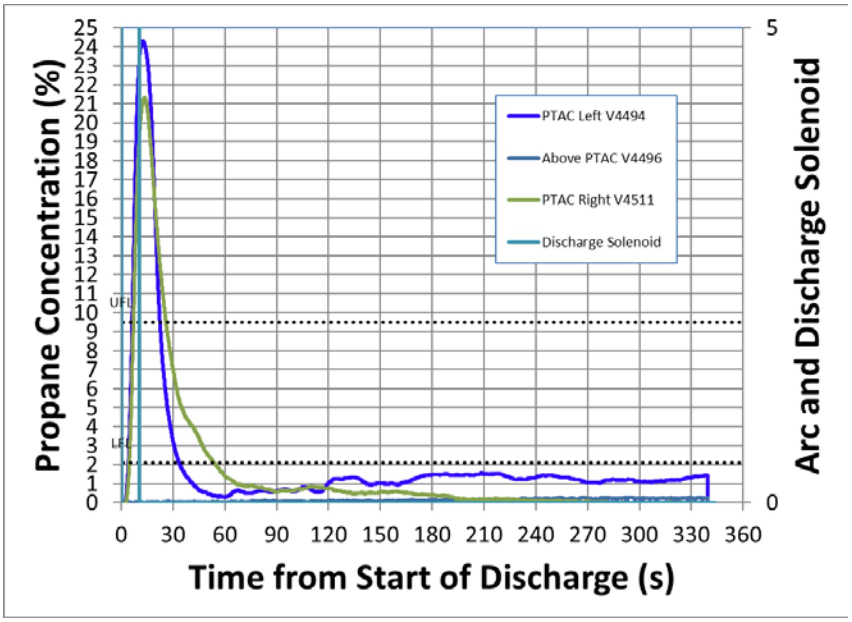


Figure 247 – PTAC_02 Concentrations near PTAC

Figure 248 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

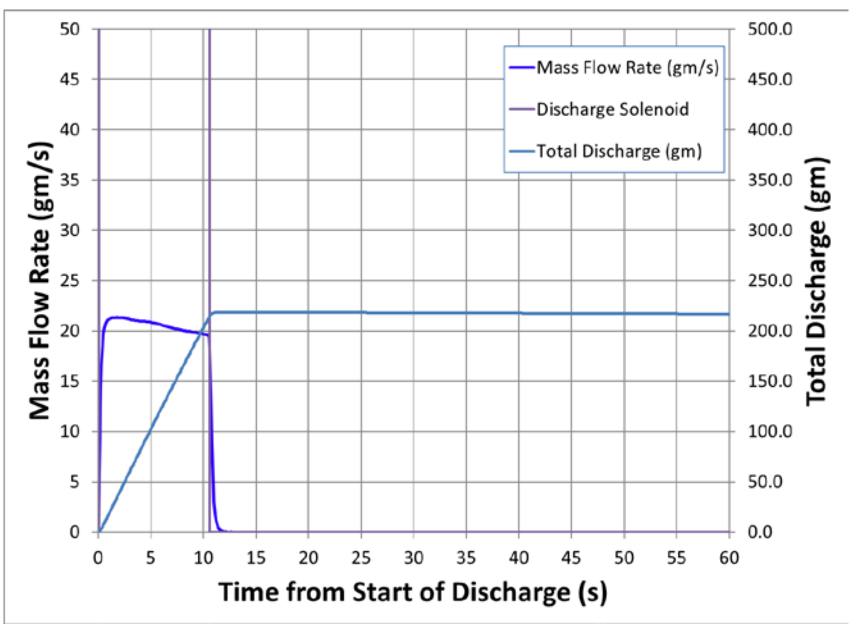


Figure 248 – PTAC_02 Mass Flow

Figure 249 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

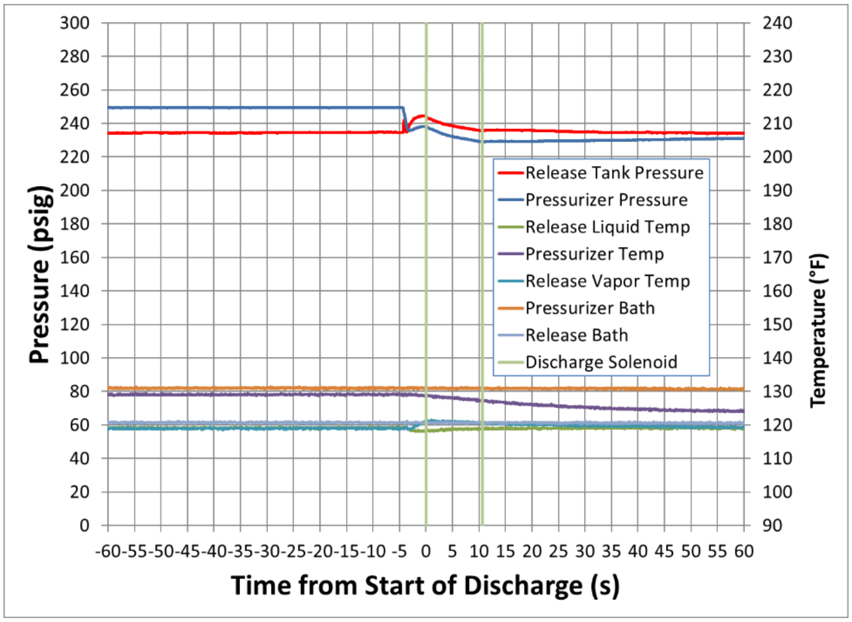


Figure 249 – PTAC_02 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_03 (114 grams; Fan Off)

Test PTAC_03 was performed without ignition sources to measure propane concentrations. This test involved release at the right side (when viewed from the front) of the evaporator coil. The key parameters and results of this test are summarized in the following table. All concentrations were less than LFL 160 seconds after the start of the discharge.

Table 52 – PTAC_03 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	114	5.3	21.4	Right side of Evaporator Coil	0.14	Calculated if well Mixed in whole room
~~Measured~~	~~110~~	~~5.5~~	~~20.0~~		~~3.5~~ ~~2.9~~	~~Location A 1-inch~~ ~~Location B 1-inch~~

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 250 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 1.5% to 1.8% at the one-inch level.

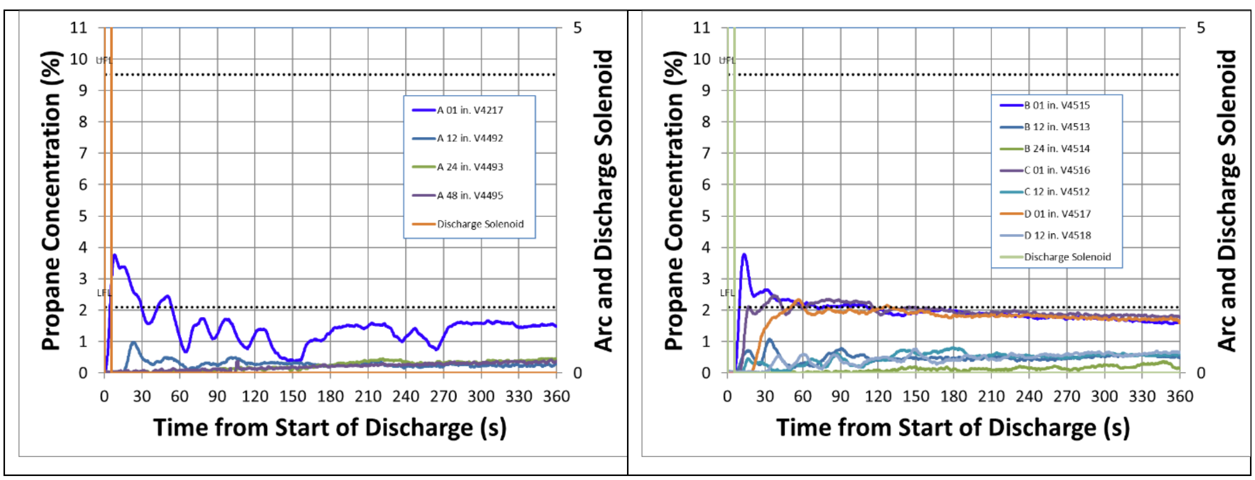


Figure 250 – PTAC_03 Concentrations

Figure 251 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. There was no indications of concentration above zero in the measurement located above the unit.

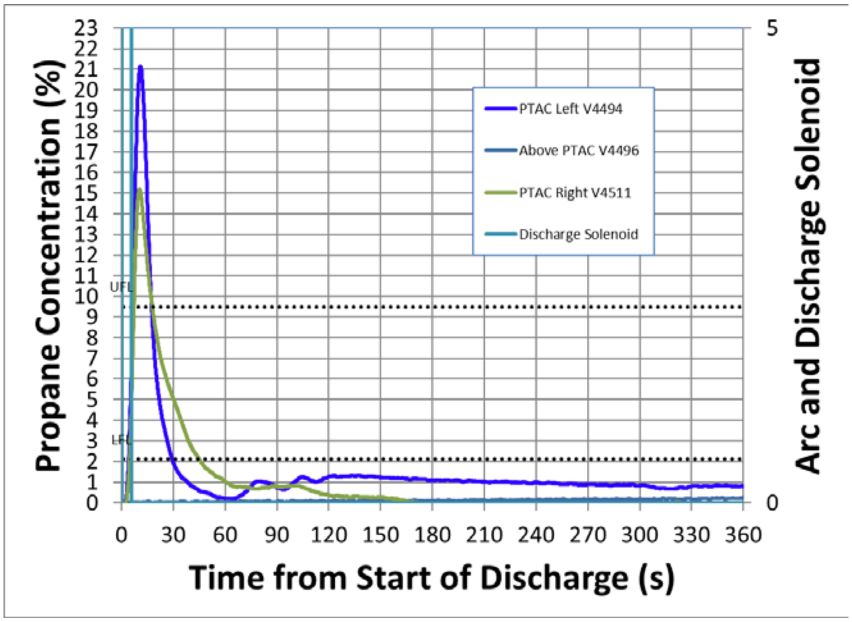


Figure 251 – PTAC_03 Concentrations near PTAC

Figure 252 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

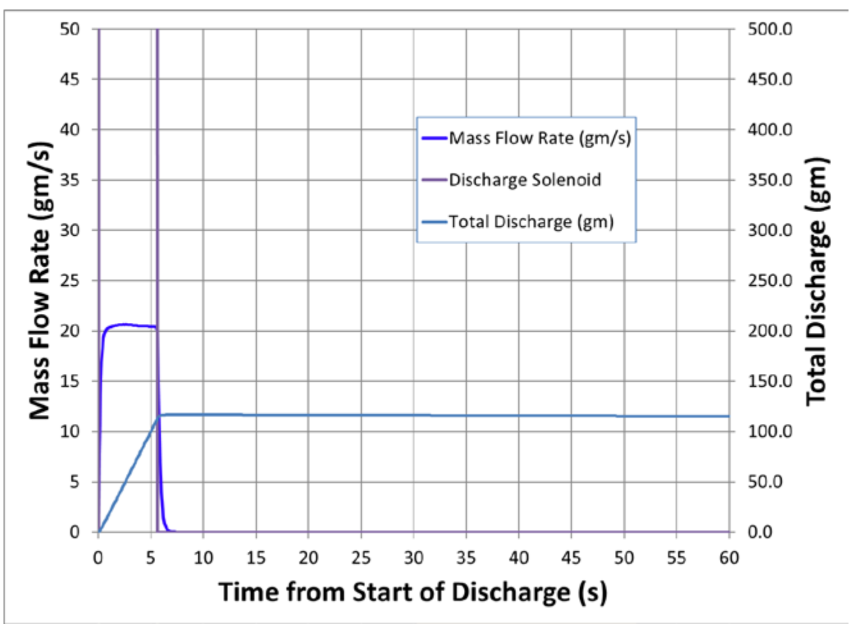


Figure 252 – PTAC_03 Mass Flow

Figure 253 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

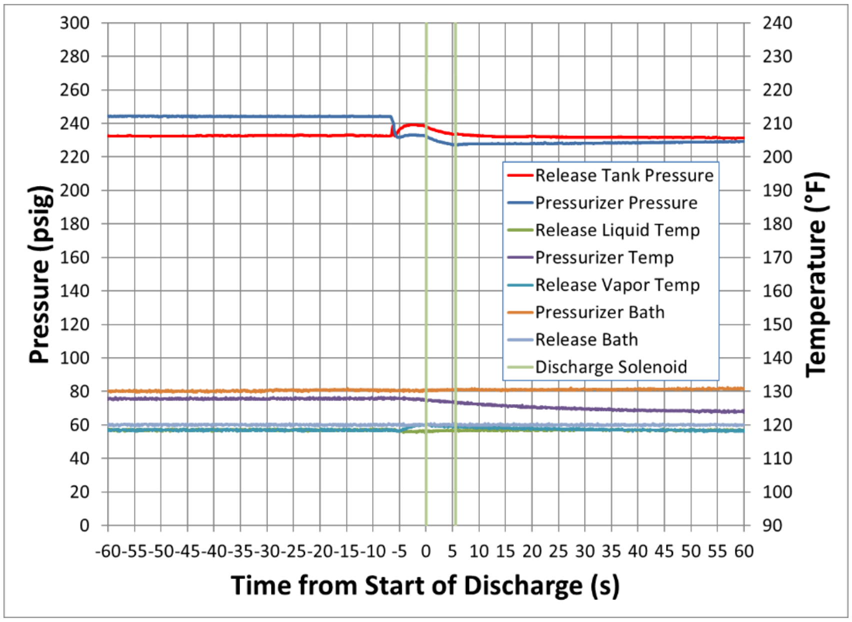


Figure 253 – PTAC_03 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_04 (325 grams; Fan Off)

Test PTAC_04 was performed without ignition sources to measure propane concentrations. This test and all subsequent involved release at the center of the evaporator coil. The key parameters and results of this test are summarized in the following table. At the end of data recording a propane-air mixture above the LFL had accumulated at floor level.

Table 53 – PTAC_04 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	325	15.2	21.4	Center of Evaporator Coil	0.39	Calculated if well Mixed in whole room
Measured	321	5.5	21.9		5.6	Location A 1-inch
					4.6	Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 254 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 1.5% to 3.2% at the one-inch level.

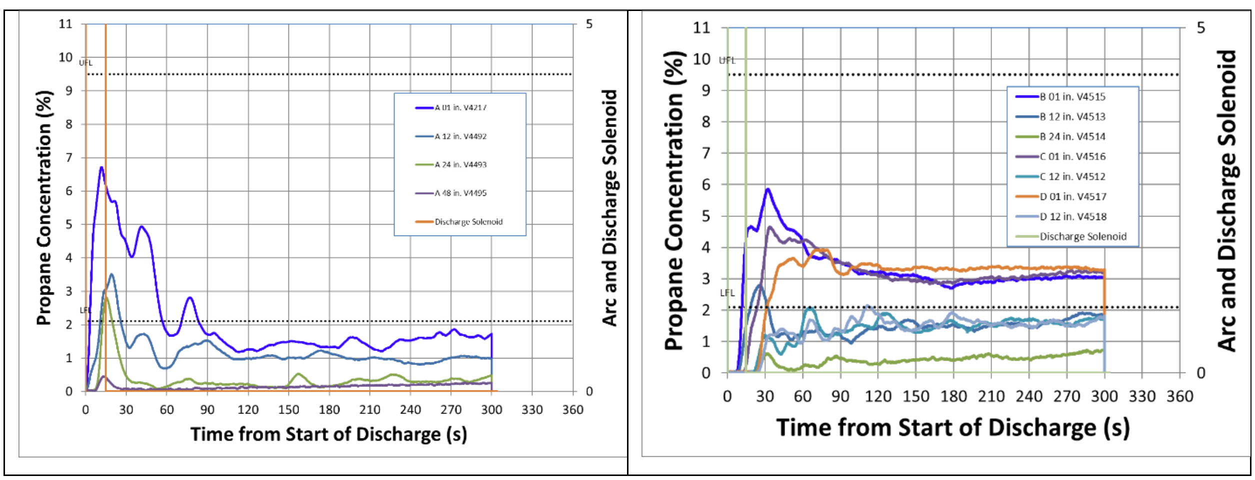


Figure 254 – PTAC_04 Concentrations

Figure 255 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. The relocation of the discharge tube to the center of the evaporator has caused some concentrations to be measured above the PTAC unit.

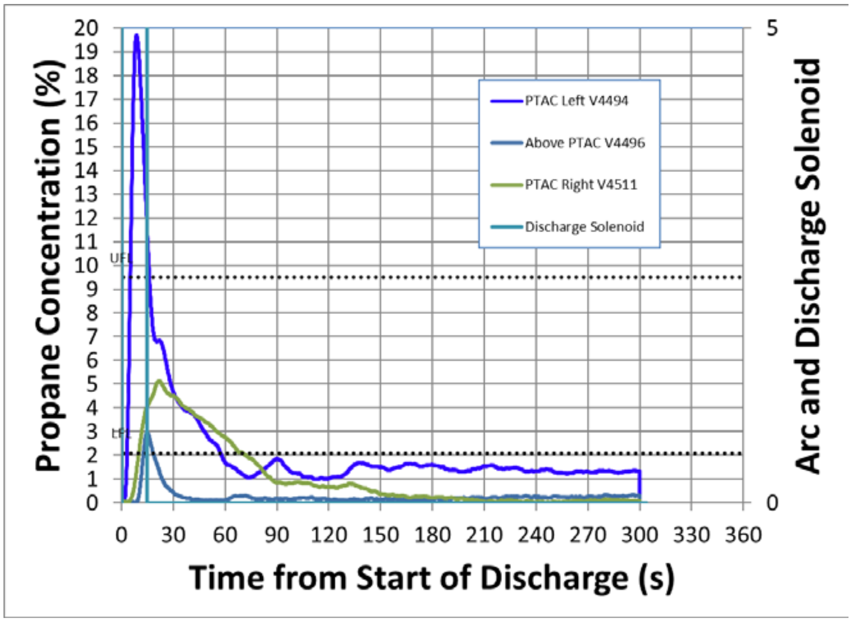


Figure 255 – PTAC_04 Concentrations near PTAC

Figure 256 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

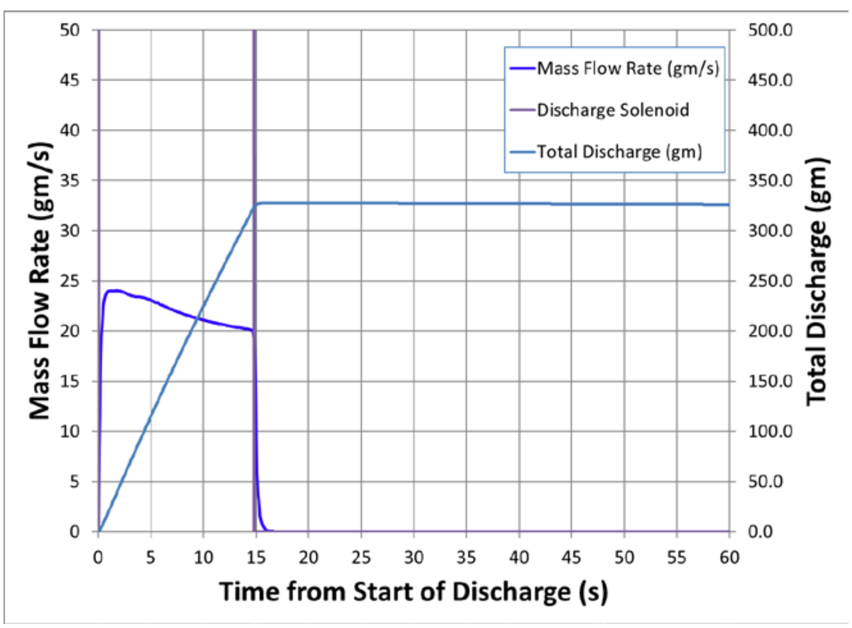


Figure 256 – PTAC_04 Mass Flow

Figure 257 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

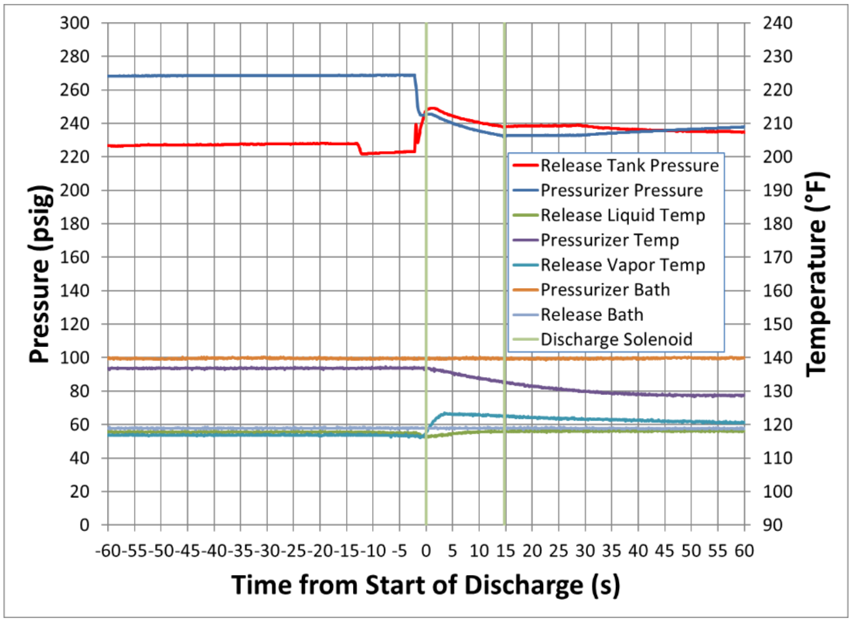


Figure 257 – PTAC_04 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_05 (325 grams; Fan On)

Test PTAC_05 was performed without ignition sources to measure propane concentrations. The unit fan was running on low speed throughout this test. The key parameters and results of this test are summarized in the following table. At the end of data recording all concentrations were less than LFL.

Table 54 – PTAC_05 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	325	15.2	21.4	Center of Evaporator Coil	0.39	Calculated if well Mixed in whole room
Measured	322	16.1	20.1		4.3	Location A 1-inch
					2.0	Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 258 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. All concentrations were less than LFL 120 seconds after the start of the discharge.

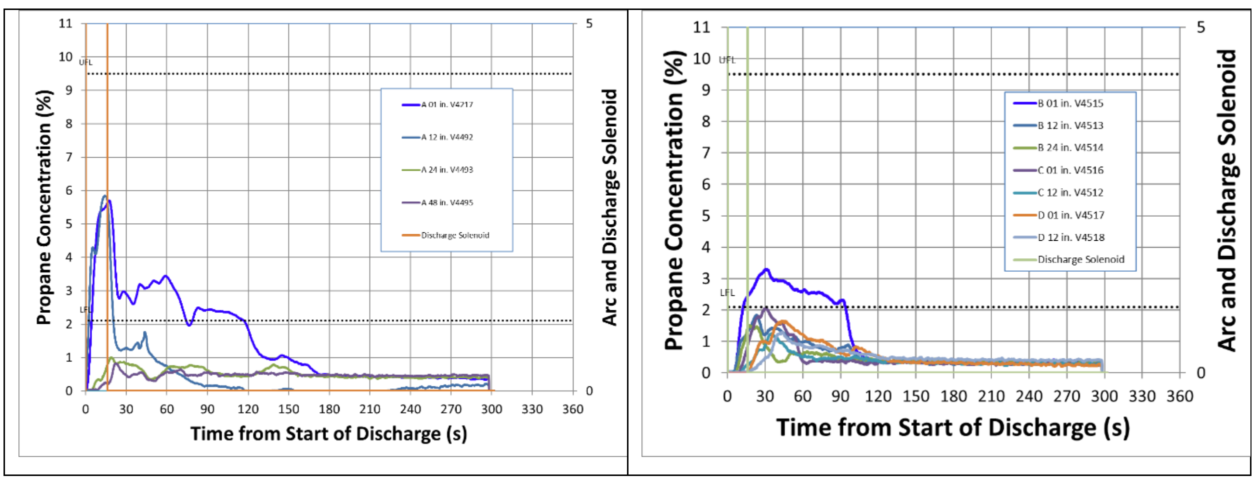


Figure 258 – PTAC_05 Concentrations

Figure 259 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. The operation of the fan reduced these concentrations to less than LFL in 23 seconds after the start of the discharge.

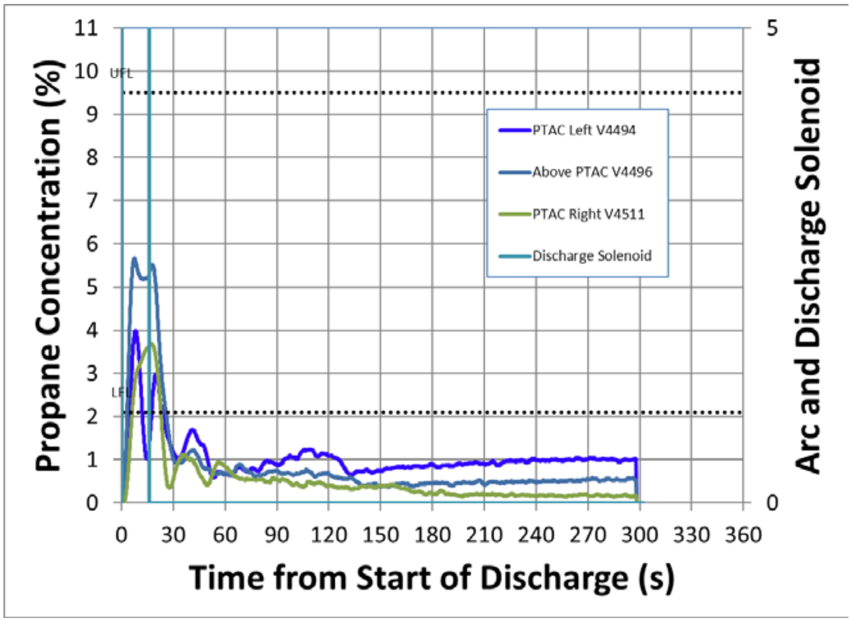


Figure 259 – PTAC_05 Concentrations near PTAC

Figure 260 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

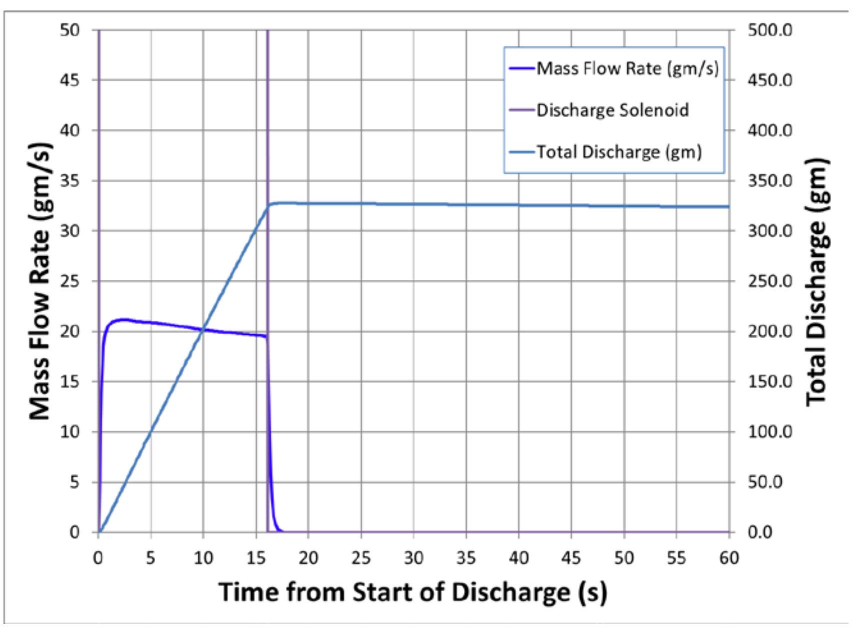


Figure 260 – PTAC_05 Mass Flow

Figure 261 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

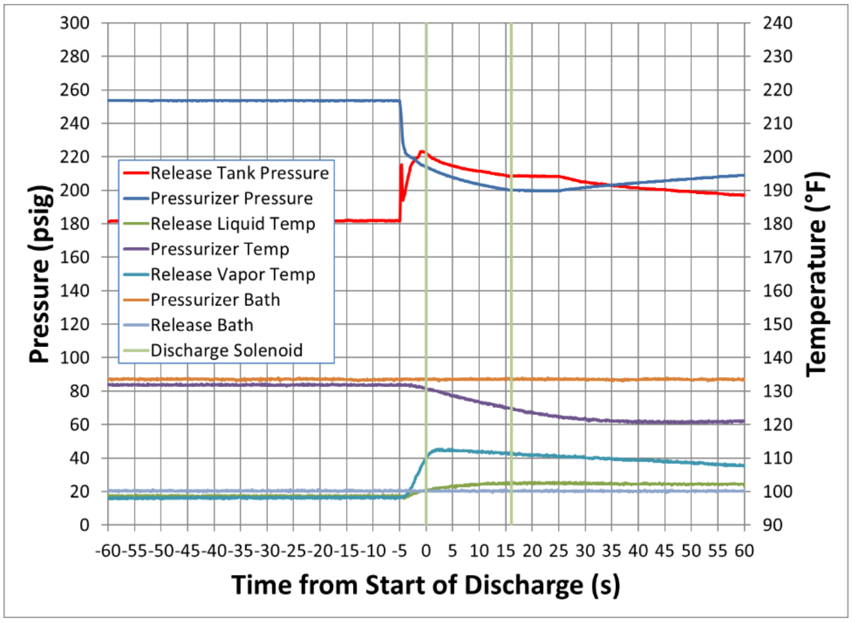


Figure 261 – PTAC_05 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_06 (217 grams; Fan On)

Test PTAC_06 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is PTAC_17. This test involved release at the front-center of the evaporator coil. The key parameters and results of this test are summarized in the following table. All measured propane concentrations were less than LFL at 80 seconds after the start of the discharge. The maximum concentration at 2.5 minutes after completion of the discharge was 1% or 50% of the propane's LFL.

Table 55 – PTAC_06 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	217	10.1	21.4	Center of Evaporator Coil	0.26	Calculated if well Mixed in whole room
Measured	207	10.9	19.0		3.8 2.3	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 524 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 0.5 to 0.8% near the floor level which is two to three times the estimated well-mixed value of 0.26%.

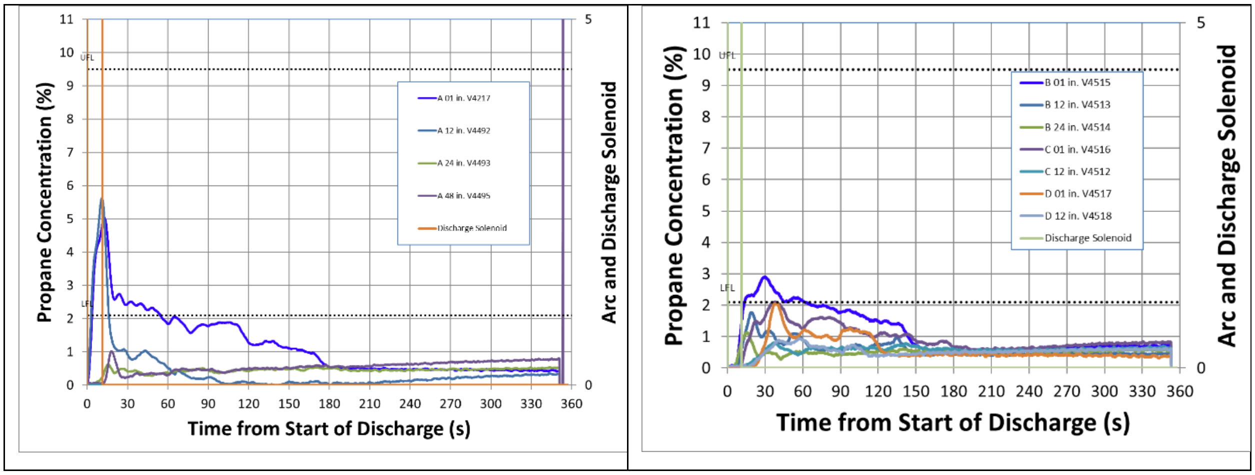


Figure 262 – PTAC_06 Concentrations

Figure 526 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

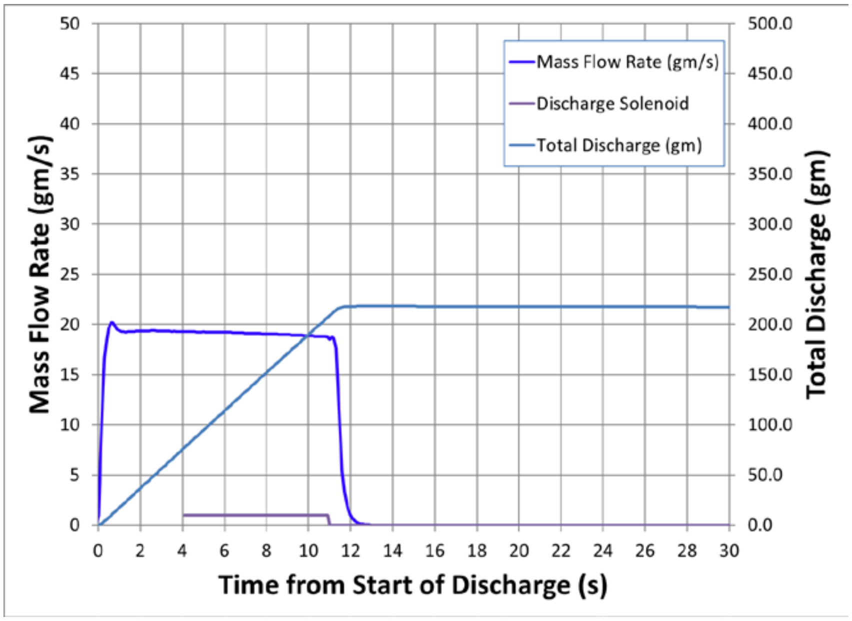


Figure 263 – PTAC_06 Mass Flow

Figure 527 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

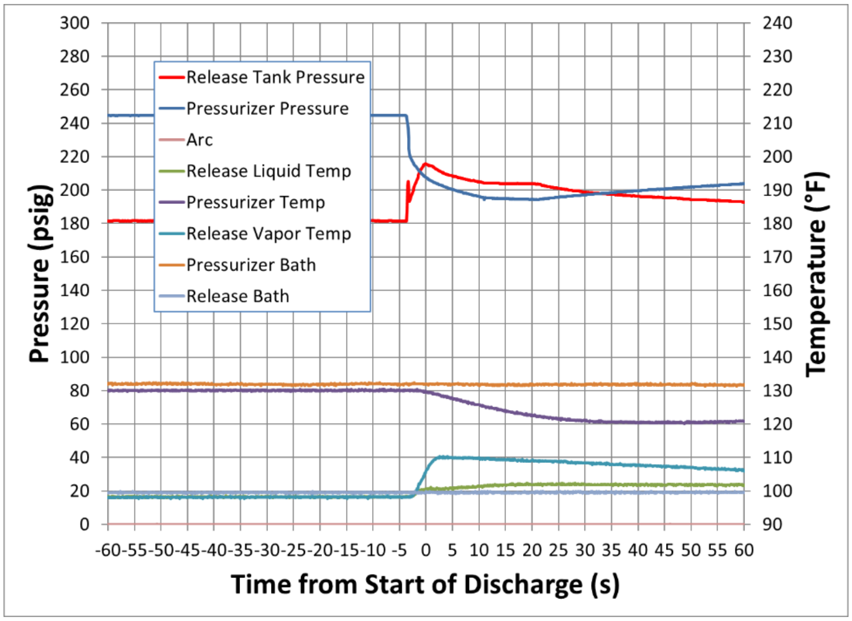


Figure 264 – PTAC_06 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_07 (114 grams; Fan On)

Test PTAC_07 was performed without ignition sources to measure propane concentrations. The unit fan was running on low speed throughout this test. The key parameters and results of this test are summarized in the following table. All measured propane concentrations were less than LFL at 13 seconds after the start of the discharge.

Table 56 – PTAC_07 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	114	5.3	21.4	Center of Evaporator Coil	0.14	Calculated if well Mixed in whole room
Measured	110	5.7	19.2		3.0 1.4	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 265 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 0.2 to 0.6% near the floor level which is two to three times the estimated well-mixed value of 0.14%.

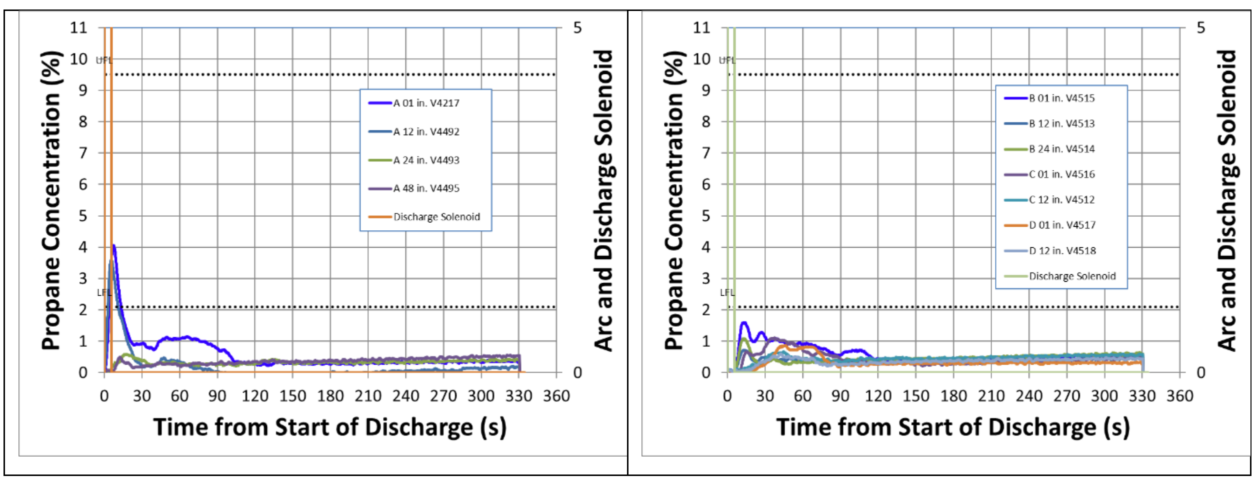


Figure 265 – PTAC_07 Concentrations

Figure 266 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. The increase in the left side concentration is an indication of evaporation of a pool of liquid propane inside the PTAC unit.

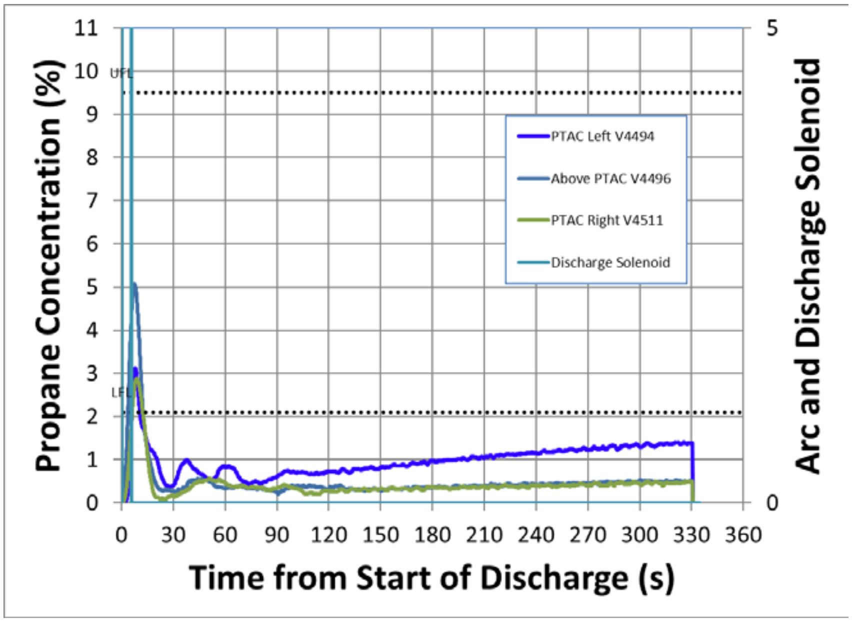


Figure 266 – PTAC_07 Concentrations near PTAC

Figure 267 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

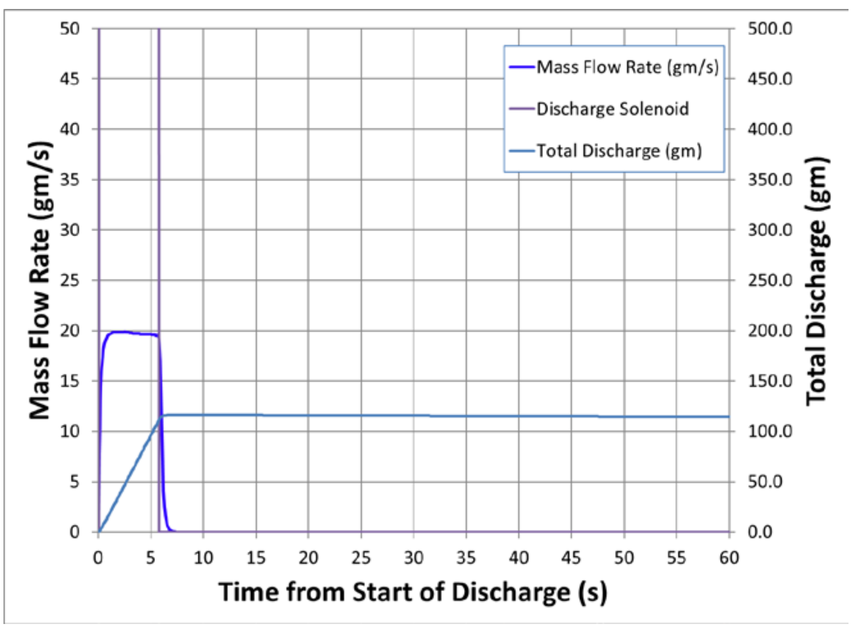


Figure 267 – PTAC_07 Mass Flow

Figure 268 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

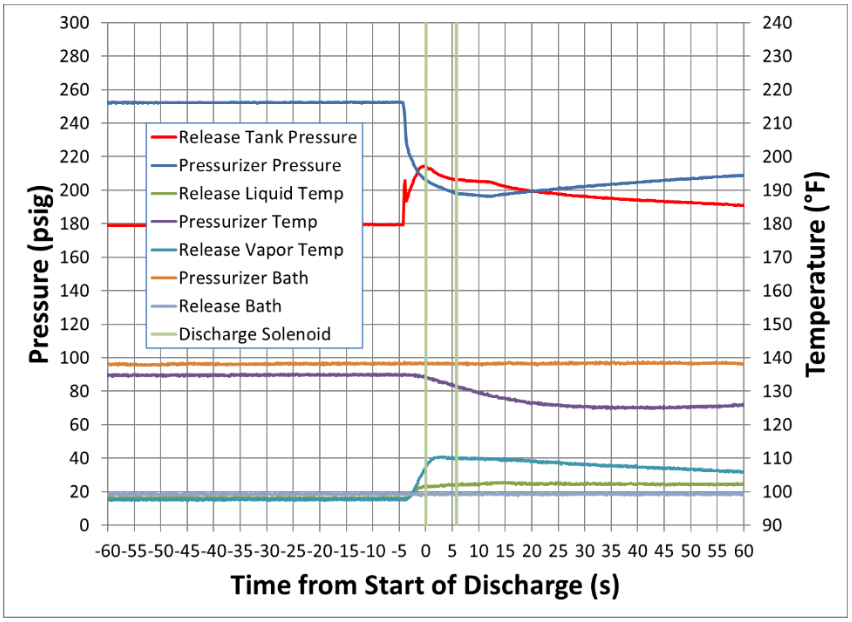


Figure 268 – PTAC_07 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_08 (217 grams; Fan Off)

Test PTAC_08 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is PTAC_14. This test involved release at the front-center of the evaporator coil. The key parameters and results of this test are summarized in the following table. All measured propane concentrations were less than LFL at 80 seconds after the start of the discharge. The maximum concentration at 2.5 minutes after completion of the discharge was 1.6% or 75% of the propane's LFL.

Table 57 – PTAC_08 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	217	10.1	21.4	Center of Evaporator Coil	0.26	Calculated if well Mixed in whole room
Measured	212	11.5	18.4		3.7 2.0	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 269 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 0.5 to 1.5% near the floor level which is two to six times the estimated well-mixed value of 0.26%.

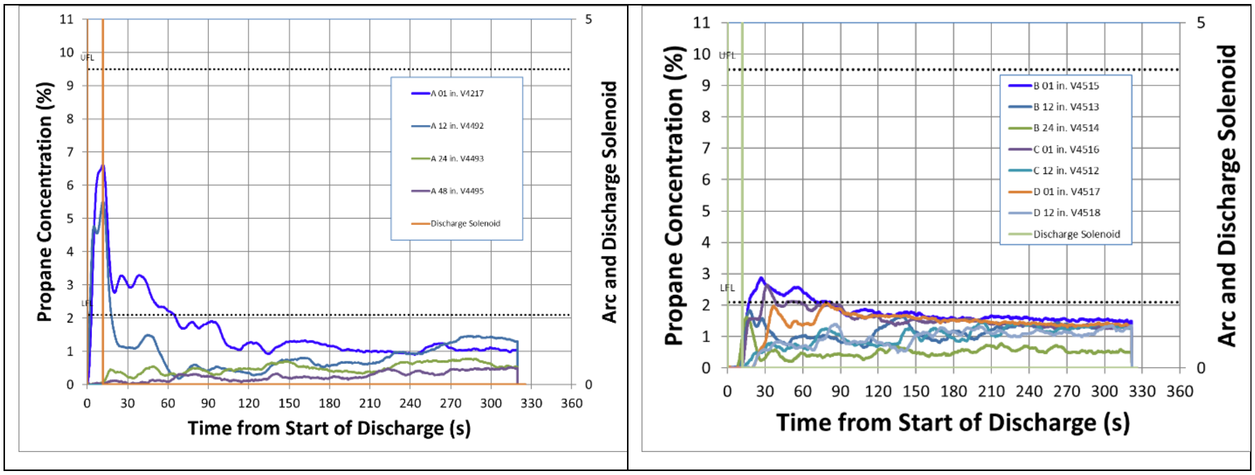


Figure 269 – PTAC_08 Concentrations

Figure 270 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

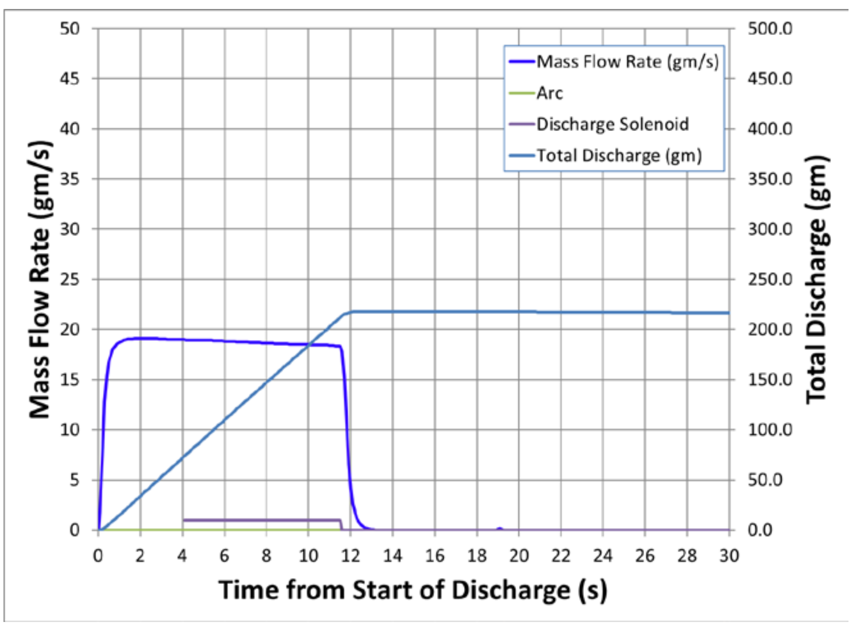


Figure 270 – PTAC_08 Mass Flow

Figure 271 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

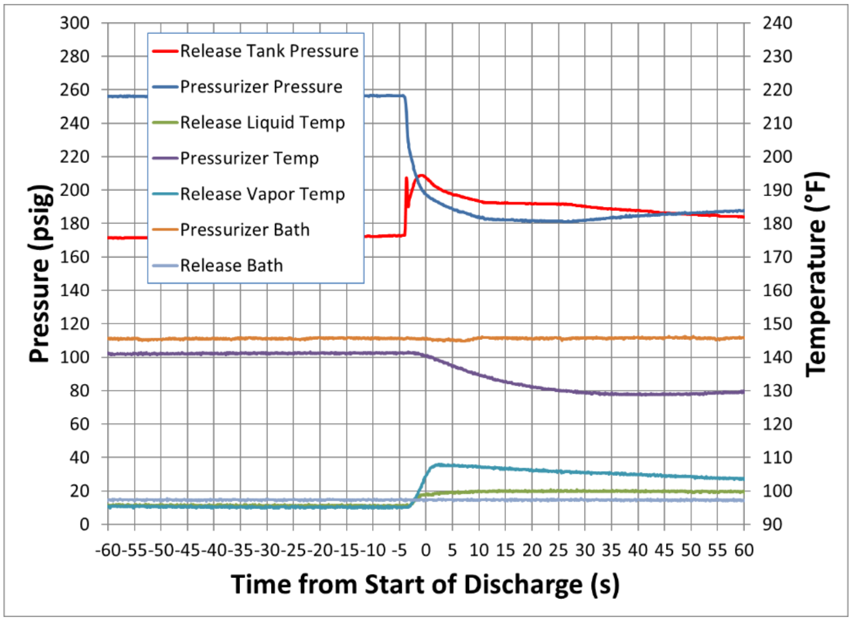


Figure 271 – PTAC_08 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_09 (114 grams; Fan Off)

Test PTAC_09 was performed without ignition sources to measure propane concentrations prior to the conduct of the equivalent test using igniters in test PTAC_16. The key parameters and results of this test are summarized in the following table.

Table 58 – PTAC_09 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	114	5.3	21.4	Evaporator Return Bend	0.14	Calculated with no leakage and well mixed
Measured	111	5.3	20.8		4.3 0.2	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 567 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data at locations A, B, C and D. At the end of data recording, the figure shows concentrations in the range of 0.5 to 1.0% near the floor level which is four to six times the estimated well-mixed value of 0.14%.

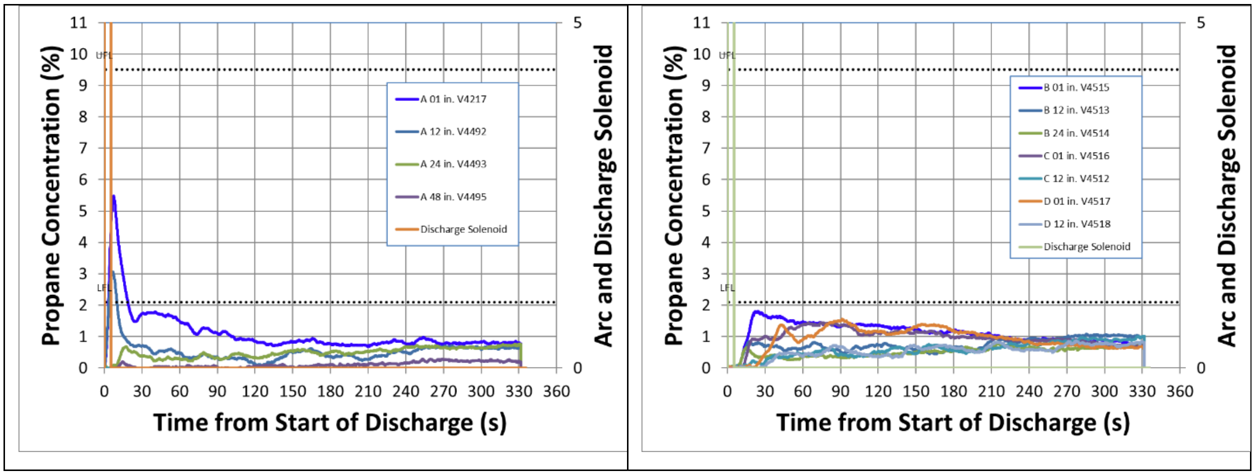


Figure 272 – PTAC_09 Concentrations

Figure 571 shows the mass flow rate and total mass flow.

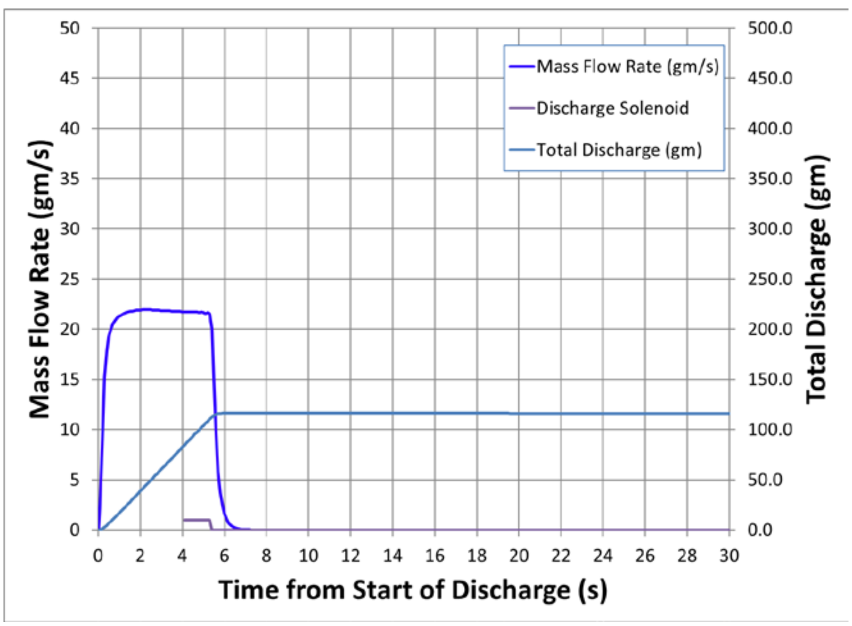


Figure 273 – PTAC_09 Mass Flow

Figure 572 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows that the pressurizer was at superheat conditions and was dry of all liquid propane. This situation led to a change in procedures for follow-on tests to insure that pressurizer temperature and pressure corresponded to saturation conditions.

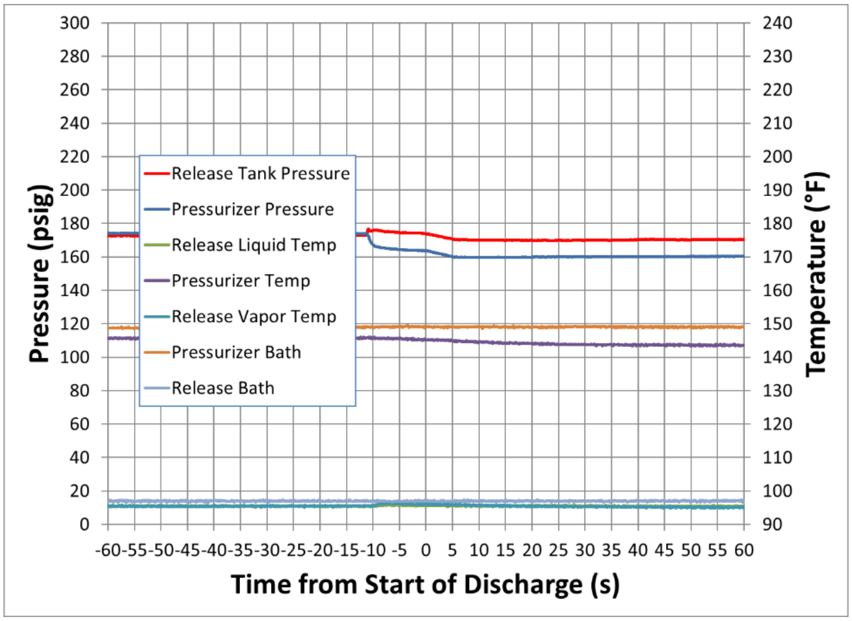


Figure 274 – PTAC_09 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_10 (325 grams; Fan On)

Test PTAC_10 was performed without ignition sources to measure propane concentrations. The unit fan was running on low speed throughout this test. The key parameters and results of this test are summarized in the following table. At the end of data recording all concentrations were less than LFL.

Table 59 – PTAC_10 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	325	15.2	21.4	Center of Evaporator Coil	0.39	Calculated if well Mixed in whole room
Measured	322	13.0	24.8		4.3 2.0	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 275 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. All concentrations were less than LFL 180 seconds after the start of the discharge.

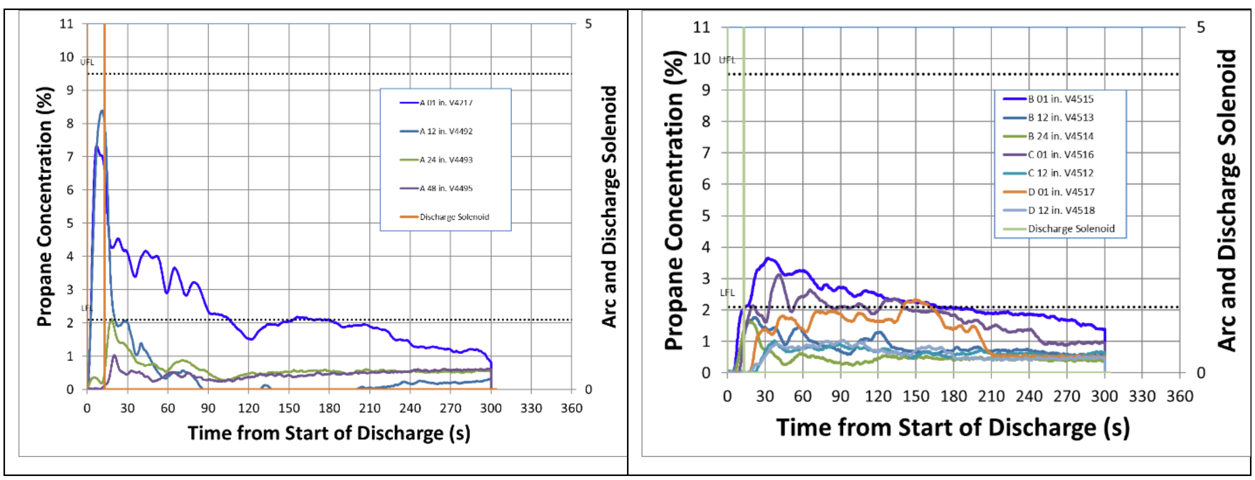


Figure 275 – PTAC_10 Concentrations

Figure 276 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. The operation of the fan reduced these concentrations to less than LFL in 22 seconds after the start of the discharge.

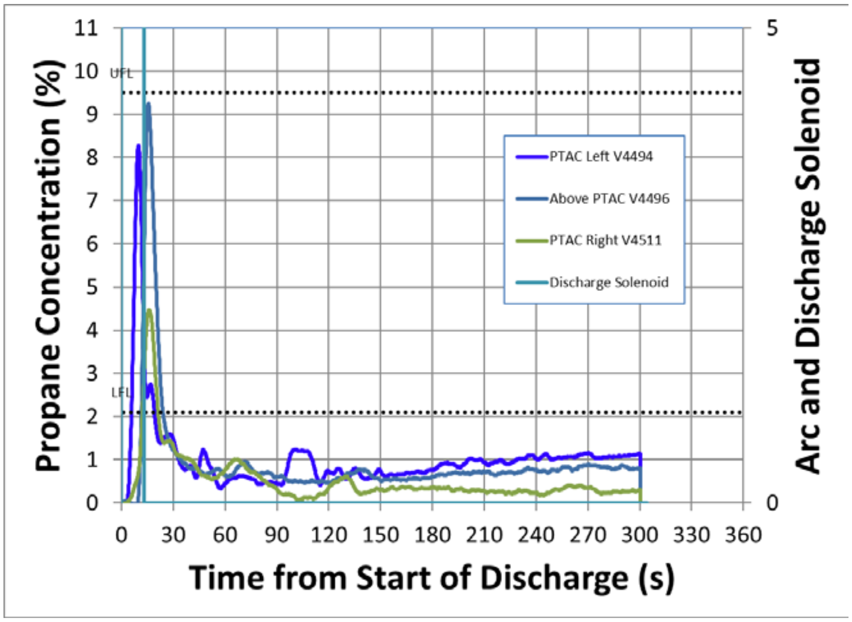


Figure 276 – PTAC_10 Concentrations near PTAC

Figure 277 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

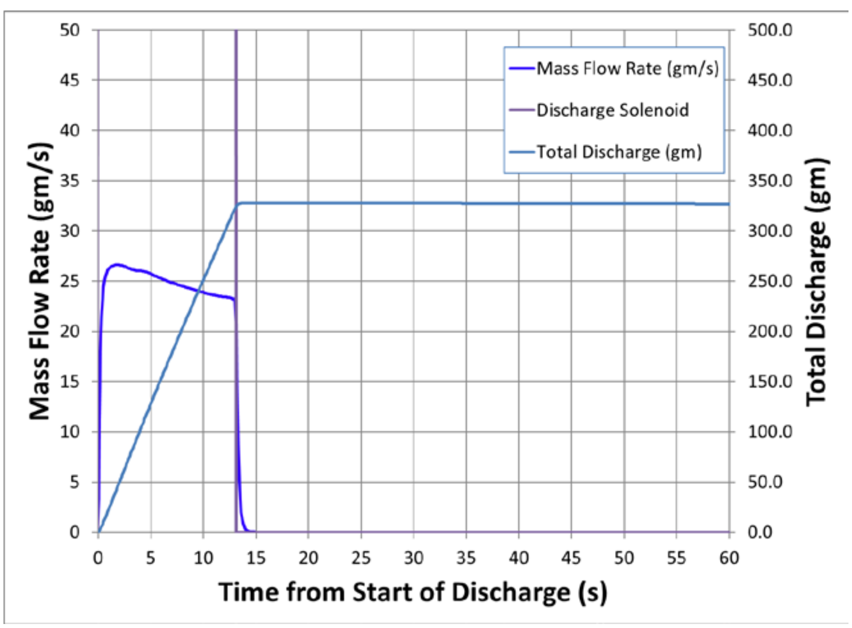


Figure 277 – PTAC_10 Mass Flow

Figure 278 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

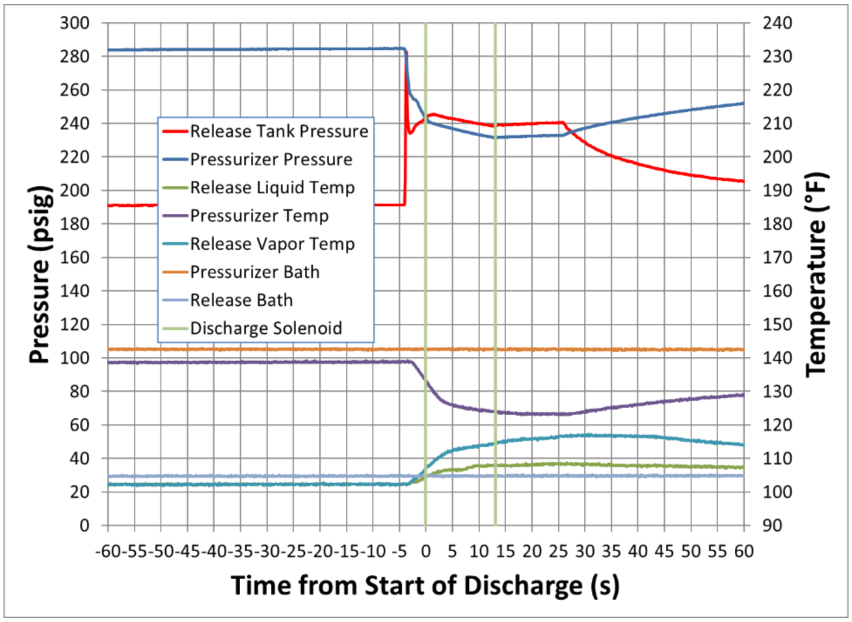


Figure 278 – PTAC_10 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_11 (325 grams; 7 s Fan Delay)

Test PTAC_11 was performed without ignition sources to measure propane concentrations. The unit fan was started 7 seconds after the start of the discharge on low speed. The key parameters and results of this test are summarized in the following table. At the end of data recording all concentrations were less than LFL.

Table 60 – PTAC_11 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	325	15.2	21.4	Center of Evaporator Coil	0.39	Calculated if well Mixed in whole room
Measured	323	15.1	21.4		5.3 2.4	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 279 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. All concentrations were less than LFL 150 seconds after the start of the discharge.

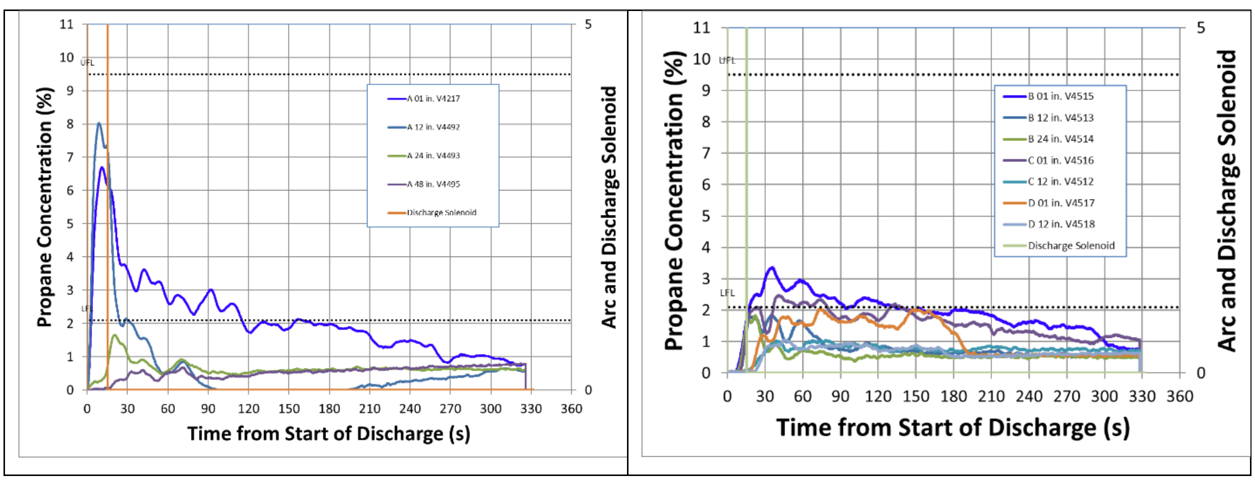


Figure 279 – PTAC_11 Concentrations

Figure 280 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. The cycling of the concentration on the internal left side of the PTAC is due to evaporation of liquid propane.

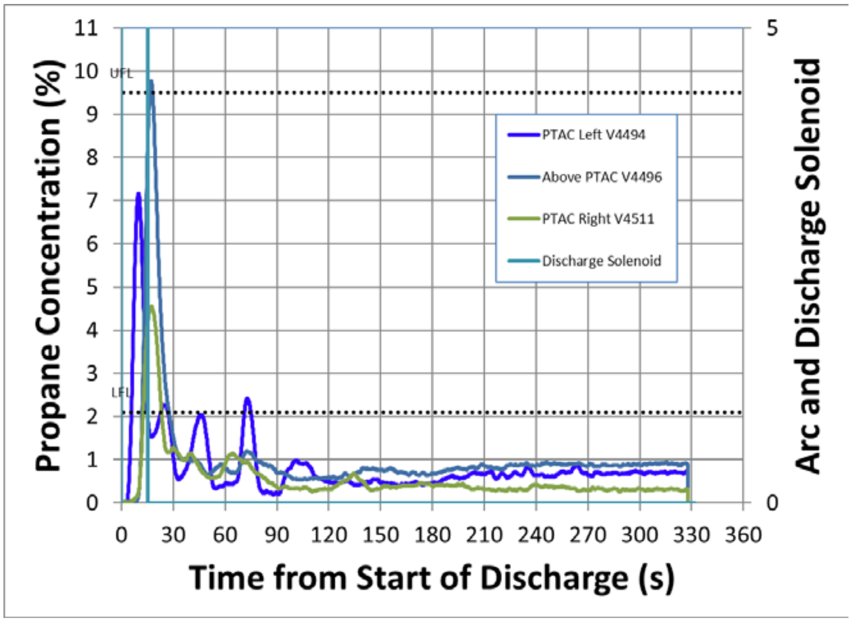


Figure 280 – PTAC_11 Concentrations near PTAC

Figure 281 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

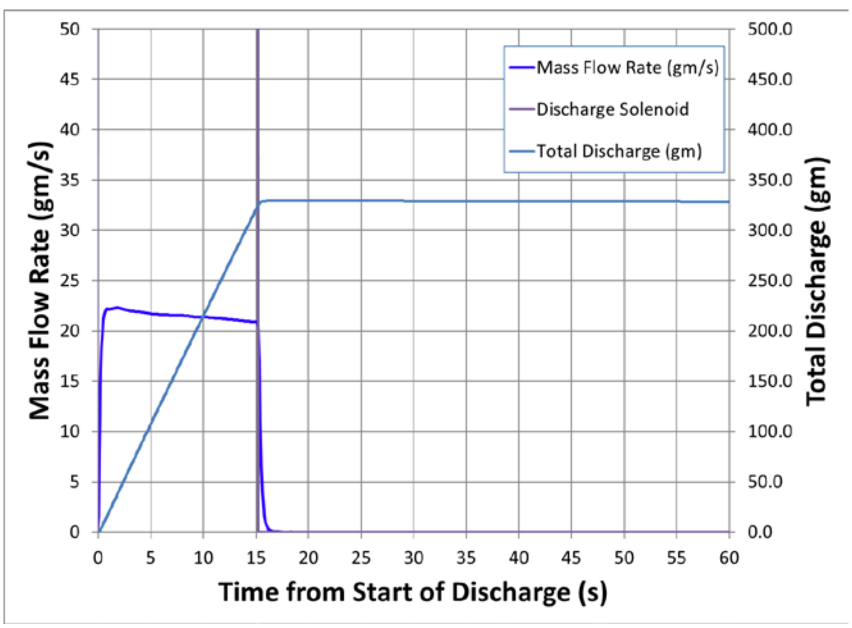


Figure 281 – PTAC_11 Mass Flow

Figure 282 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

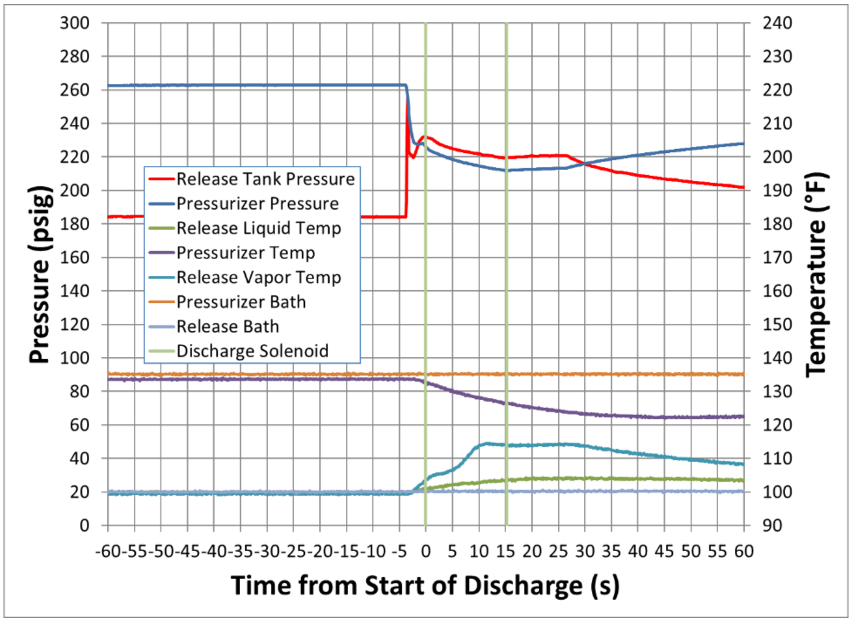


Figure 282 – PTAC_11 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_12 (217 grams; 7 s Fan Delay)

Test PTAC_12 was performed without ignition sources to measure propane concentrations. The unit fan was started 7 seconds after the start of the discharge on low speed. The key parameters and results of this test are summarized in the following table. At the end of data recording all concentrations were less than LFL.

Table 61 – PTAC_12 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	217	10.1	21.4	Center of Evaporator Coil	0.26	Calculated if well Mixed in whole room
Measured	213	10.1	21.1		4.7 1.6	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 283 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. All concentrations were less than LFL 105 seconds after the start of the discharge.

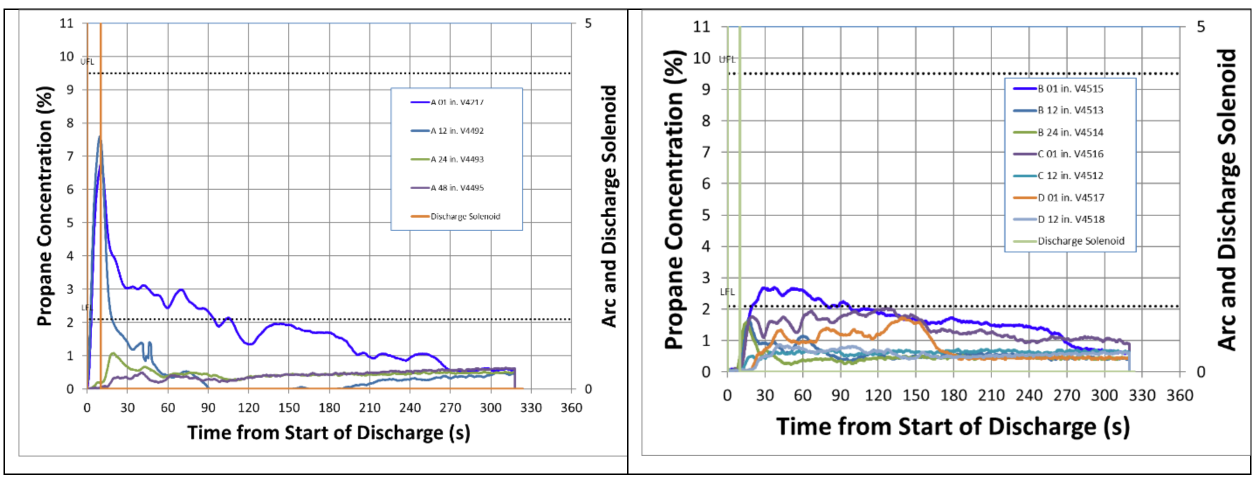


Figure 283 – PTAC_12 Concentrations

Figure 284 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. The cycling of the concentration on the internal left side of the PTAC is due to evaporation of liquid propane.

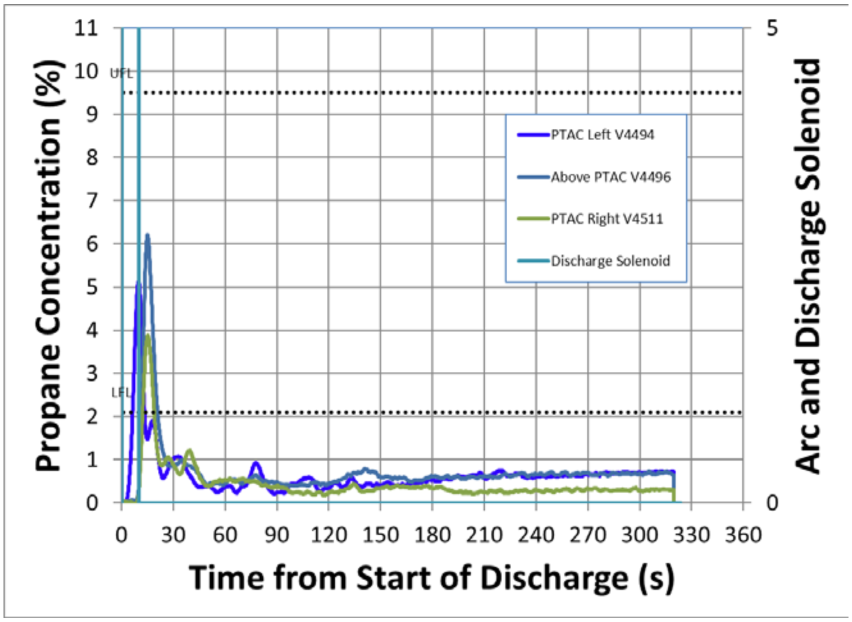


Figure 284 – PTAC_12 Concentrations near PTAC

Figure 285 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

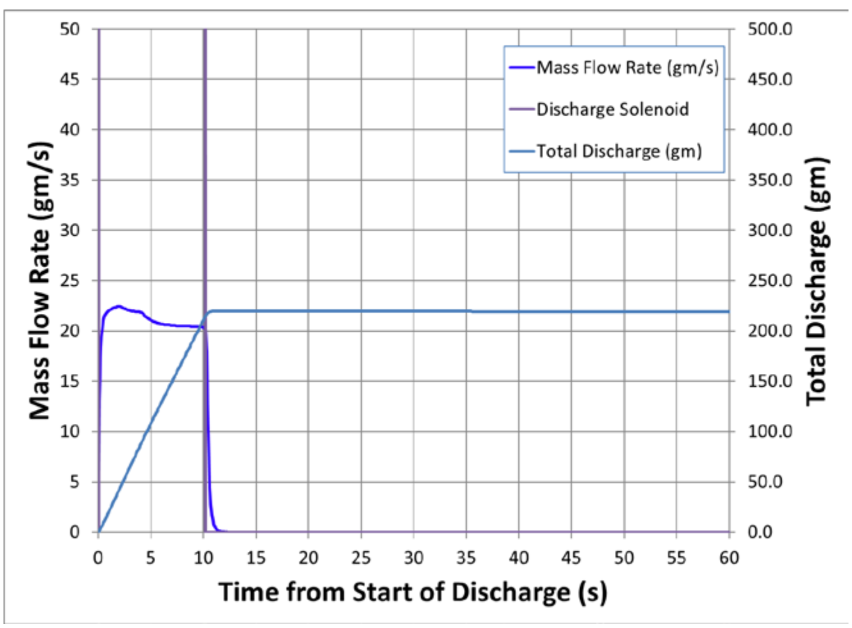


Figure 285 – PTAC_12 Mass Flow

Figure 286 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

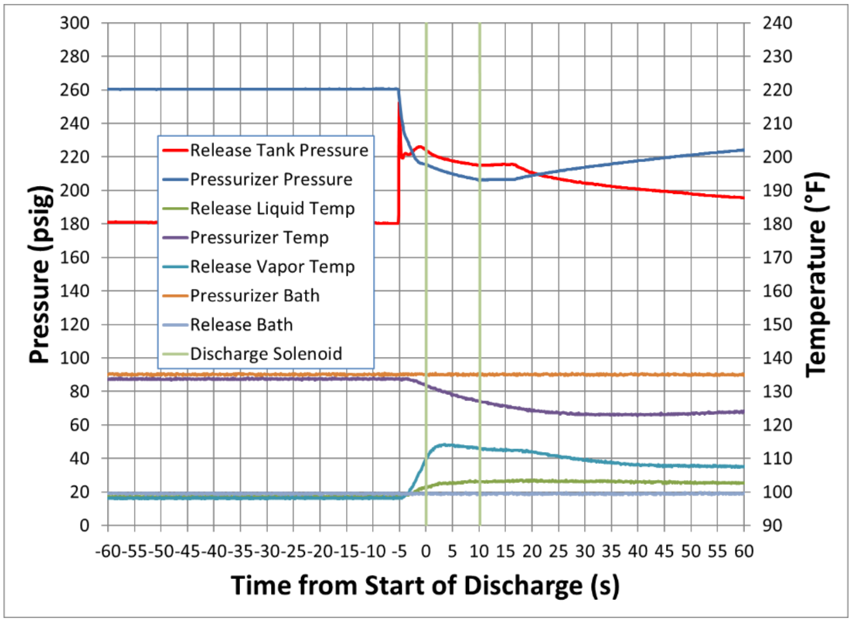


Figure 286 – PTAC_12 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_13 (114 grams; 7 s Fan Delay)

Test PTAC_13 was performed without ignition sources to measure propane concentrations. The unit fan was started 7 seconds after the start of the discharge on low speed. The key parameters and results of this test are summarized in the following table. At the end of data recording all concentrations were less than LFL.

Table 62 – PTAC_13 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	114	5.3	21.4	Center of Evaporator Coil	0.14	Calculated if well Mixed in whole room
Measured	111	5.4	20.5		3.4 0.7	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 287 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. All concentrations were less than LFL at 35 seconds after the start of the discharge.

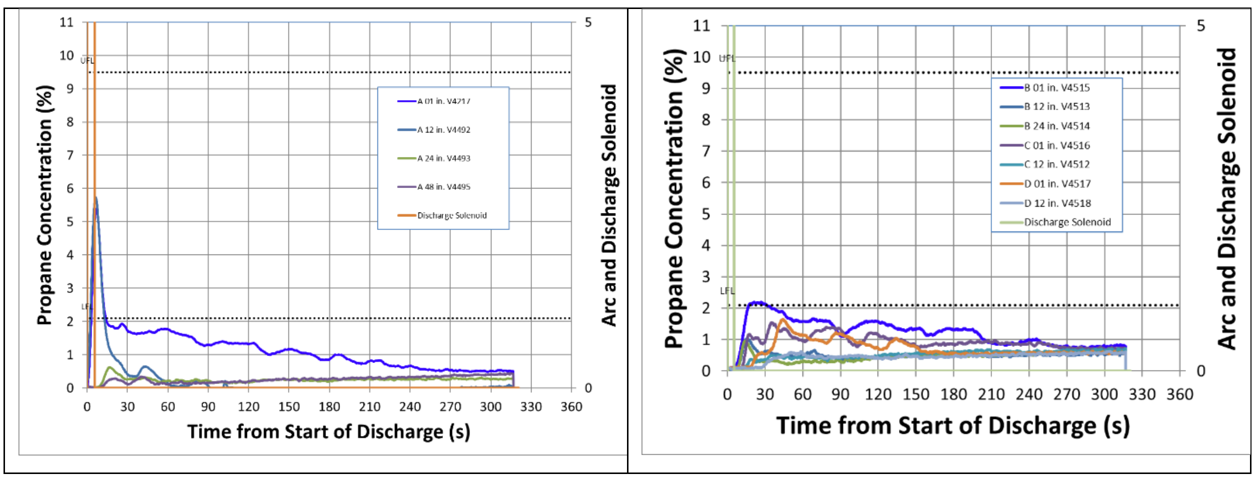


Figure 287 – PTAC_13 Concentrations

Figure 288 shows the concentrations at the sensors located internally on the left and right sides of the PTAC. The increase of concentration on the internal left side of the PTAC is due to evaporation of liquid propane.

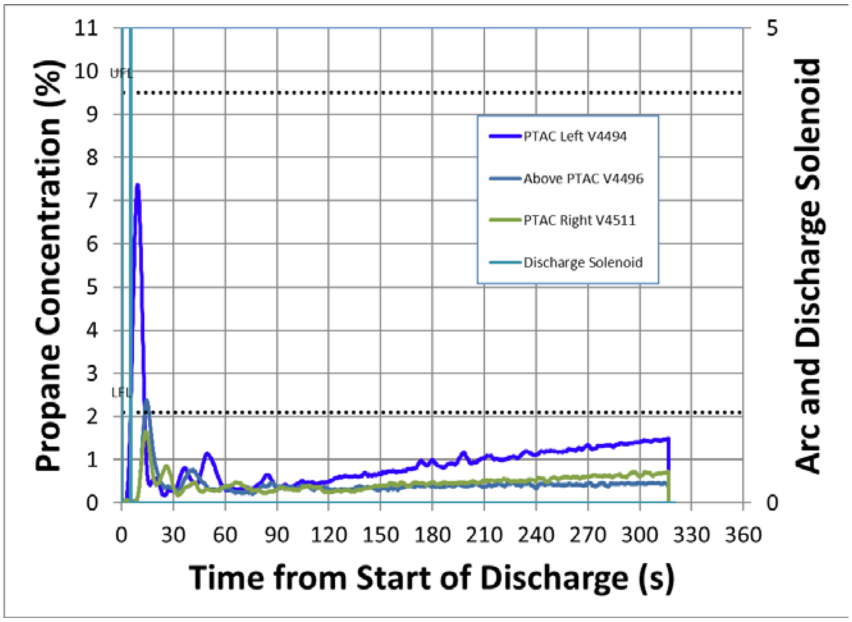


Figure 288 – PTAC_13 Concentrations near PTAC

Figure 289 shows liquid propane dripping from the front of the PTAC grill. It is suspected that splash back into the unit resulted in some accumulation of liquid propane in the drip pan at the left side of the unit.

Figure 289 – PTAC_13 Discharge showing accumulation of liquid propane on the PTAC grill

Figure 290 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing and does not represent a residual flow into the PTAC unit.

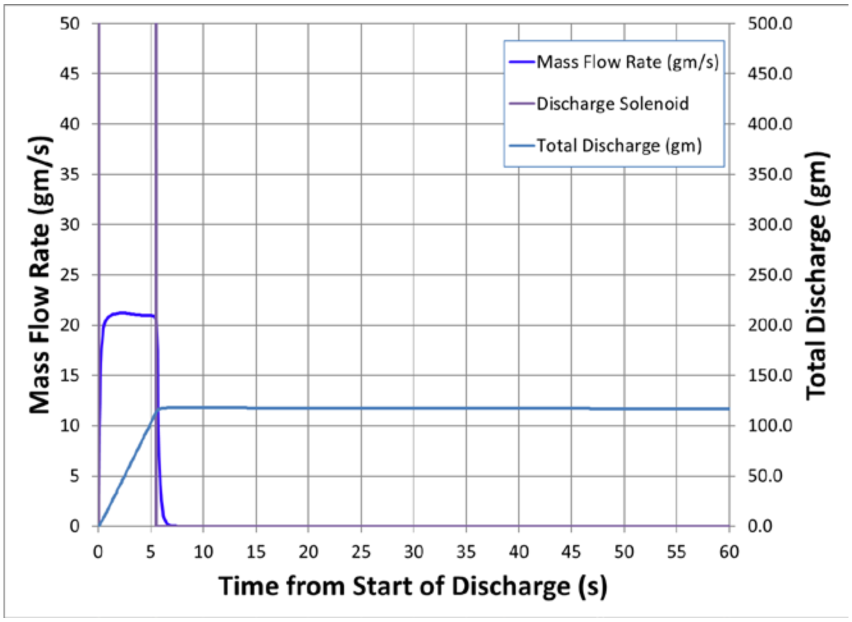


Figure 290 – PTAC_13 Mass Flow

Figure 291 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

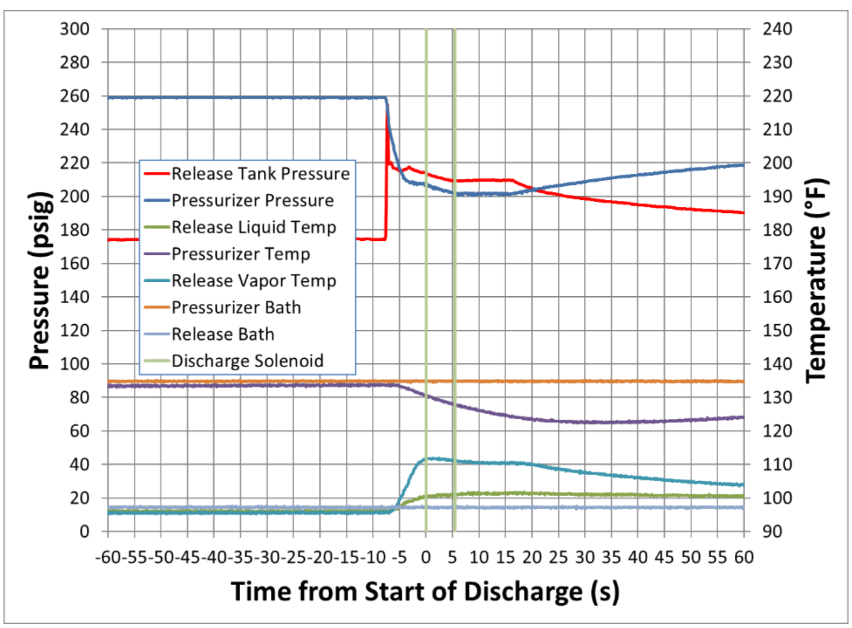


Figure 291 – PTAC_13 Pressurizer and Release Tank Pressure and Temperatures

Test PTAC_14 (217 grams; Fan Off)

Test PTAC_14 was performed with ignition sources and resulted in ignition at arc location A and B.

Table 63 – PTAC_14 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	217	10.1	21.4	Center of Evaporator Coil
Measured	214	11.7	18.3	

Figure 573 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration.

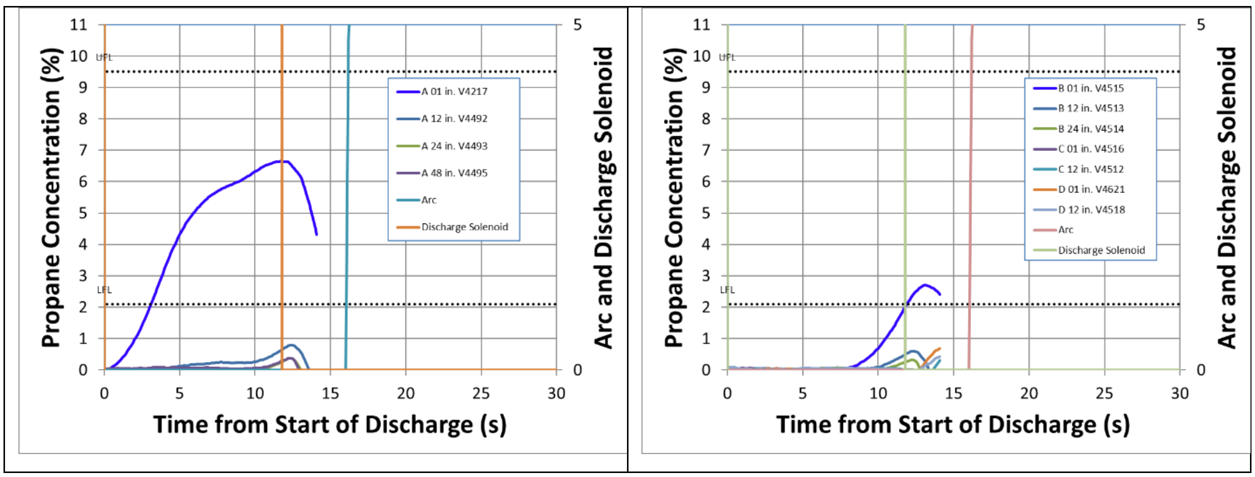


Figure 292 – PTAC_14 Concentrations

Figure 575 compares the concentrations at the 1-inch level at locations A and B for the pre-test and ignition tests (PTAC_08 and PTAC_14). The data shown is not deconvoluted in order to show repeatability up to the point of ignition. Location A data shows good agreement, but there is insufficient data to explain the divergence of the location B data.

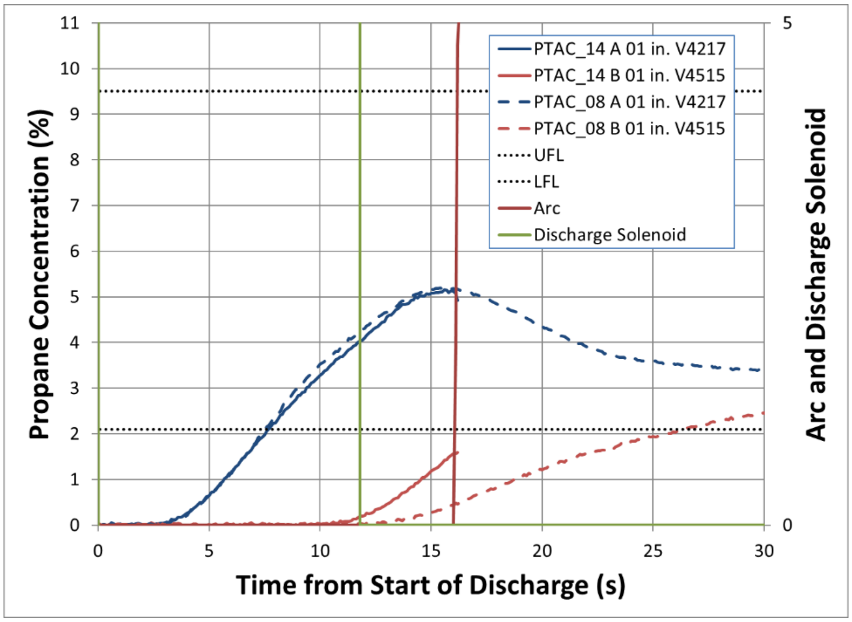


Figure 293 – PTAC_14 to PTAC_08 Concentration Comparison

Figure 576 shows the mass flow rate and total mass flow.

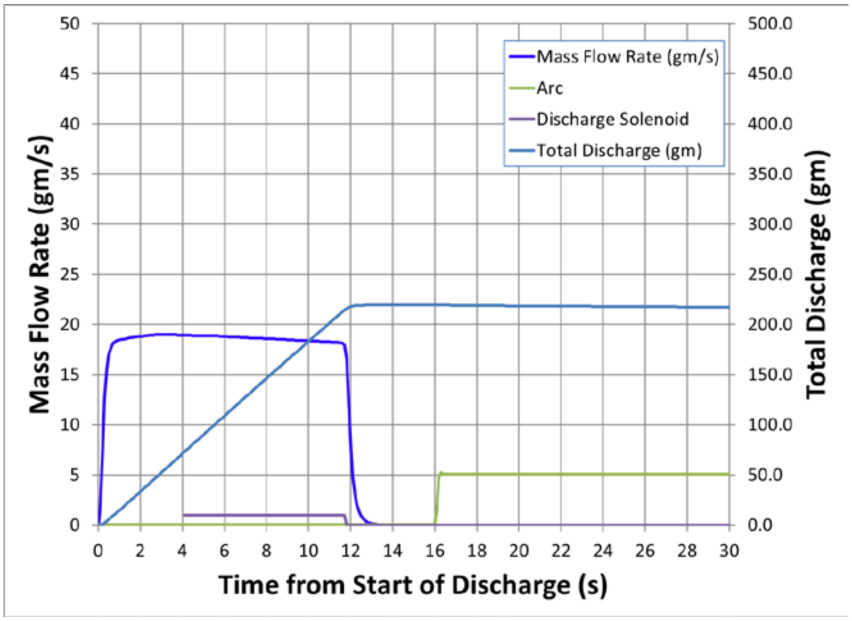


Figure 294 – PTAC_14 Mass Flow

Figure 577 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

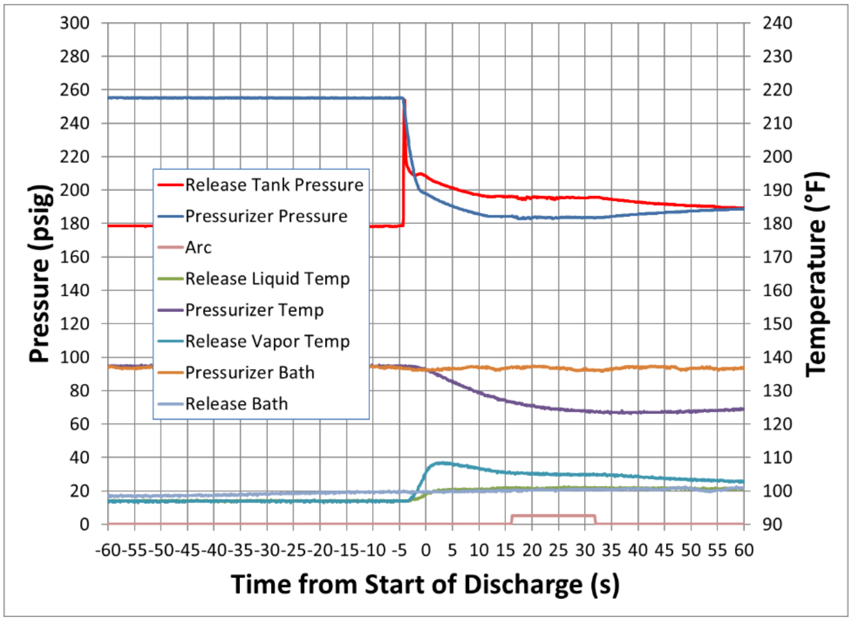
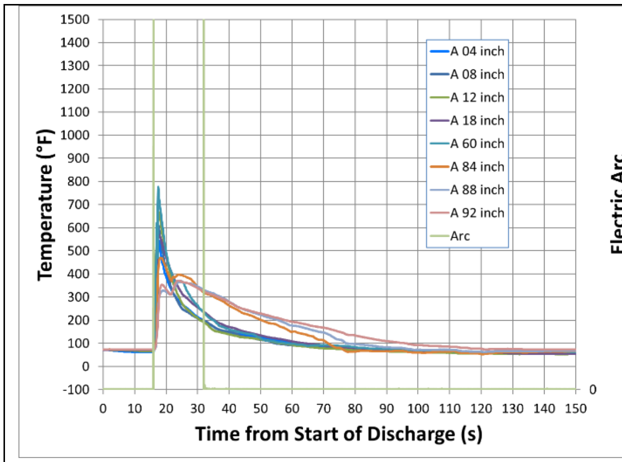
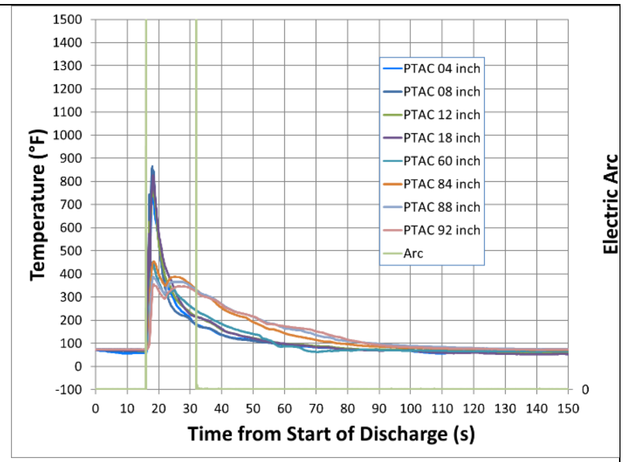


Figure 295 – PTAC_14 Pressurizer and Release Tank Pressure and Temperatures

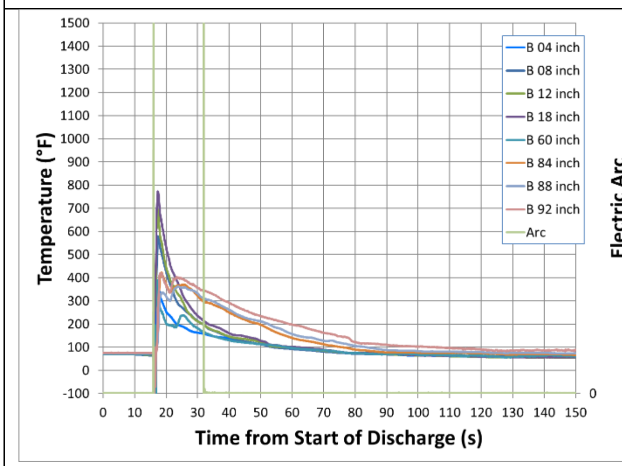
Figure 578 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at the PTAC location. The temperatures locations A, B and PTAC show a sharp spike temperatures due to the presence of flames. Location D does not show the same spike due to the lack of flames in that area. All thermocouple trees show the delayed increase of higher level temperatures due to the rise of hot gases.



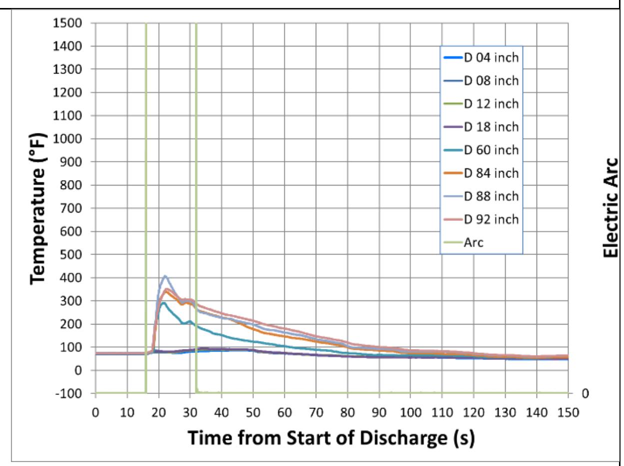
Location A



PTAC Location



Location B



Location D

Figure 296 – PTAC_14 Temperatures at Locations A, B, C, and D

The videos showed ignition nearly simultaneously at locations A and B. Flames within the mixed volume of room air and propane endured for approximately 2 seconds. Flaming continued for another 7 seconds at a liquid pool of propane in front of the PTAC unit. Figure 76 shows several frames from the videos of this test.

Flaming continued inside the PTAC unit due to the remaining propane and ignition of the PTAC filters. The filter fires continued and were suppressed with a water spray. The plastic housing did not ignite, but did deform from the heat. The unit filters did ignite.

Three deflagration vents burst due to the initial flaming and three others were melted by the hot gases.

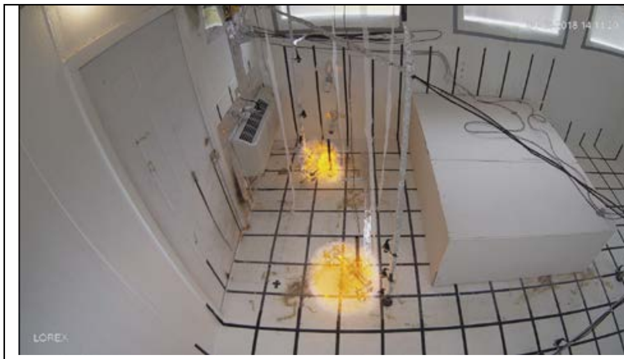
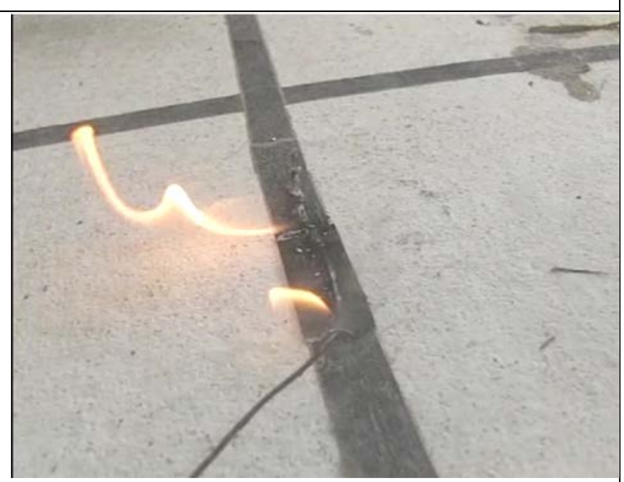
	
Simultaneous ignition at Locations A and B	Maximum size of flaming
	
Flames attached to a pool of liquid propane	Liquid propane pool evaporated 9 seconds after ignition

Figure 297 – PTAC_14: Frames of flaming from videos

Test PTAC_15 (114 grams; Fan Off; with Igniters)

Test PTAC_15 was performed with ignition sources and resulted in ignition at arc location A and B. This test was considered invalid because the electric arcs were energized too soon after the completion of the discharge (1 second vs. 5 seconds specified). This test was repeated in test PTAC_16 with the proper arc delay time.

Table 64 – PTAC_15 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	114	5.3	21.4	Center of Evaporator Coil
Measured	114	5.4	20.9	

Figure 298 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration.

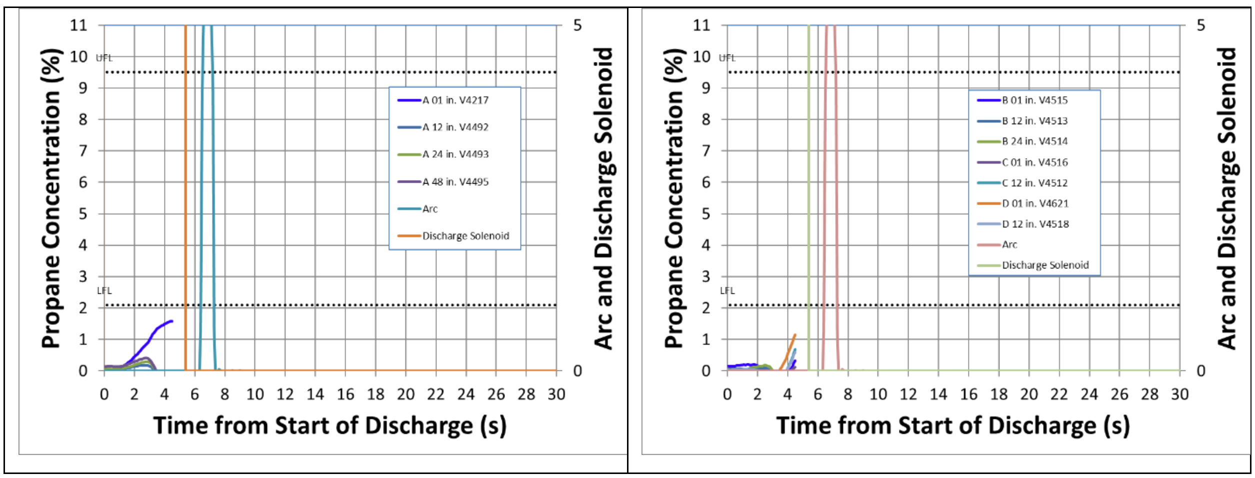


Figure 298 – PTAC_15 Concentrations

Figure 299 shows the mass flow rate and total mass flow.

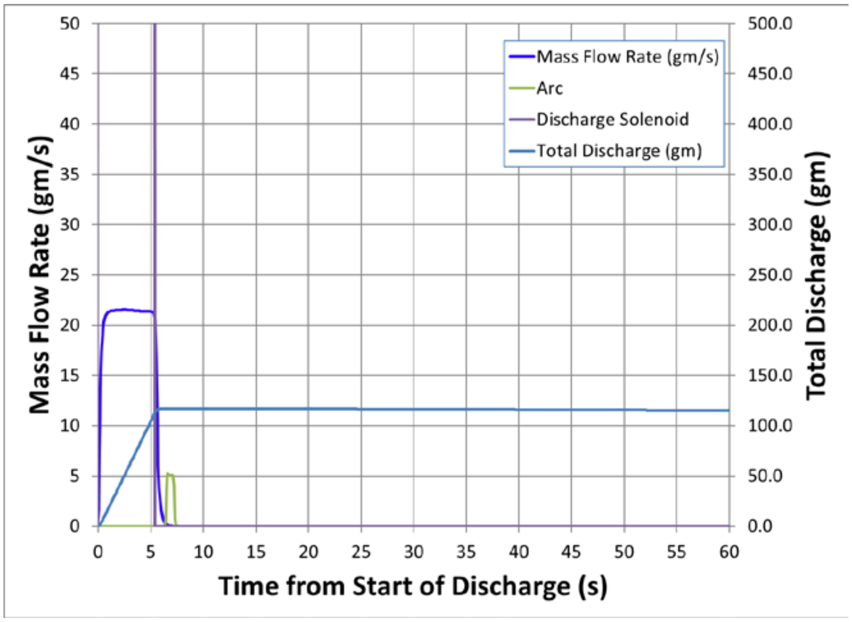


Figure 299 – PTAC_15 Mass Flow

Figure 300 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

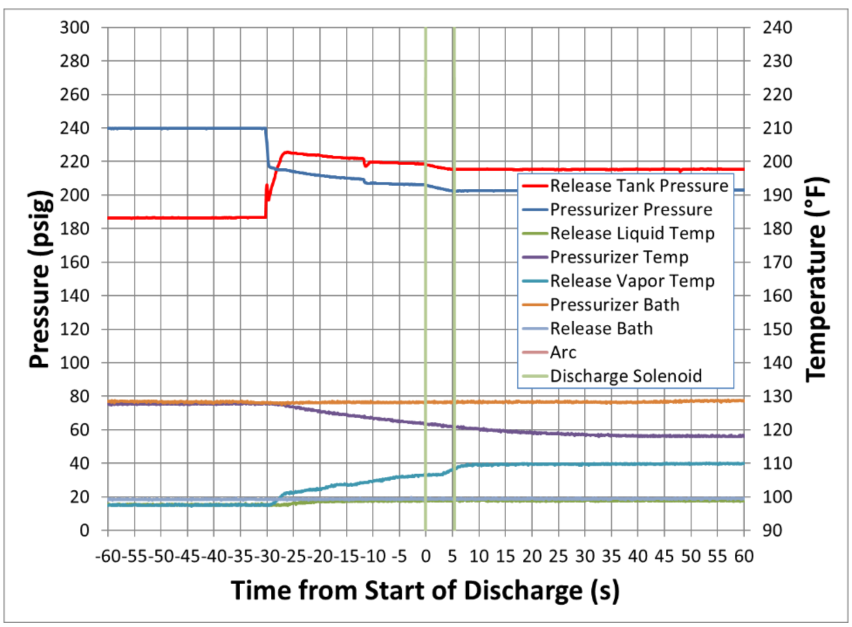


Figure 300 – PTAC_15 Pressurizer and Release Tank Pressure and Temperatures

Figure 301 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at the PTAC location. The temperatures locations A, B and PTAC show a sharp spike temperatures due to the presence of flames. Location D does not show the same spike due to the lack of flames in that area. All thermocouple trees show the delayed increase of higher level temperatures due to the rise of hot gases.

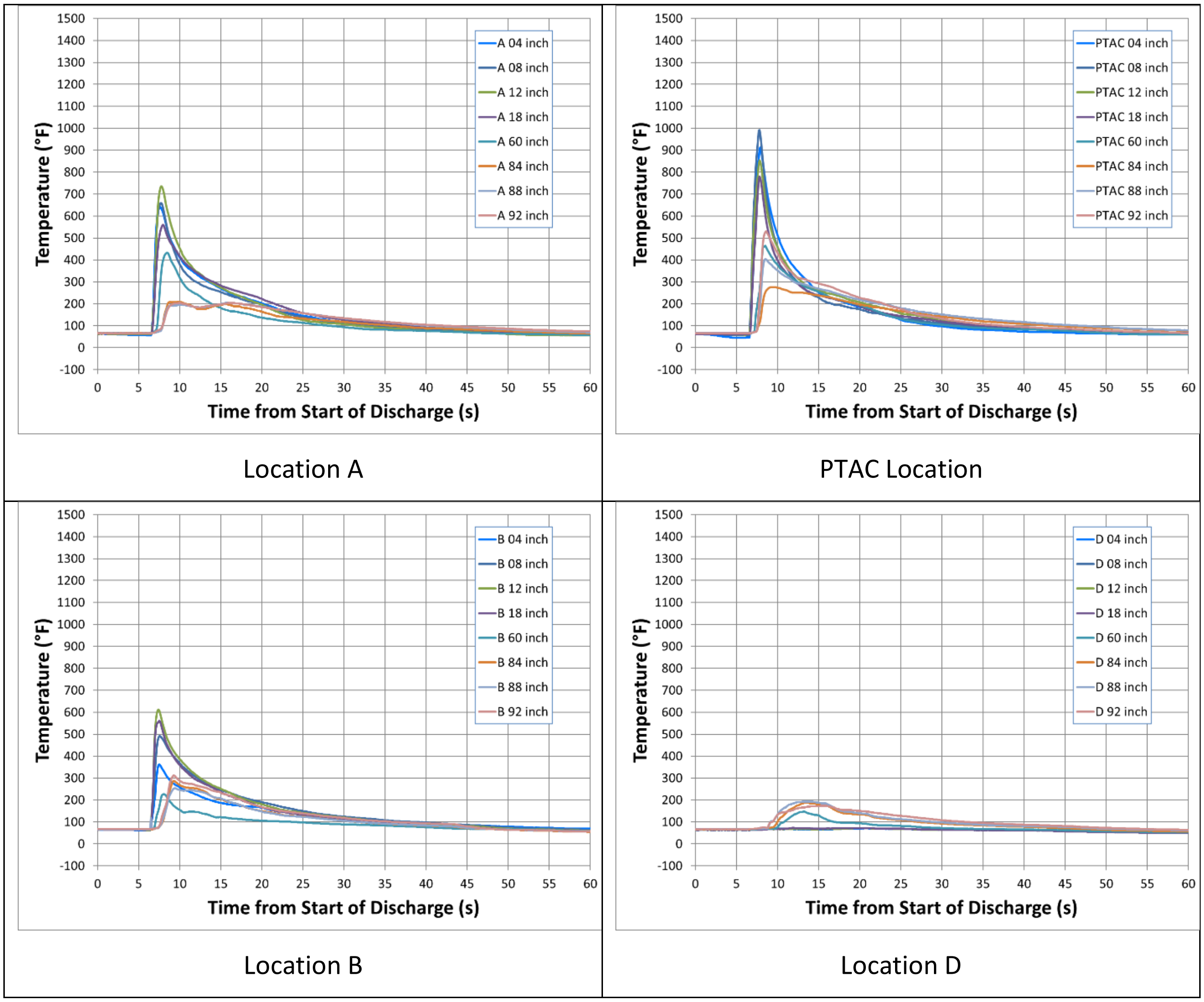


Figure 301 – PTAC_15 Temperatures at Locations A, B, C, and D

The videos showed ignition at Location A followed by Location B with a slight delay. Flames within the mixed volume of room air and propane endured for approximately 3 seconds. Flaming continued inside the PTAC unit due to the remaining propane and ignition of the PTAC filters. The filter fires continued and were suppressed with a water spray.

A pool of liquid propane was not observed. Four deflagration vents burst due to the initial flaming and one other was melted by the hot gases.

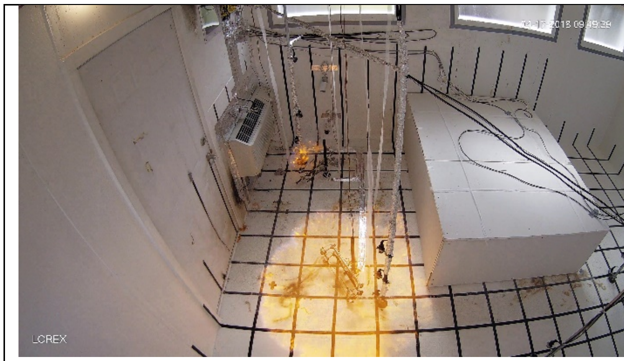
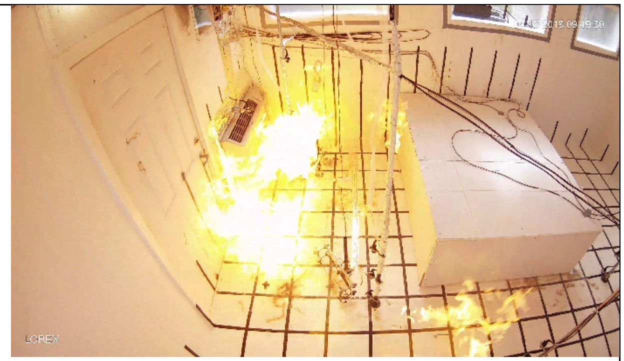
	
Ignition at Location B with a delayed ignition at Location A	Maximum size of flaming

Figure 302 – PTAC_15: Frames of flaming from videos

Test PTAC_16 (114 grams; Fan Off)

Test PTAC_16 was performed with ignition sources and resulted in ignition at arc location A and B.

Table 65 – PTAC_16 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	114	5.3	21.4	Center of Evaporator Coil
Measured	110	5.4	20.4	

Figure 303 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration.

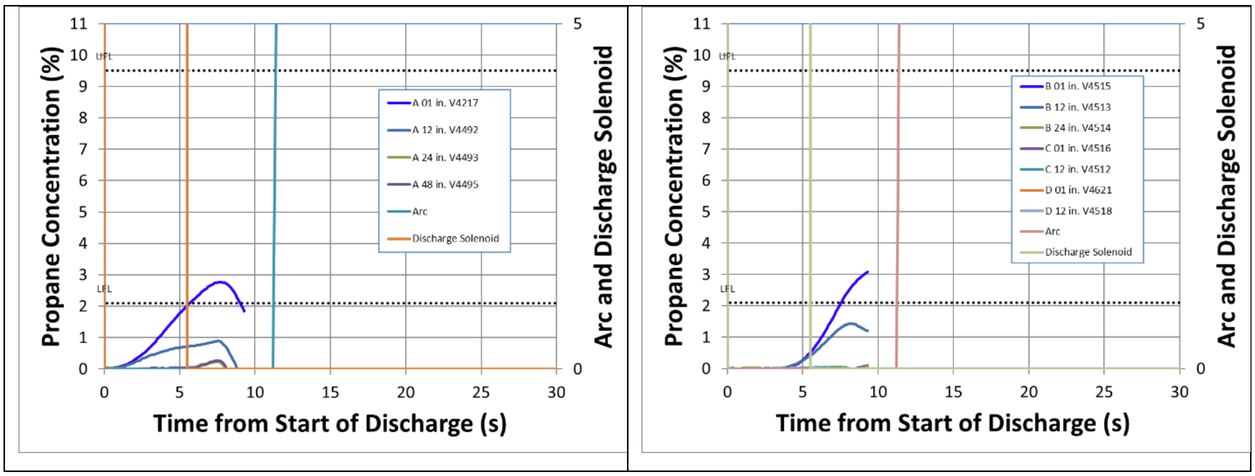


Figure 303 – PTAC_16 Concentrations

Figure 304 compares the concentrations at the 1-inch level at locations A and B for the pre-test and ignition tests (PTAC_09 and PTAC_16). The data shown is not deconvoluted to provide the maximum amount of data for comparison. The repeatability is poor because of the difference in discharge pressures (see Figure 572 and Figure 307). The discharge tank pressure in PTAC_09 was approximately 170 psig, compared to 210 psig in PTAC_16. The lower pressure in PTAC_09 was close to saturation pressure at the discharge metering valve while the higher pressure in PTAC_16 represents between 20 and 30 °F of sub-cooling at the same point. The result was a difference in quality (vapor mass to total mass) at the discharge location and resulting concentration measurement.

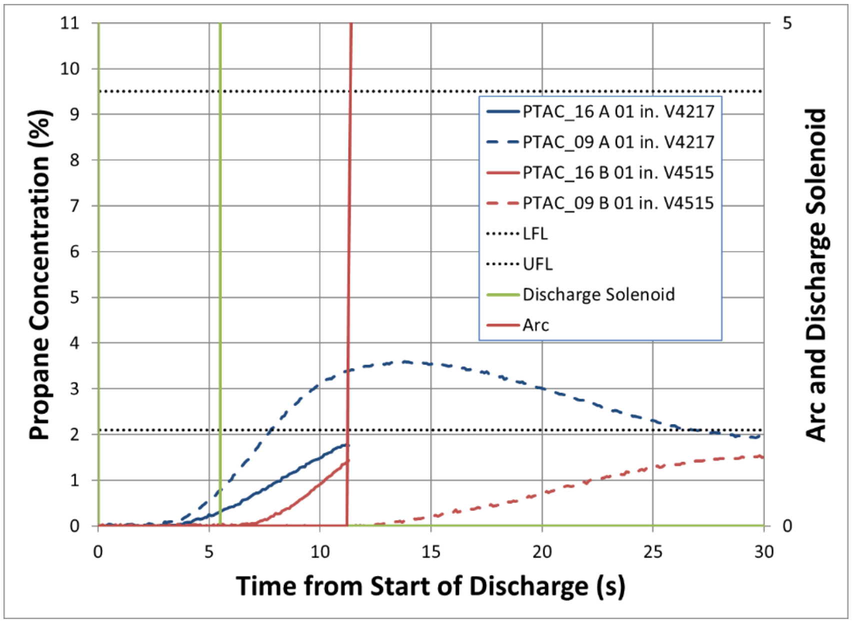


Figure 304 – PTAC_16 to PTAC_09 Concentration Comparison

Figure 305 compares the visual of the propane mist between PTAC_09 (left) and PTAC_16 (right). The comparison shows that the streams exited the grill of the PTAC at different angles which is a factor in the distribution of measured propane concentrations. The PTAC_16 stream is angled away from the corner which reduced the accumulation at location A and increases the concentration at location B. The stream from PTAC_09 is nearly perpendicular to the mounting wall except for the down angle. This behavior increased concentration at location A and decreased concentration at location B.

It was noted that the PTAC grill assembly had slightly warped from the exposure to fire in PTAC_14 and PTAC15 tests. The result was that the discharge impacted the grill face at slightly different conditions.

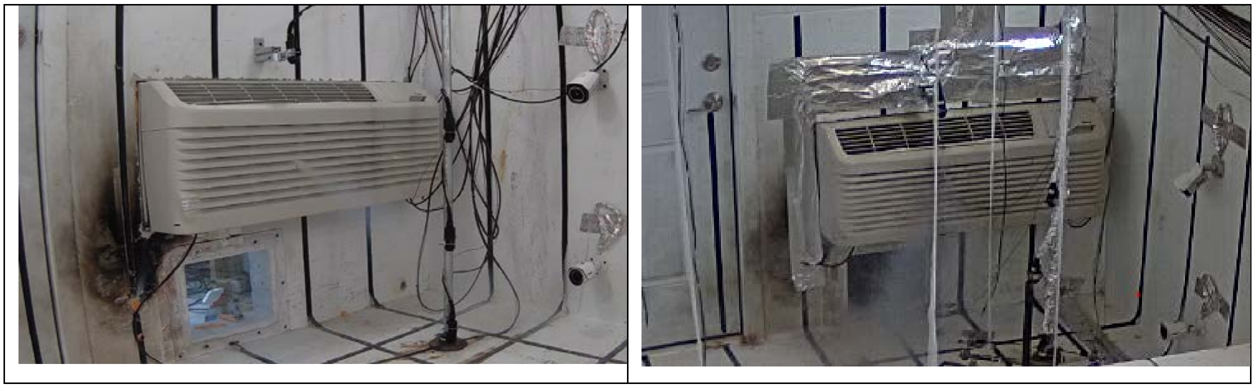


Figure 305 – PTAC_09 (left) to PTAC_16 (right) Stream Comparison

Figure 306 shows the mass flow rate and total mass flow.

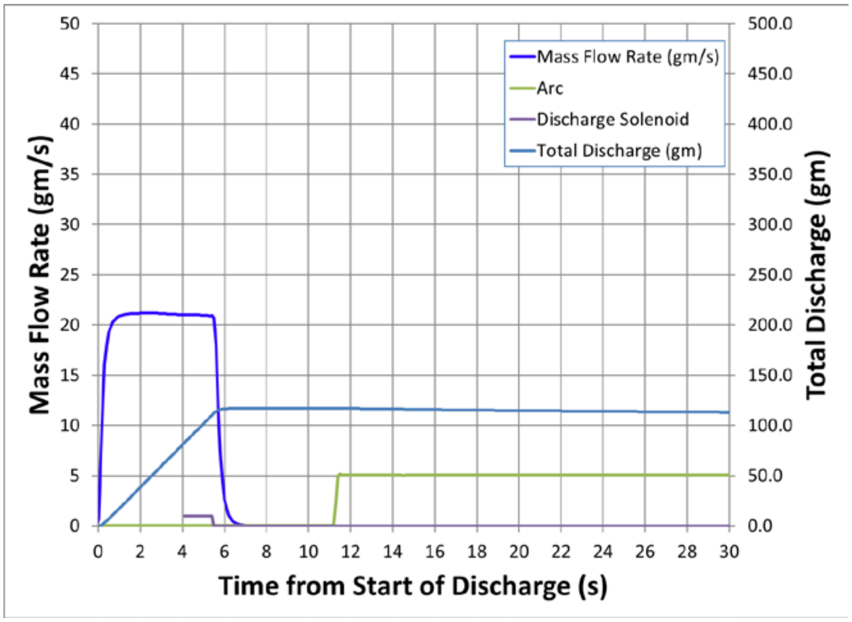


Figure 306 – PTAC_16 Mass Flow

Figure 307 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

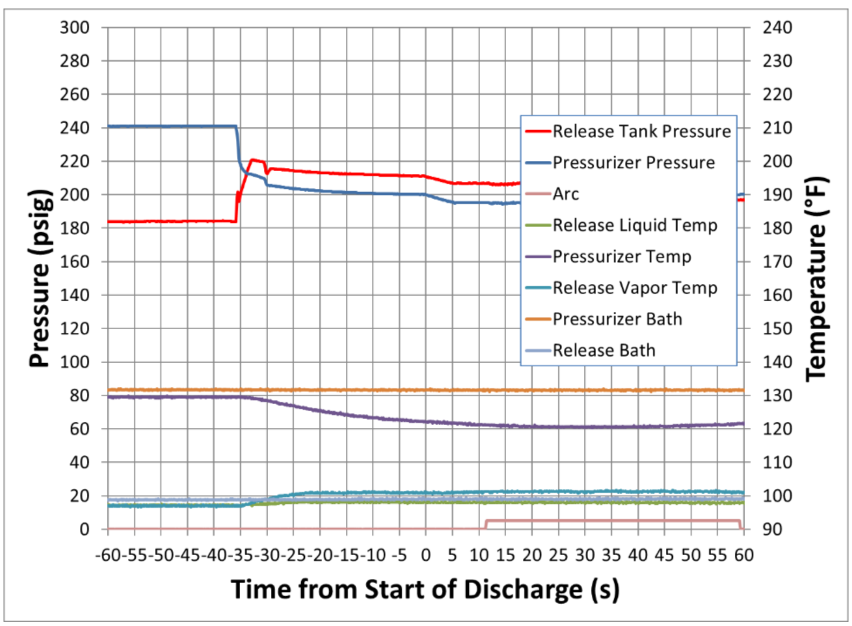


Figure 307 – PTAC_16 Pressurizer and Release Tank Pressure and Temperatures

Figure 308 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at the PTAC location. The temperatures locations A, B and PTAC show a sharp spike temperatures due to the presence of flames. Location D does not show the same spike due to the lack of flames in that area. All thermocouple trees show the delayed increase of higher level temperatures due to the rise of hot gases.

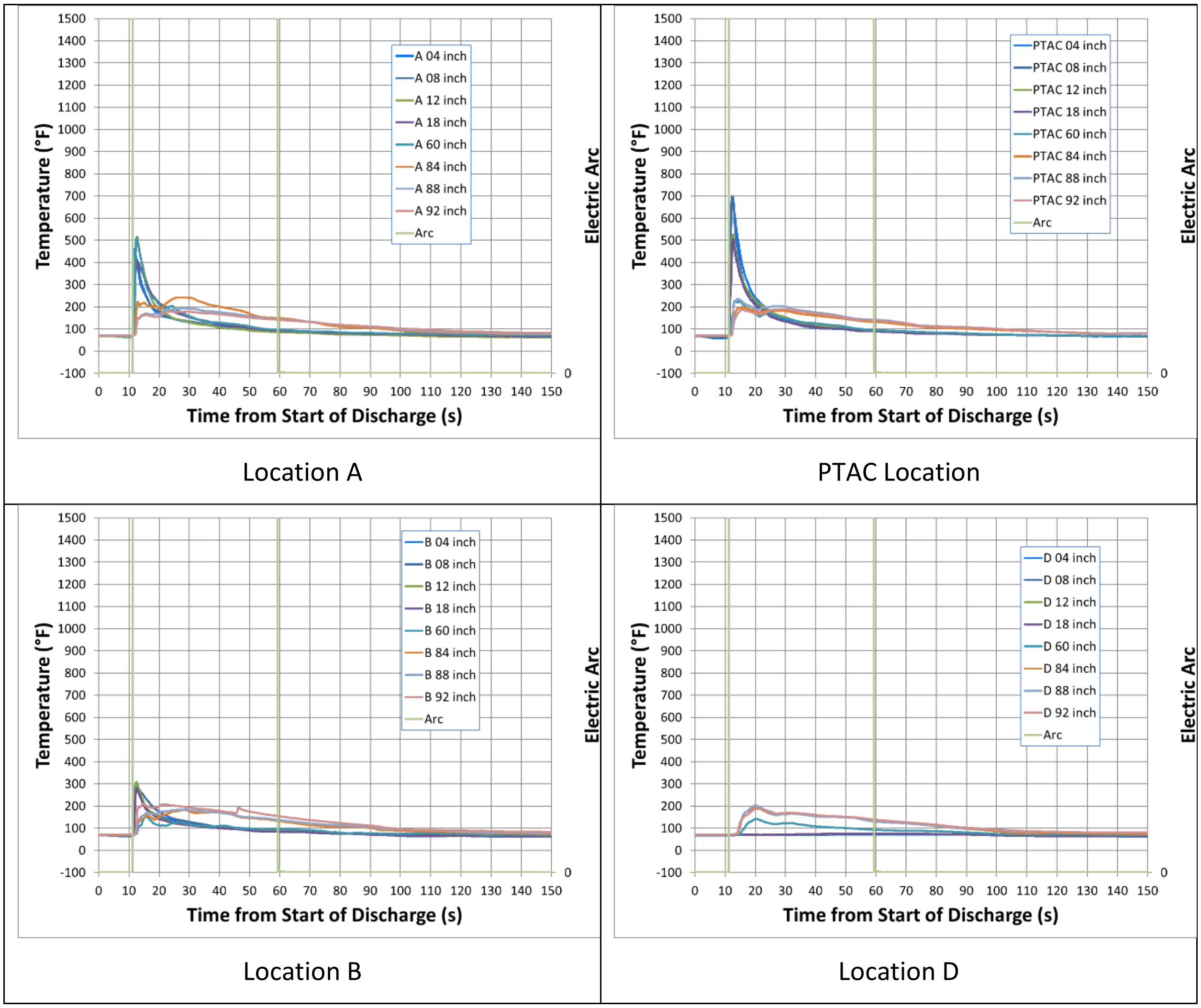
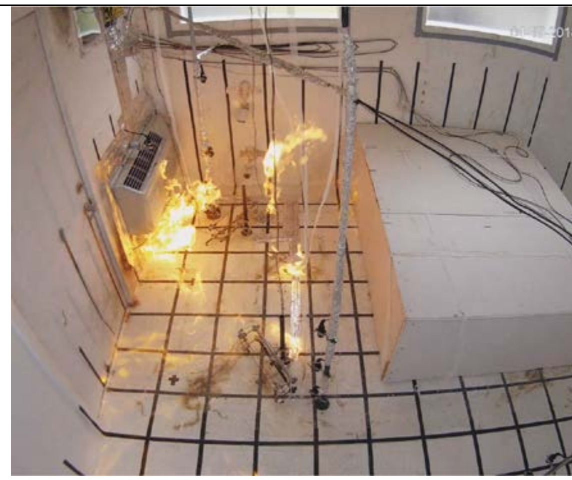


Figure 308 – PTAC_16 Temperatures at Locations A, B, C, and D

The videos showed ignition at Location A followed by Location B with a slight delay. Flames within the mixed volume of room air and propane endured for approximately 3 seconds. Flaming continued inside the PTAC unit due to the remaining propane and ignition of the PTAC filters. The filter fires continued and were suppressed with a water spray. The plastic housing did not ignite, but did deform from the heat. The unit filters did ignite.

A pool of liquid propane was not observed. Two deflagration vents burst due to the initial flaming and one other was melted by the hot gases.

Ignition at Location A with a delayed ignition at Location B



Maximum size of flaming

Figure 309 – PTAC_16: Frames of flaming from videos

Test PTAC_17 (217 grams; Fan On)

Test PTAC_16 was performed with ignition sources and resulted in ignition at arc location A and B.

Table 66 – PTAC_17 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	217	10.1	21.4	Center of Evaporator Coil
Measured	215	10.5	20.4	

Figure 310 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration.

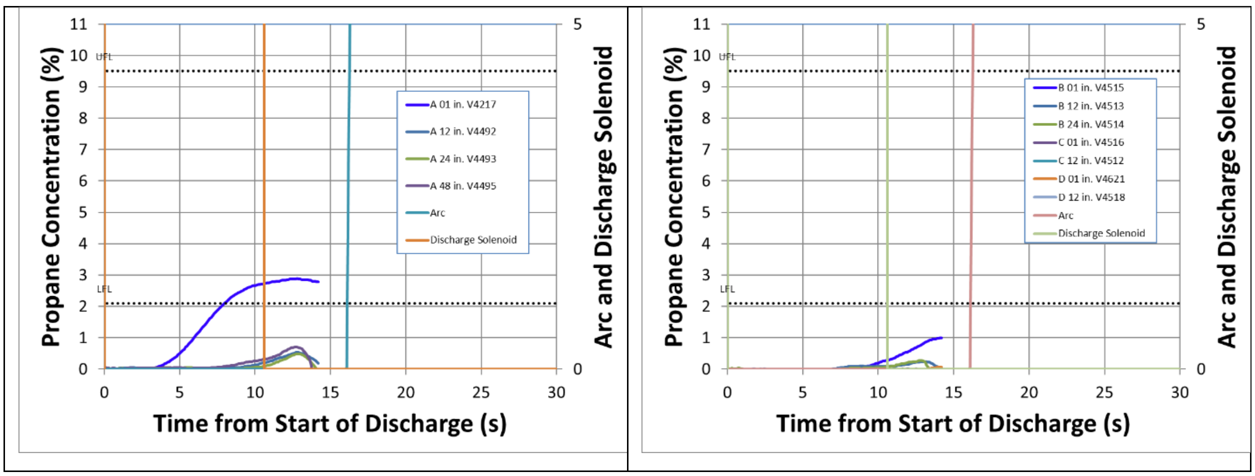


Figure 310 – PTAC_17 Concentrations

Figure 311 compares the concentrations at the 1-inch level at locations A and B for the pre-test and ignition tests (PTAC_06 and PTAC_17). The data shown is not deconvoluted to provide the maximum amount of data for comparison.

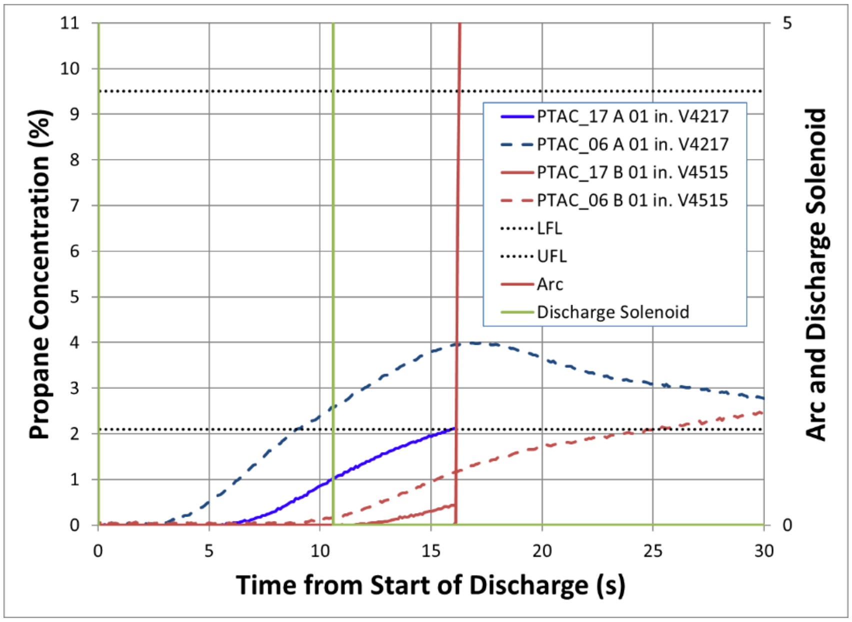


Figure 311 – PTAC_17 to PTAC_06 Concentration Comparison

Figure 312 compares the visual of the propane mist between PTAC_06 (left) and PTAC_17 (right). The comparison shows that the streams exited the grill of the PTAC at different angles which is a factor in the distribution of measured propane concentrations. The video shows the PTAC_06 with a smaller amount of liquid propane droplets while the PTAC_17 video shows a much larger flow of liquid propane.

The lesser amount of liquid propane in PTAC_06 contributed to higher gaseous propane concentrations shown in Figure 311. It was noted that the PTAC grill assembly had warped from the exposure to fires in PTAC_14, PTAC_15, and PTAC_16 tests. The result was that the discharge impacted the grill face at different conditions.

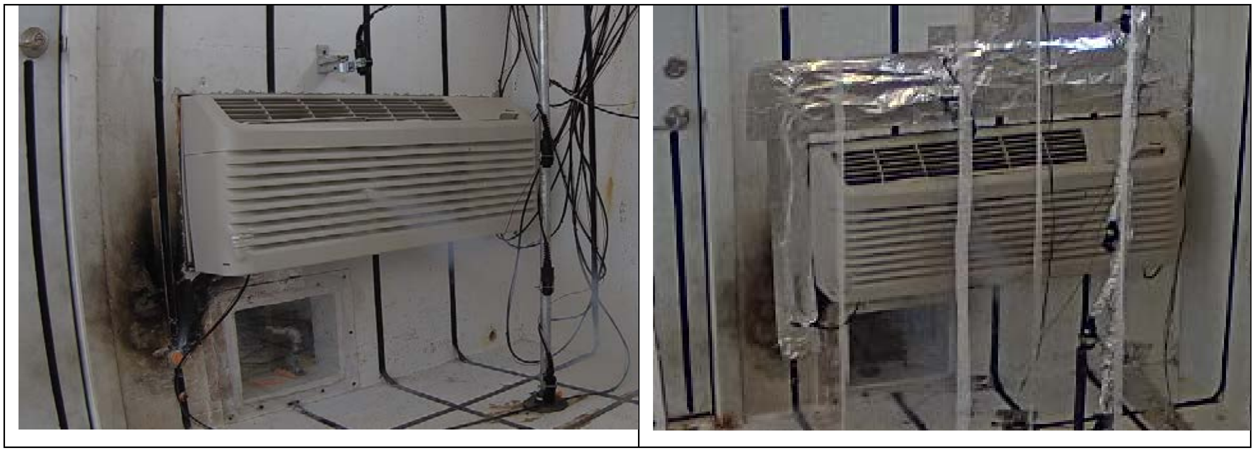


Figure 312 – PTAC_06 (left) to PTAC_17 (right) Stream Comparison

Figure 313 shows the mass flow rate and total mass flow.

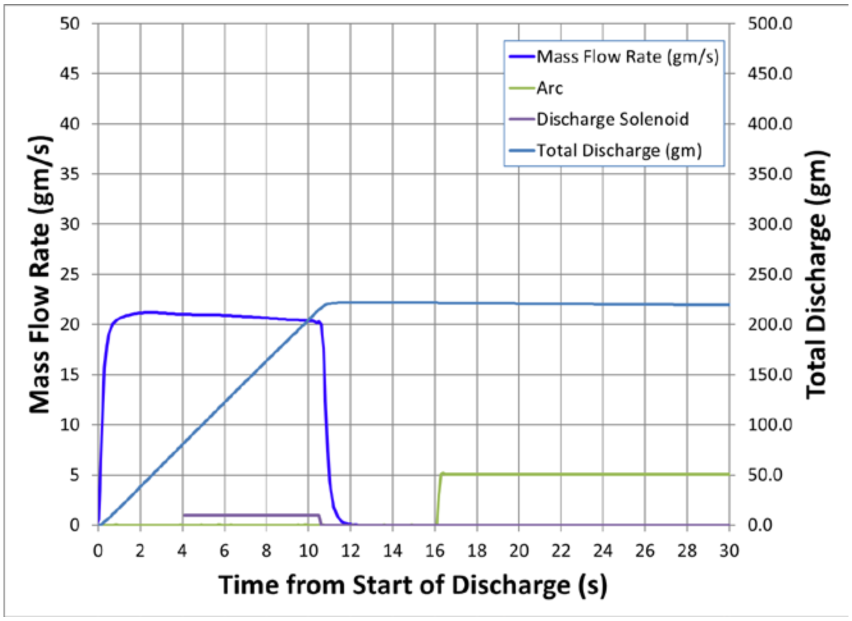


Figure 313 – PTAC_17 Mass Flow

Figure 314 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

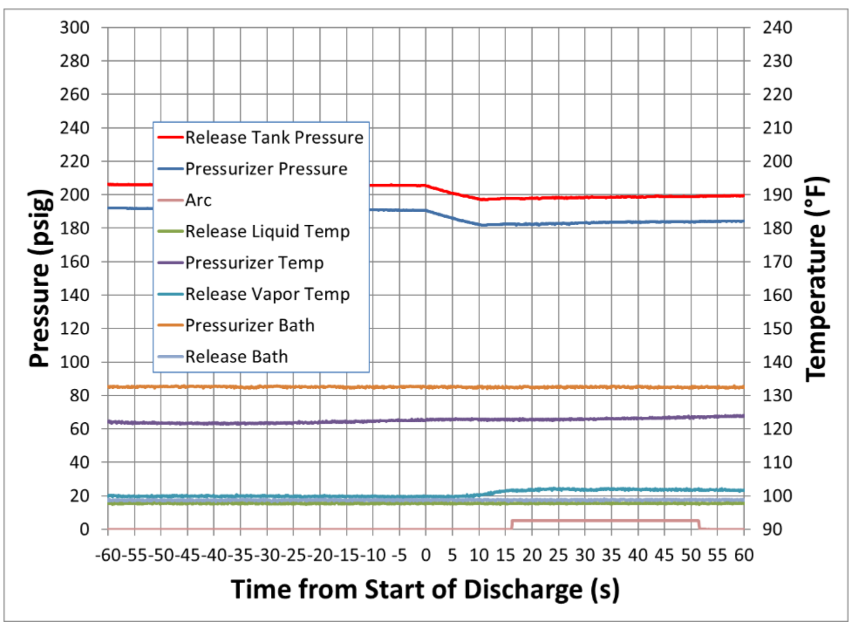


Figure 314 – PTAC_17 Pressurizer and Release Tank Pressure and Temperatures

Figure 315 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at location A. The temperatures locations A, B and PTAC show a sharp spike temperatures due to the presence of flames. Location D does not show the same spike due to the lack of flames in that area. All thermocouple trees show the delayed increase of higher level temperatures due to the rise of hot gases.

The thermocouple at the 4-inch location at the PTAC shows an anomalous spike due to the nearby burning pool of liquid propane. The flames from that pool swept over this thermocouple causing the delayed spike.

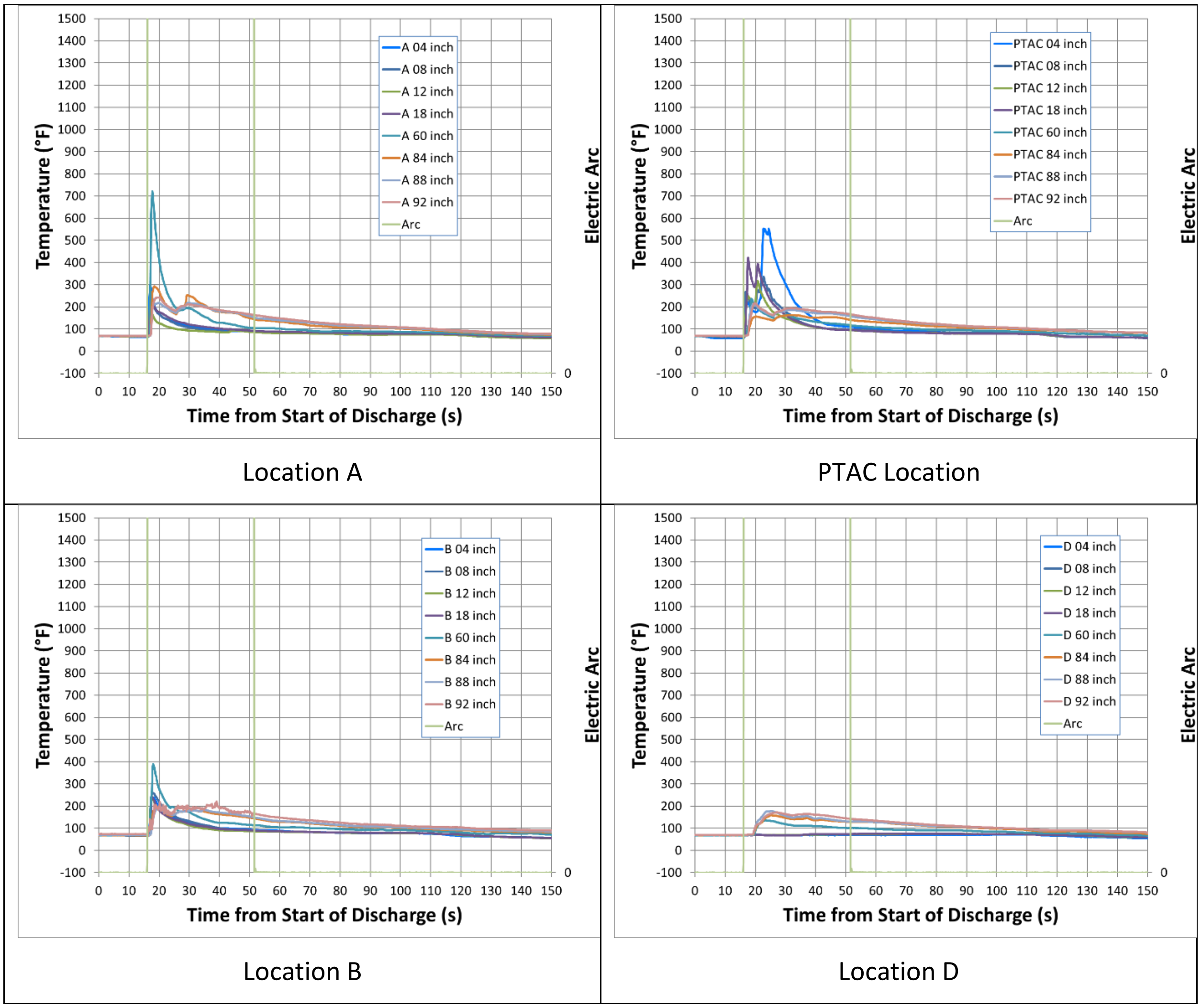


Figure 315 – PTAC_17 Temperatures at Locations A, B, C, and D

The videos showed ignition nearly simultaneously at locations A and B. Flames within the mixed volume of room air and propane endured for approximately 2 seconds. Flaming continued for another 15 seconds at a liquid pool of propane in front of the PTAC unit. Figure 76 shows several frames from the videos of this test.

Flaming continued inside the PTAC unit due to the remaining propane and ignition of the PTAC filters. The filter fires continued and were suppressed with a water spray.

Three deflagration vents burst due to the initial flaming and one other was melted by the hot gases.

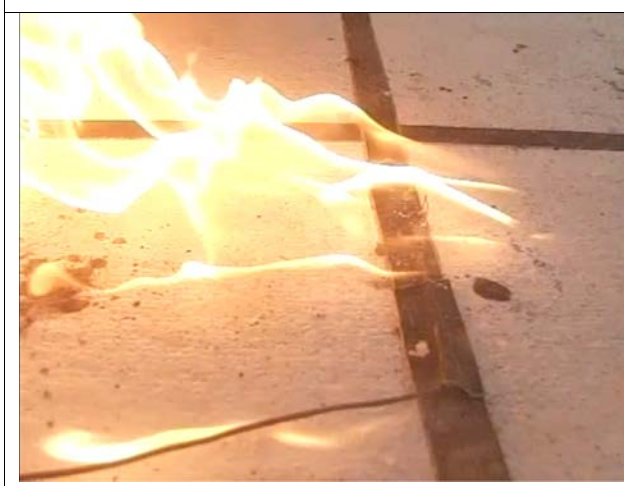
	 Maximum size of flaming
 Flames attached to a pool of liquid propane	 Liquid propane pool evaporated 15 seconds after ignition

Figure 316 – PTAC_17: Frames of flaming from videos

Appendix C Mini-Split Test Data and Summary

This appendix summarizes the tests with the Mini-Split unit.

The following table summarizes all mini-split tests. The sections that follow describe each test in detail.

Temperatures are color coded according to the following legend:

Range
< 0°F
0 – 105 °F
105 – 400 °F
400°F and higher

Table 103 summarizes all tests with the Mini-Split units. The sections that follow describe each test in detail.

Table 67 – Mini-Split Tests

												Raw Video													
Test Code	Date	Purpose	Fan State	Fan Flow (CFM)	Arc Delay (s)	Planned Discharge (g)	Planned Discharge Rate (g/s)	Measured Mass (g)	Measured Rate (g/s)	Discharge Location (m)	Discharge Opening	Discharge Start HH:MM:SS	Discharge Stop HH:MM:SS	Electric Arc HH:MM:SS	Max Pressure (mmHg)	Max Temp (°F)	Max Temp Location	Max Ceiling Temp (°F)	Number of Vents Burst /Melted	Ignited	Location	Conc. @+ 5s (%)	Location	Decon. @+ 5 (%)	Analysis File
MS_01	09-May-2018	Concentrations	Off	0	NA	329	21.4	325	22.9	0.6	1/4 OD	Igniters not used									A 01 in.	6.7	A 01 in.	8.5	MS_01_2018-05-09-1123 Analysis.xlsx
MS_02	09-May-2018	Concentrations	Off	0		114	21.4	111	17.4	0.6	1/4 OD										A 01 in.	0.2	A 01 in.	3.8	MS_02_2018-05-09-1342 Analysis.xlsx
MS_03	09-May-2018	Concentrations	On	468		650	21.4	649	19.8	0.6	1/4 OD										A 24 in.	3.0	A 12 in.	2.8	MS_03_2018-05-09-1403 Analysis.xlsx
MS_04	09-May-2018	Concentrations	Delay 5 s	468		650	21.4	646	13.2	0.6	1/4 OD										A 24 in.	3.7	A 12 in.	3.2	MS_04_2018-05-09-1435 Analysis.xlsx
MS_05	09-May-2018	Concentrations	On	505		975	21.4	975	21.5	0.6	1/4 OD										A 24 in.	3.4	A 12 in.	2.9	MS_05_2018-05-09-1506 Analysis.xlsx
MS_06	10-May-2018	Concentrations	Off	0		114	21.4	113	21.8	0.6	1/4 OD										A 01 in.	0.2	A 01 in.	3.2	MS_06_2018-05-10-1036 Analysis.xlsx
MS_07	10-May-2018	Concentrations	Delay 5 s	468		650	21.4	649	23.7	0.6	1/4 OD										A 12 in.	3.0	B 01 in.	2.4	MS_07_2018-05-10-1313 Analysis.xlsx
MS_08	10-May-2018	Ignition	Off	0	5	114	21.4	115	23.4	0.6	1/4 OD	13:59:15	13:59:20	13:59:25	0.2	758	A-04	328	2/1	Yes	A 60 in.	0.1	NA		MS_08_2018-05-10-1355 Analysis.xlsx
MS_09	10-May-2018	Ignition	On	468	5	329	21.4	327	21.2	0.6	1/4 OD	NA								No	A 48 in.	2.4	A 24 in.	2.5	MS_09_2018-05-10-1441 Analysis.xlsx
MS_10	10-May-2018	Ignition	On	468	5	650	21.4	649	19.3	0.6	1/4 OD									No	A 01 in.	2.9	A 12 in.	3.1	MS_10_2018-05-10-1505 Analysis.xlsx
MS_11	10-May-2018	Ignition	Off	0	5	329	21.4	327	24.8	0.6	1/4 OD	15:42:30	15:42:43	15:42:48	0.2	1005	A-18	600	5/1	Yes	A 01 in.	5.9	NA		MS_11_2018-05-10-1539 Analysis.xlsx
MS_12	16-May-2018	Ignition	Delay 15 s	468	NA	650	21.4	648	21.9	0.6	1/4 OD	13:37:58	13:38:28	NA	0.1	75	D-92	75	NA	NA	A 01 in.	5.7	B 12 in.	4.1	MS_12_2018-05-16-1333 Analysis.xlsx
MS_13	16-May-2018	Ignition	Delay 15 s	468	5	650	21.4	647	21.6	0.6	1/4 OD	15:15:41	15:16:11	15:16:16	0.0	700	D-08	534	4/2	Yes	A 01 in.	4.8	NA		MS_13_2018-05-16-1411 Analysis.xlsx

Notes:

- The times recorded for the raw video are from the date/time stamp (time portion only) in the video.
- Temperatures are recorded in the cases where ignition occurred.
- Propane concentrations are recorded in cases where the igniters were not used.
- Refer to the main body of the report for the description of sensor locations.

Videos for each test are stored separately. The correspondence of channel number to camera view is as follows:

Video Channels	Usage
1	Northeast Upper Corner
2	East Wall
3	Northeast Floor Corner
4	Southwest Upper Corner
6	East Side Vents
7	West Side Vents
8	Northeast Floor IR Camera
9	Test Marquee and Clock
13	Northwest Upper Hi Def Camera

High speed camera videos are stored in the same folder for each test. High speed cameras were used where ignition was expected. The following table matches the test number with the high-speed camera video:

High Speed Cameras		
Test	**Floor Level**	**High Level**
MS_08	CIMG3353 (2).MOV	CIMG3353.MOV
MS_11	CIMG3356 (2).MOV	CIMG3356.MOV
MS_12	CIMG3357.MOV	CIMG3358.MOV
MS_13	CIMG3358.MOV	CIMG3359.MOV

The cameras named the files automatically. The table above shows some duplicate names, but these are stored in separate file folders (per test). The videos contain the test and view as specified above.

Test MS_01 (329 g; Fan Off)

Test MS_01 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is MS_11. This test involved release at a return bend of the evaporator coil. The key parameters and results of this test are summarized in the following table. At 7 minutes after the start of the discharge, sensors at locations A, B, C, and D recorded concentrations slightly above the LFL of 2.1%.

Table 68 – MS_01 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Average Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	329	15.4	21.4	Return Bend of Evaporator Coil	0.39	Calculated if well Mixed in whole room
Measured	325	14.2	22.9		8.5 2.4	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 187 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. Sensors at the 1-inch level remained above the LFL of 2.1% to the end of data recording, but were slowly decreasing. Sensors at the 24 and 48-inch level were slowly increasing indicating slow mixing of concentrations within the test room due to either diffusion, convection, or a combination of both mechanisms.

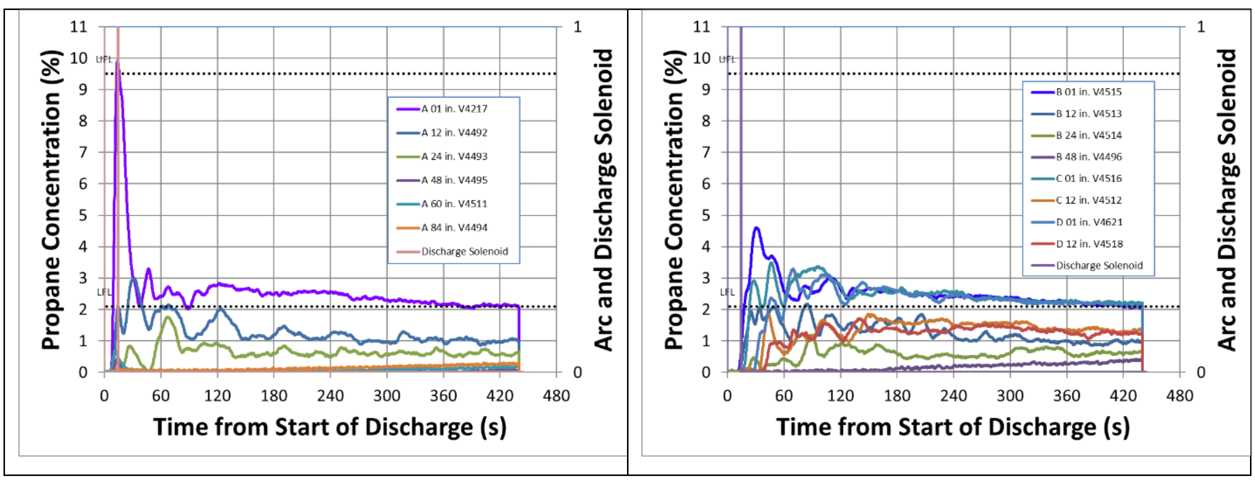


Figure 317 – MS_01 Concentrations

Figure 188 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

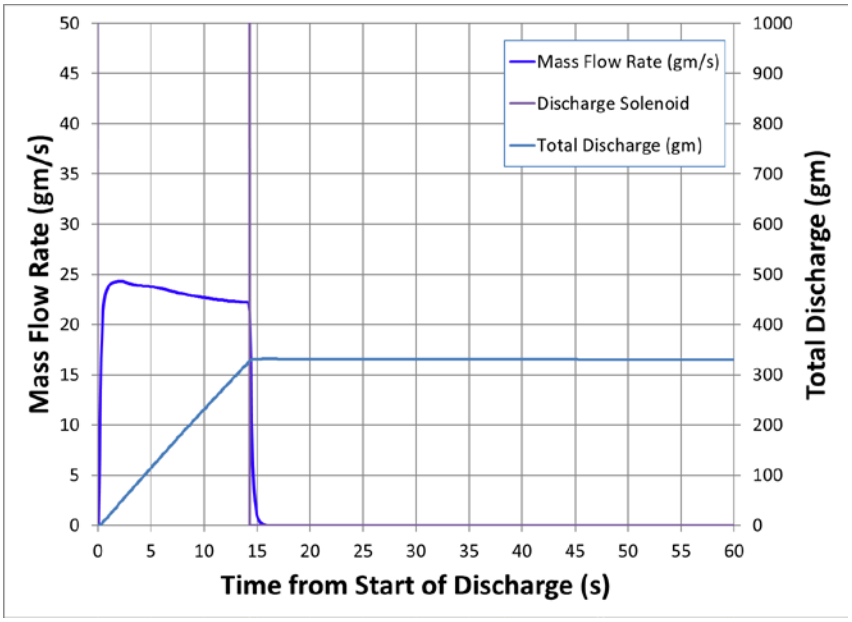


Figure 318 – MS_01 Mass Flow

Figure 189 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

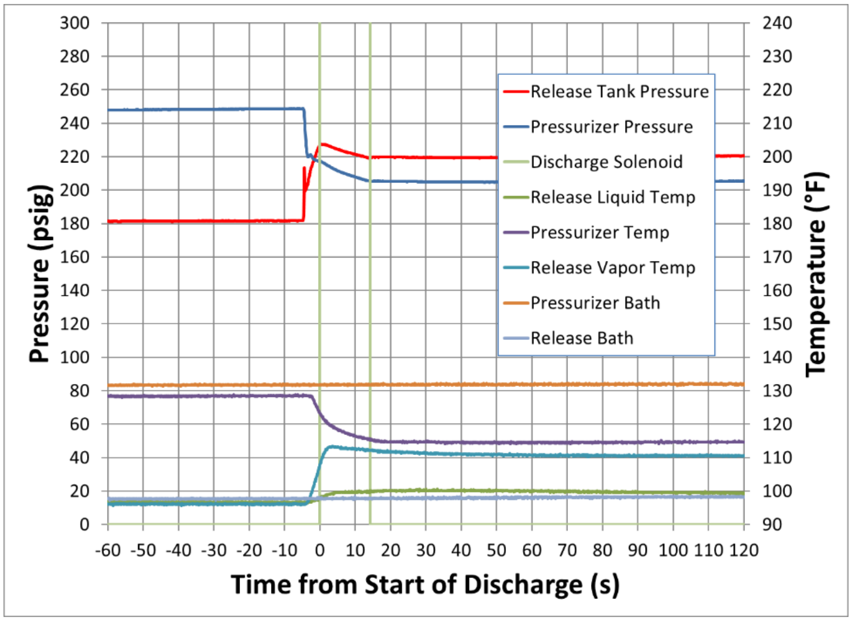


Figure 319 – MS_01 Pressurizer and Release Tank Pressure and Temperatures

Test MS_02 (114 g; Fan Off)

Test MS_02 was performed without ignition sources to measure propane concentrations. The mass flow rate was lower than specifications and this test was repeated in test MS_06. This test involved release at a return bend of the evaporator coil. The key parameters and results of this test are summarized in the following table. At 33 seconds after the start of the discharge all sensors recorded less than LFL concentrations.

~~Table 69 – MS_02 Summary~~

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	114	5.3	21.4	Return Bend of Evaporator Coil	0.14	Calculated if well Mixed in whole room
Measured	111	6.5	17.4		3.8 0.0	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 320 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. Sensors at the 1-inch level throughout the test room stabilized at 1.3% to 1.8%.

The measured concentrations did not begin to increase until after the discharge valve closed at 6.4 seconds. This delay is due to the discharge location at the evaporator return bend and the fact that the unit fan was not operating. When the fan is not operating the lower flaps on the indoor unit are closed. This causes the propane to lose momentum inside the unit and slowly drop to the floor level based on density differences alone.

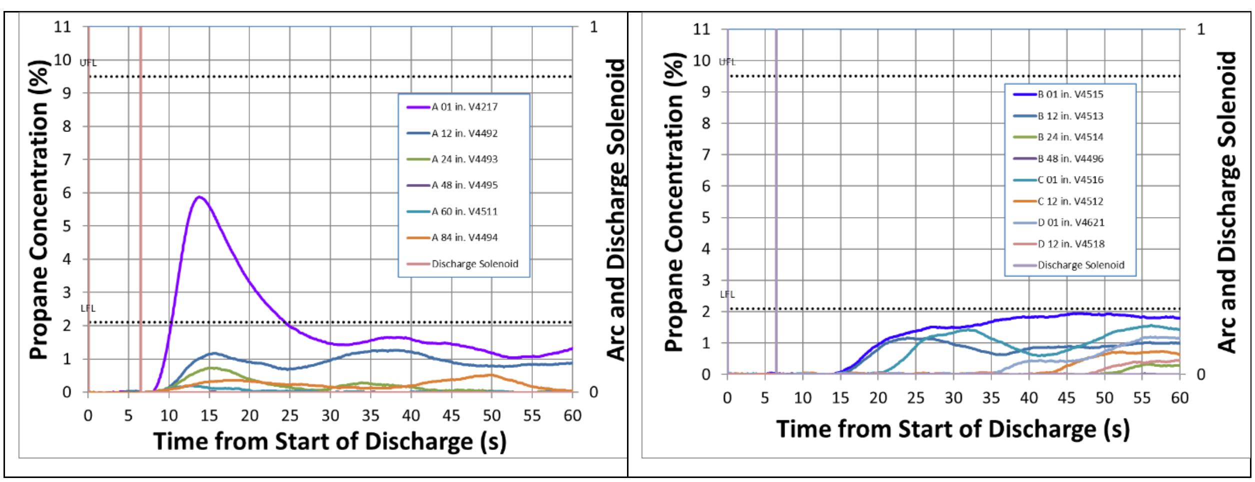


Figure 320 – MS_02 Concentrations

Figure 321 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

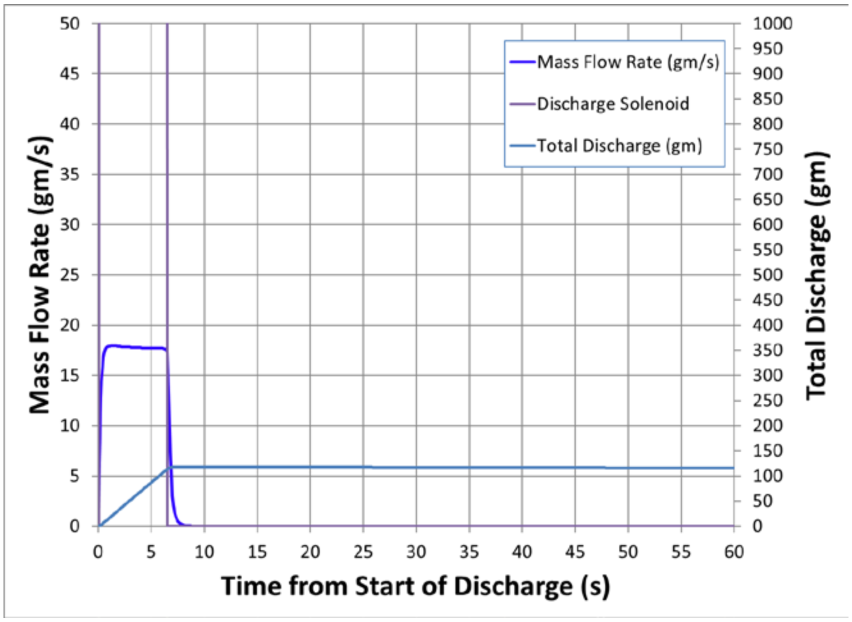


Figure 321 – MS_02 Mass Flow

Figure 322 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The cross-connect valve between the pressurizer and release tank was not opened during this test due to a procedure error.

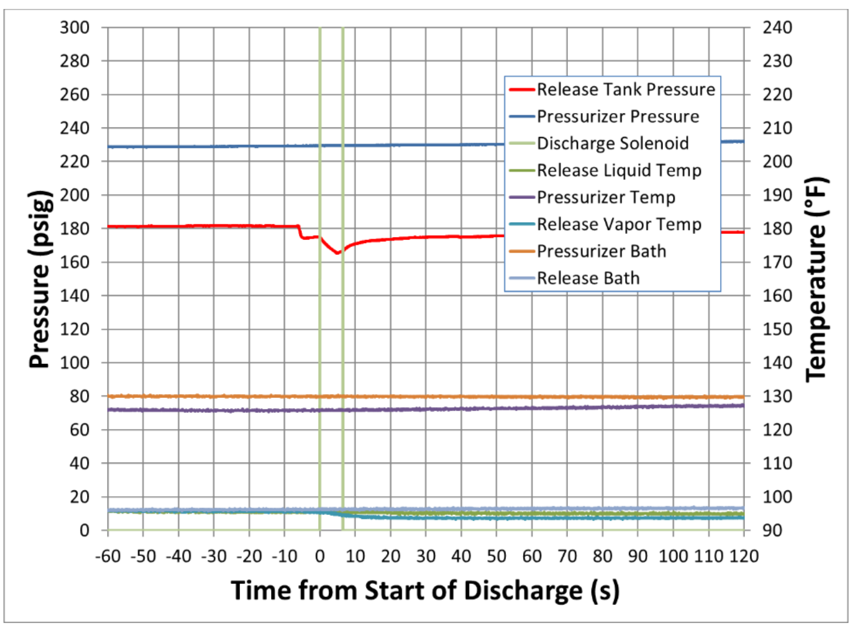


Figure 322 – MS_02 Pressurizer and Release Tank Pressure and Temperatures

Test MS_03 (650 g; Fan On)

Test MS_03 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is MS_10. This test involved release at a return bend of the evaporator coil with the fan operating continuously at 468 CFM. The key parameters and results of this test are summarized in the following table. At 40 seconds after the start of the discharge all sensors recorded less than LFL concentrations.

Table 70 – MS_03 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	650	30.4	21.4	Return Bend of Evaporator Coil	0.78	Calculated if well Mixed in whole room
Measured	649	32.8	19.8		2.8 1.9	Location A 12-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 323 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. The action of the fan resulted in nearly complete uniform mixing within the test room at 5 minutes after the start of the discharge. Final concentrations stabilized close to the estimated well-mixed value of 0.78%. The discharge solenoid closed at 32.9 seconds and all measured concentrations were less than LFL 6.4 seconds later (39.3 seconds after the start of the discharge).

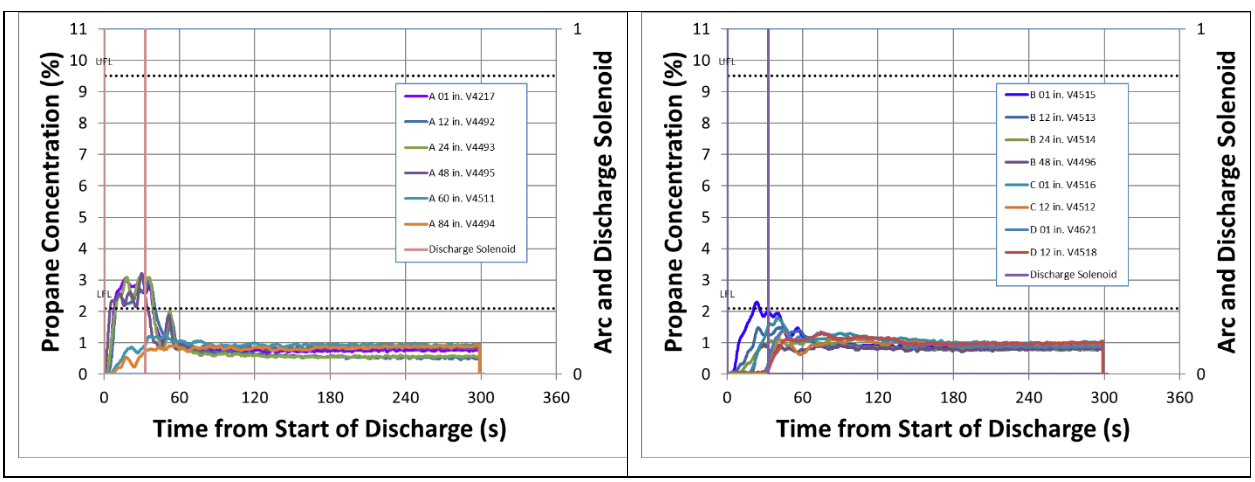


Figure 323 – MS_03 Concentrations

Figure 324 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

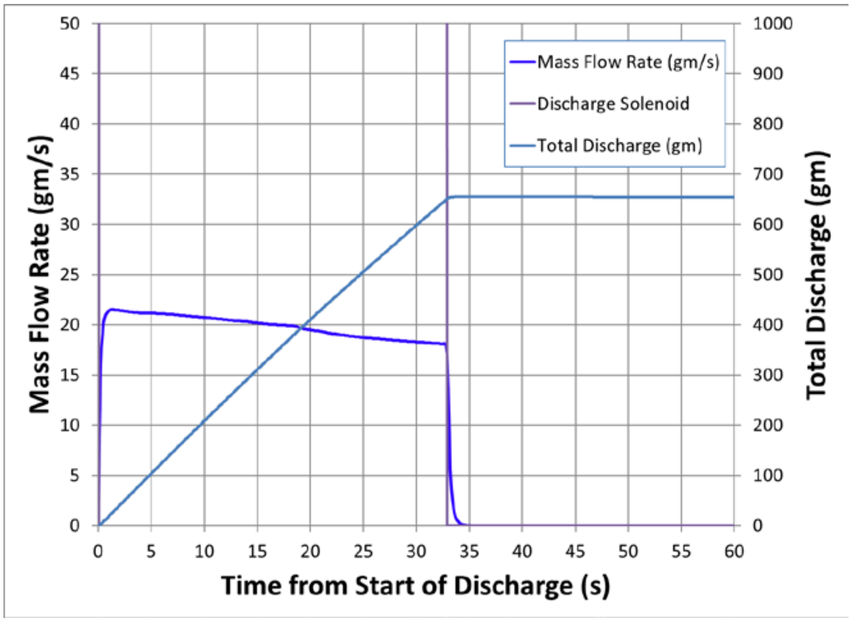


Figure 324 – MS_03 Mass Flow

Figure 325 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

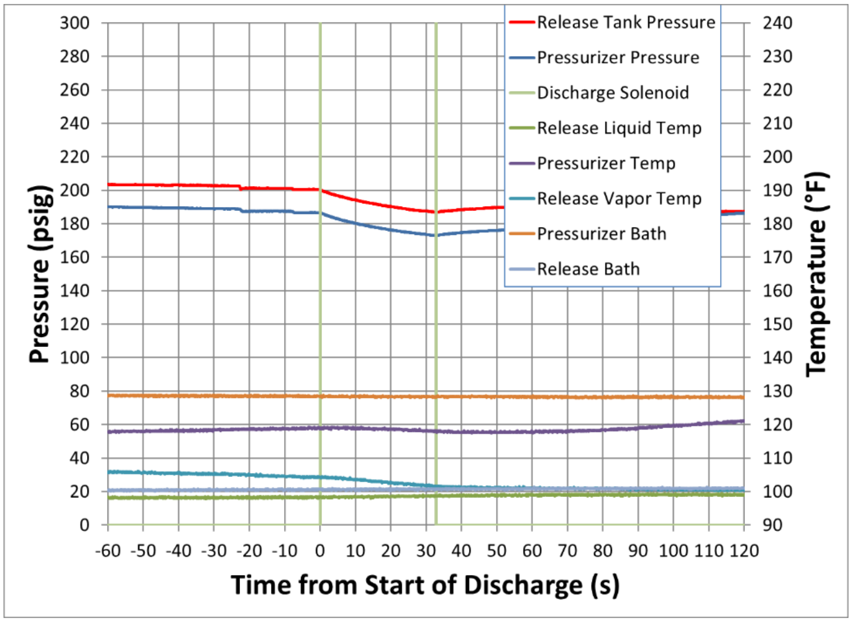


Figure 325 – MS_03 Pressurizer and Release Tank Pressure and Temperatures

Test MS_04 (650 g; 5 s Fan Delay)

Test MS_04 was performed without ignition sources to measure propane concentrations. This test was repeated in MS_12 for two reasons. The first is that the specified flow rate of 21.4 g/s was not achieved. The second reason is that the time delay for fan activation was changed from 5 seconds to 15 seconds. This test involved release at a return bend of the evaporator coil. The key parameters and results of this test are summarized in the following table.

Table 71 – MS_04 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	650	30.4	21.4	Return Bend of Evaporator Coil	0.78	Calculated if well Mixed in whole room
Measured	646	48.9	13.2		2.2 1.7	Location A 1-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed. The unit fan was started at 5 seconds after the start of the discharge.

Figure 326 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. The action of the fan resulted in nearly complete uniform mixing within the test room at 5 minutes after the start of the discharge. Final concentrations stabilized close to the estimated well-mixed value of 0.78%. The discharge solenoid closed at 48.9 seconds. All measured concentrations were less than LFL at 56 seconds after the start of the discharge.

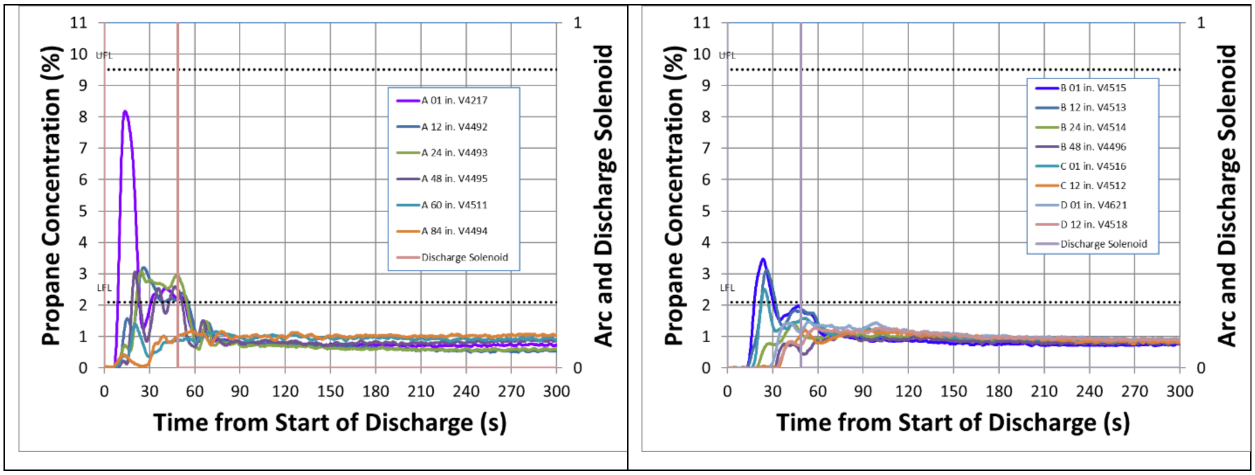


Figure 326 – MS_04 Concentrations

Figure 327 concentrates on the first 60 seconds of this test. The fan start command was given at 5 seconds after the start of the discharge. The fan was observed to require 10 seconds to come up to full speed and fully deploy the flaps on the bottom of the unit (fan discharge). The figure shows a sharp decline at location A 1-inch level following the fan achieving full speed. Locations B, C, and D at the 1-inch level show the sweeping action of this air flow as the concentrations at floor level are pushed away from location A and toward locations B, C, and D

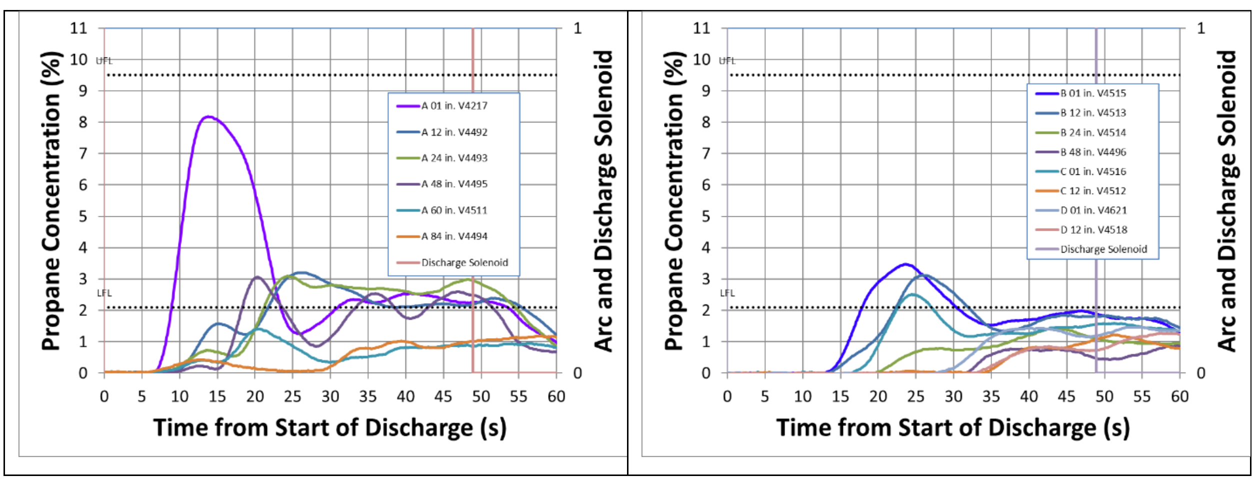


Figure 327 – MS_04 Concentrations and fan behavior

Figure 328 shows the mass flow rate and total mass flow. The poor control was the result of draining the release tank of liquid propane followed by attempted control of the resulting vapor flow.

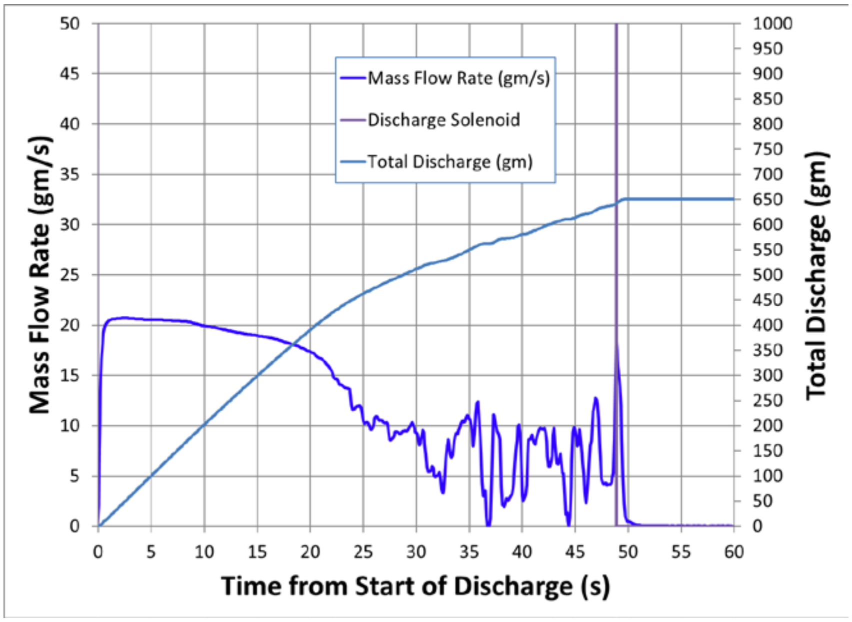


Figure 328 – MS_04 Mass Flow

Figure 329 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures. In this test, the pressurizer and release tank were placed in series at time -70 seconds and does not show on the figure below.

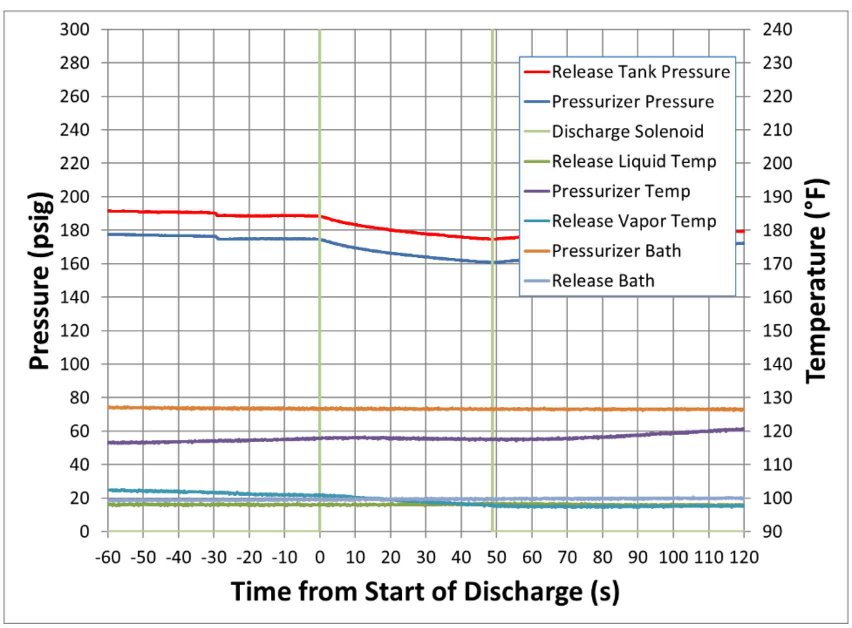


Figure 329 – MS_04 Pressurizer and Release Tank Pressure and Temperatures

Test MS_05 (975 g; Fan On)

Test MS_05 was performed without ignition sources to measure propane concentrations. There was no associated ignition test. This test involved release at a return bend of the evaporator coil with the fan operating continuously at 505 CFM. The key parameters and results of this test are summarized in the following table. At 63 seconds after the start of the discharge all sensors recorded less than LFL concentrations.

Table 72 – MS_05 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	975	45.6	21.4	Return Bend of Evaporator Coil	1.2	Calculated if well Mixed in whole room
Measured	975	45.3	21.5		2.9	Location A 12-inch
					2.3	Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 330 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. The action of the fan resulted in nearly complete uniform mixing within the test room at 5 minutes after the start of the discharge. Final concentrations stabilized close to the estimated well-mixed value of 1.2%. The discharge solenoid closed at 45.5 seconds and all measured concentrations were less than LFL 17.5 seconds later (63 seconds after the start of the discharge).

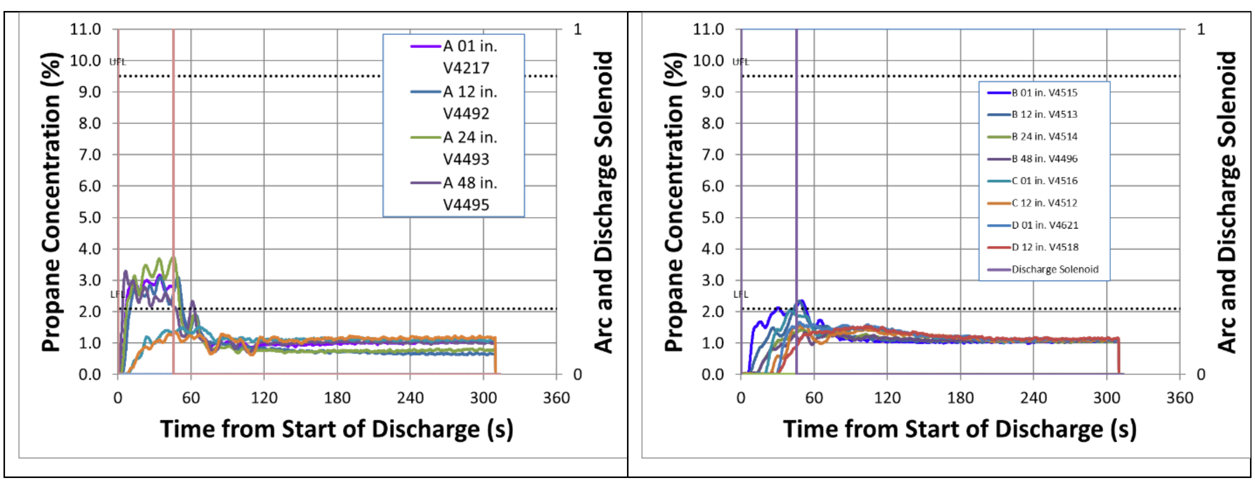


Figure 330 – MS_05 Concentrations

Figure 331 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

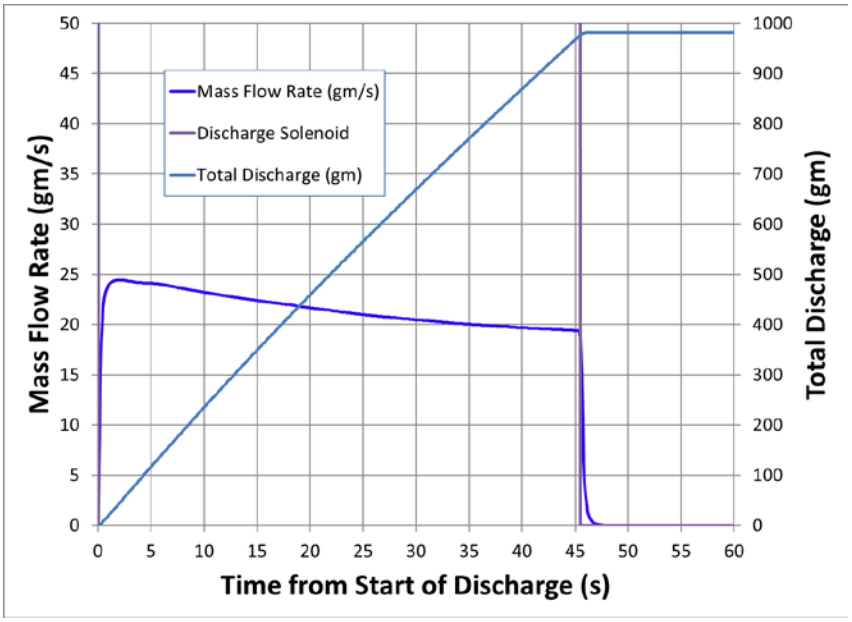


Figure 331 – MS_05 Mass Flow

Figure 332 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

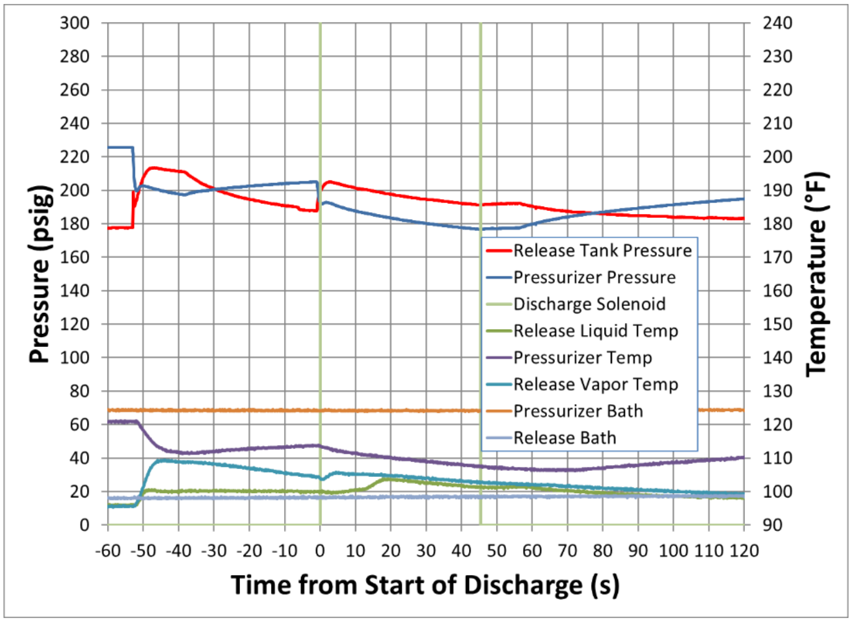


Figure 332 – MS_05 Pressurizer and Release Tank Pressure and Temperatures

Test MS_06 (114 g; Fan Off)

Test MS_06 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is MS_08. This test involved release at a return bend of the evaporator coil. The key parameters and results of this test are summarized in the following table. At 45 seconds after the start of the discharge all sensors recorded less than LFL concentrations.

Table 73 – MS_06 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	114	5.3	21.4	Return Bend of Evaporator Coil	0.14	Calculated if well Mixed in whole room
Measured	113	5.2	21.8		3.4	Location A 1-inch
					0.0	Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 333 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. Sensors at the 1-inch level throughout the test room stabilized at 1.3% to 1.5%.

The measured concentrations did not begin to increase until after the discharge valve closed at 5.2 seconds. This delay is due to the discharge location at the evaporator return bend and the fact that the unit fan was not operating. When the fan is not operating the lower flaps on the indoor unit are closed. This causes the propane to lose momentum inside the unit and slowly drop to the floor level based on density differences alone.

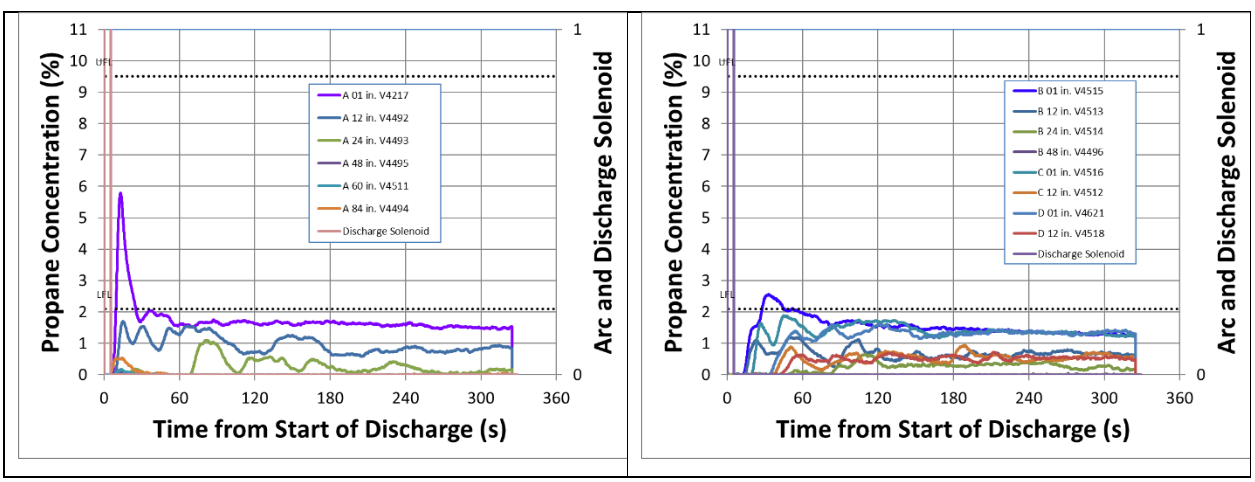


Figure 333 – MS_06 Concentrations

Figure 334 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing. The rapid drop and recovery of the mass flow rate was due to overcompensation by the mass flow control system. It is possible that this instability affected the measurement of total mass flow. The manufacturer's data show that the accuracy of flow rate for vapor flow is 0.5% of reading versus 0.2% of reading for liquid flow. Using this value of accuracy as the worst case and the effect on total mass is similar, then the total discharge amount is 113 ± 0.5% g or 113 ± 0.6 g.

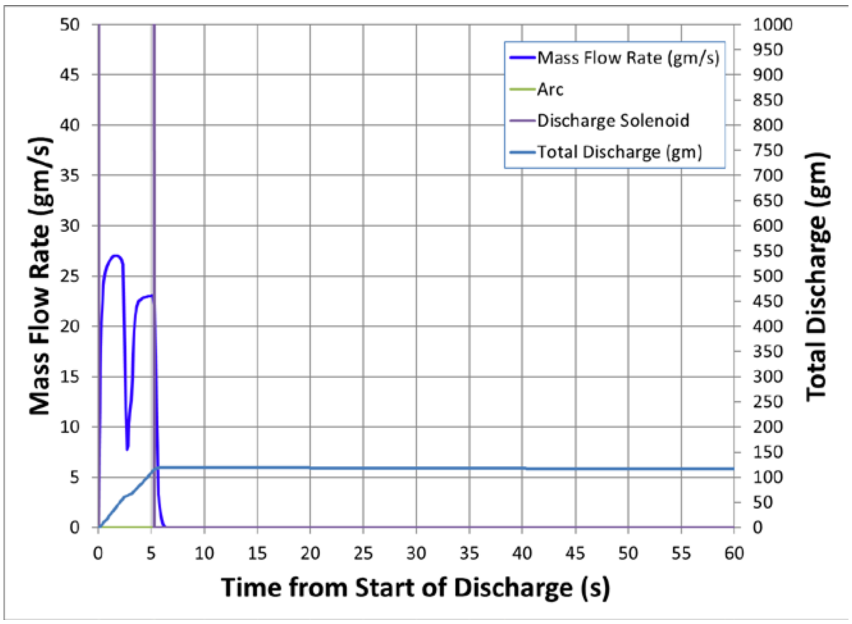


Figure 334 – MS_06 Mass Flow

Figure 335 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

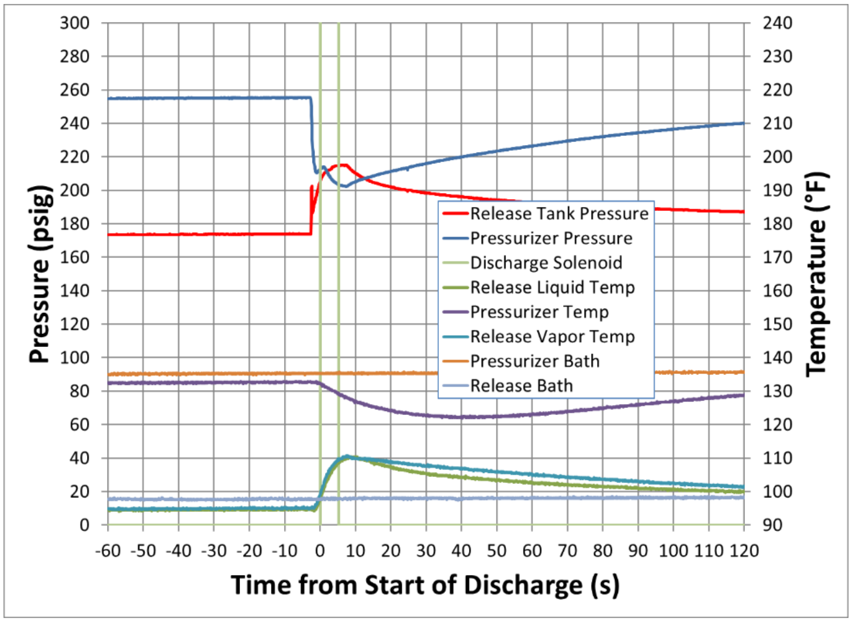


Figure 335 – MS_06 Pressurizer and Release Tank Pressure and Temperatures

Test MS_07 (650 g; 5 s Fan Delay)

Test MS_07 was performed without ignition sources to measure propane concentrations. This test was repeated in MS_12 because the specification for fan delay changed from 5 seconds (this test) to 15 seconds test MS_12. This test involved release at a return bend of the evaporator coil. The key parameters and results of this test are summarized in the following table. At 57 seconds after the start of the discharge all sensors recorded less than LFL concentrations.

Table 74 – MS_07 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	650	30.4	21.4	Return Bend of Evaporator Coil	0.78	Calculated if well Mixed in whole room
Measured	649	27.6	23.7		2.1 2.3	Location A 12-inch Location B 12-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed. The unit fan was started at 5 seconds after the start of the discharge.

Figure 336 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. The action of the fan resulted in nearly complete uniform mixing within the test room at 5 minutes after the start of the discharge. Final concentrations stabilized close to the estimated well-mixed value of 0.78%. The discharge solenoid closed at 27.6 seconds. All measured concentrations were less than LFL at 56 seconds after the start of the discharge.

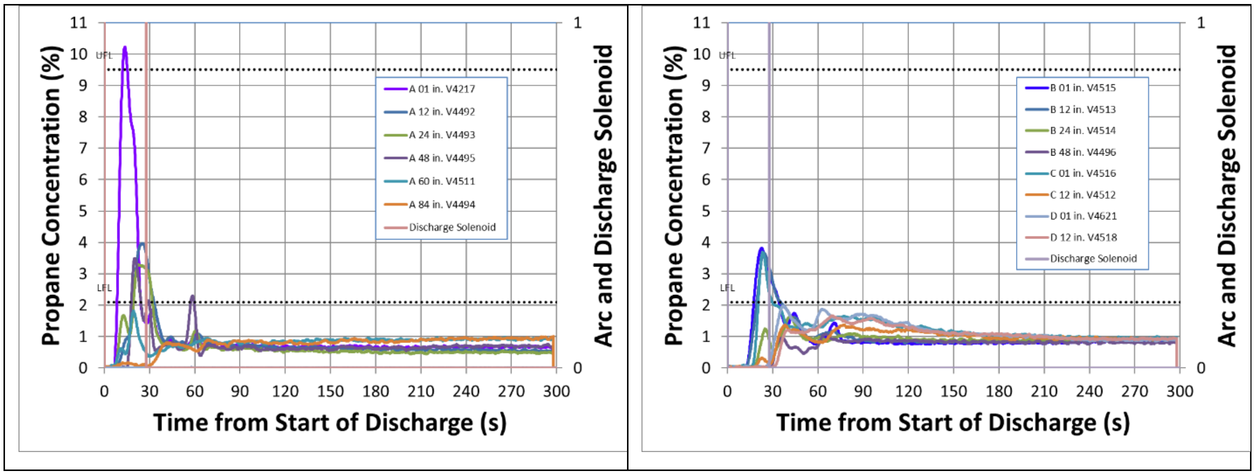


Figure 336 – MS_07 Concentrations

Figure 337 concentrates on the first 60 seconds of this test. The fan start command was given at 5 seconds after the start of the discharge. The fan was observed to require 10 seconds to come up to full speed and fully deploy the flaps on the bottom of the unit (fan discharge). The figure shows a sharp decline at location A 1-inch level following the fan achieving full speed. Locations B, C, and D at the 1-inch level show the sweeping action of this air flow as the concentrations at floor level are pushed away from location A and toward locations B, C, and D

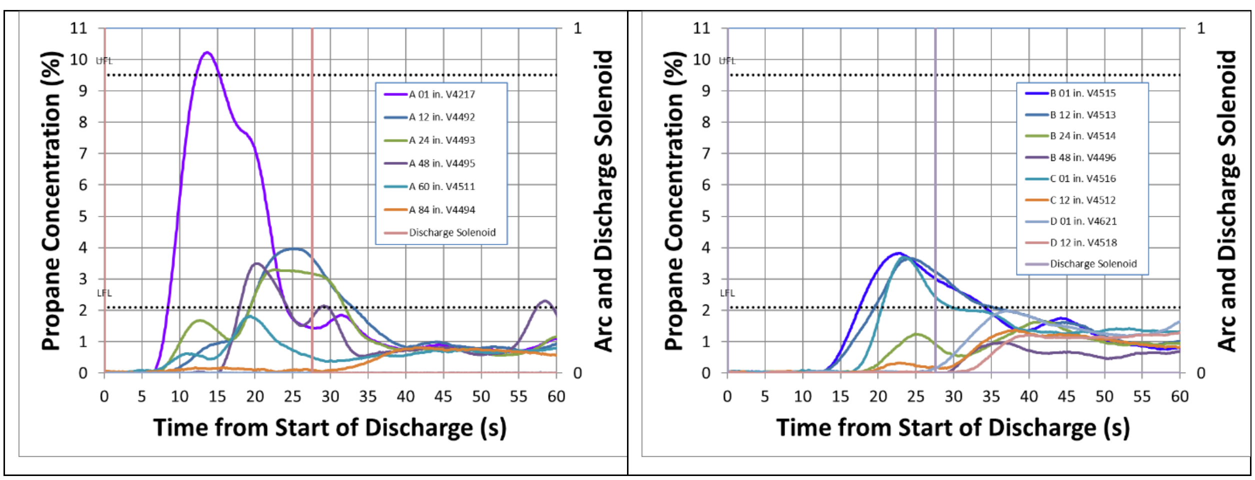


Figure 337 – MS_07 Concentrations and fan behavior

Figure 338 shows the mass flow rate and total mass flow. The poor control was the result of draining the release tank of liquid propane followed by attempted control of the resulting vapor flow.

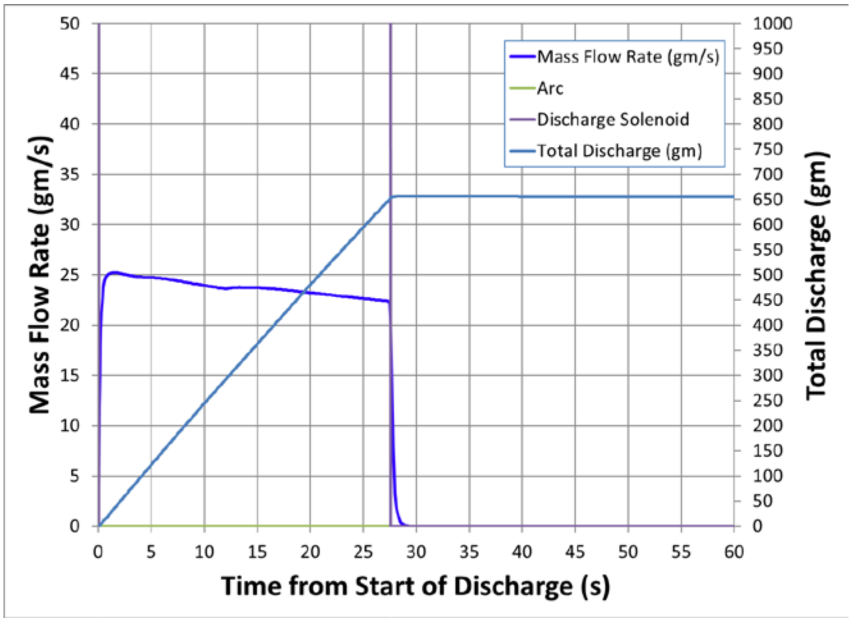


Figure 338 – MS_07 Mass Flow

Figure 339 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

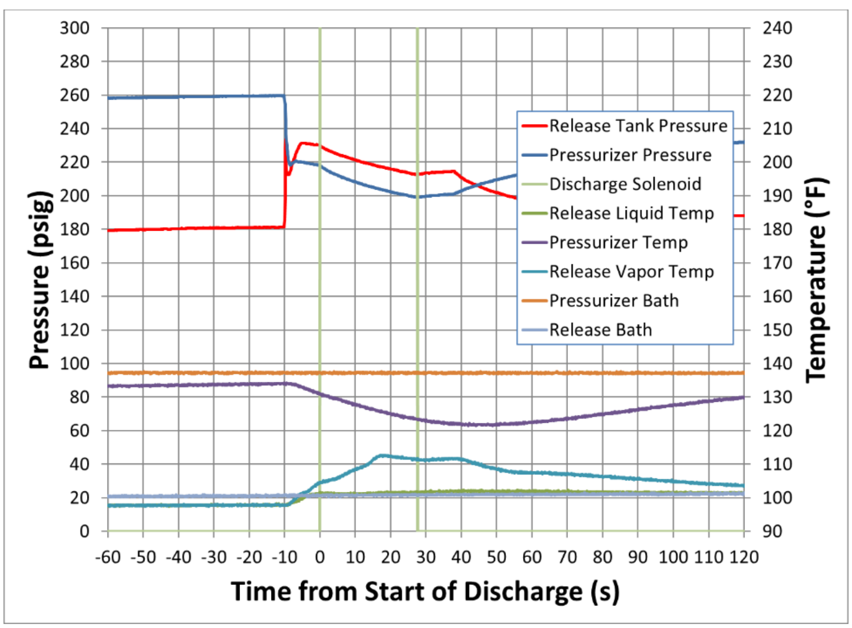


Figure 339 – MS_07 Pressurizer and Release Tank Pressure and Temperatures

Test MS_08 (114 g; Fan Off; with Igniters)

Test MS_08 was performed with ignition sources and resulted in ignition at arc location A.

Table 75 – MS_08 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	114	5.3	21.4	Return Bend of Evaporator Coil
Measured	115	4.9	23.4	

Figure 340 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time (10 seconds) so the data has been chopped at 8 seconds to filter out the effects of combustion on the oxygen sensors used to measure propane concentration.

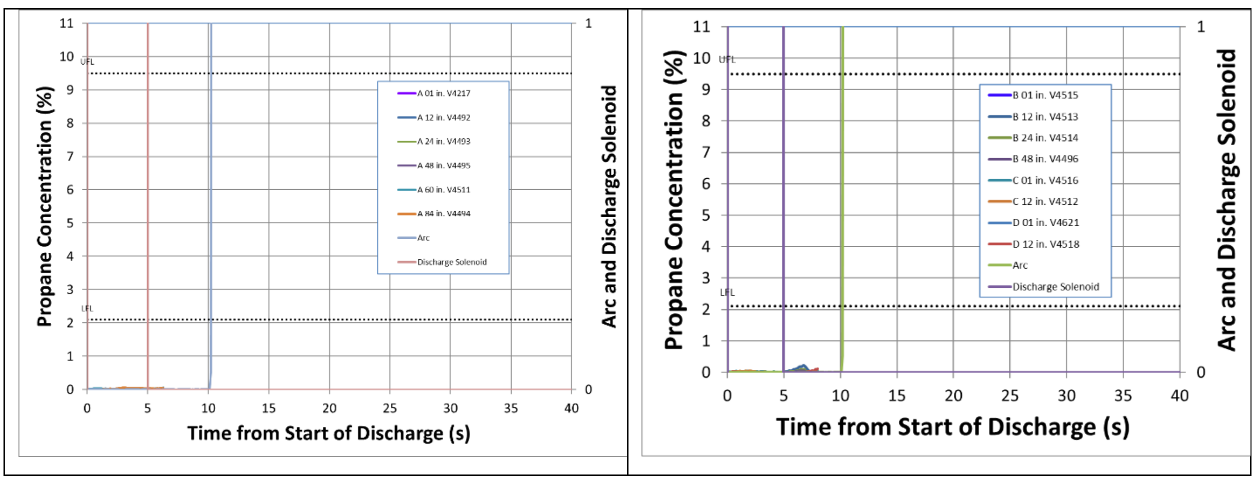


Figure 340 – MS_08 Concentrations

Figure 341 compares the concentrations at the 1-inch level at locations A and B for the pre-test and ignition tests (MS_06 and MS_08). The concentration data shown is deconvoluted to show an ignitable concentration existed (3%) according to the MS_06 non-ignition test. The MS_08 data does not show because the deconvoluted data had to be clipped at 8 seconds because of combustion product effects on the sensors. The MS_08 videos showed ignition occurred as soon as the arcs were energized indicating the presence of a mixture above LFL.

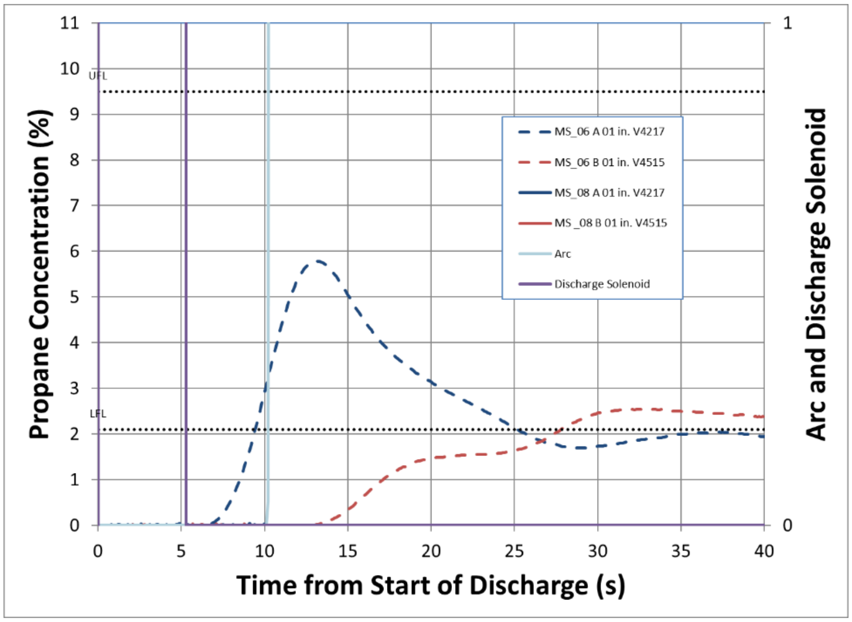


Figure 341 – MS_06 and MS_08 Concentration Comparison

Figure 342 shows the mass flow rate and total mass flow.

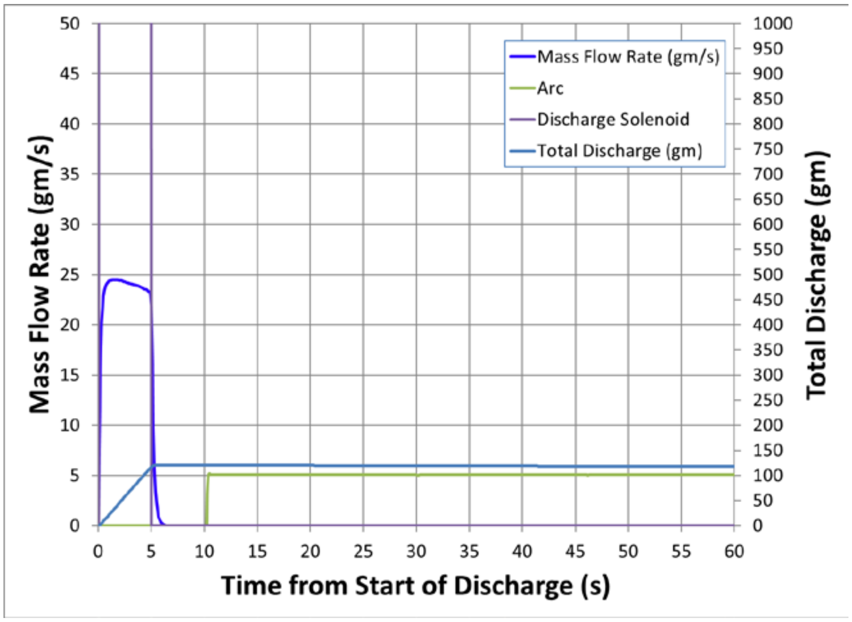


Figure 342 – MS_08 Mass Flow

Figure 343 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

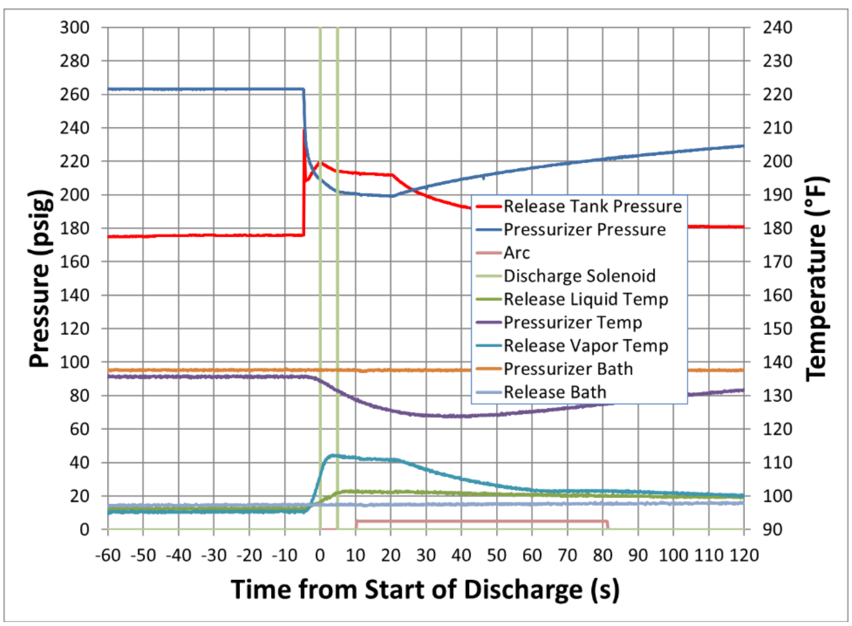


Figure 343 – MS_08 Pressurizer and Release Tank Pressure and Temperatures

Figure 344 shows the temperatures developed at the various locations following ignition. Location A shows the highest temperatures occurred at floor level followed by buoyant plume rising to the ceiling level. Locations C and D showed temperature increases from the buoyant plume and no increases at the 18-inch level and below.

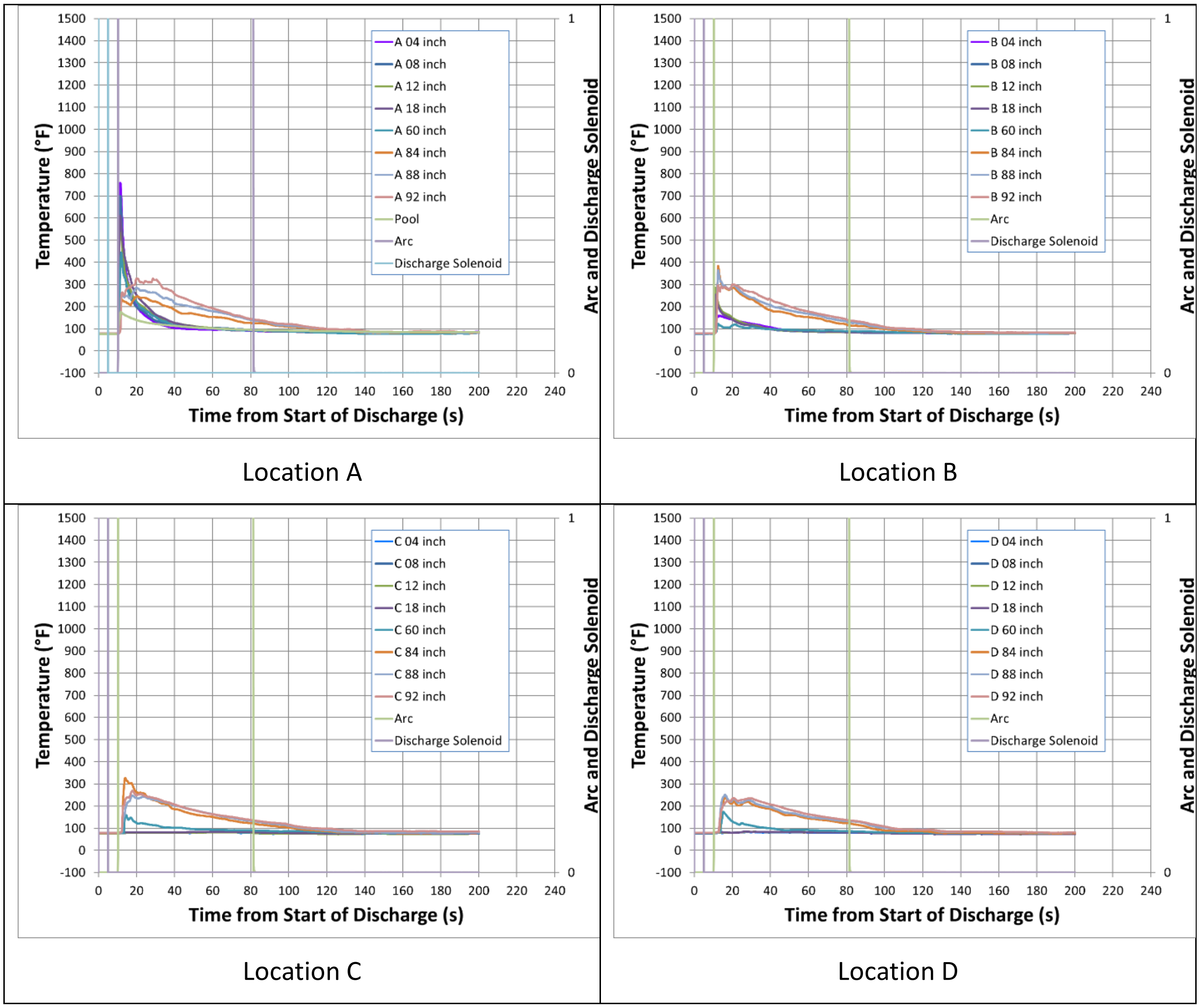
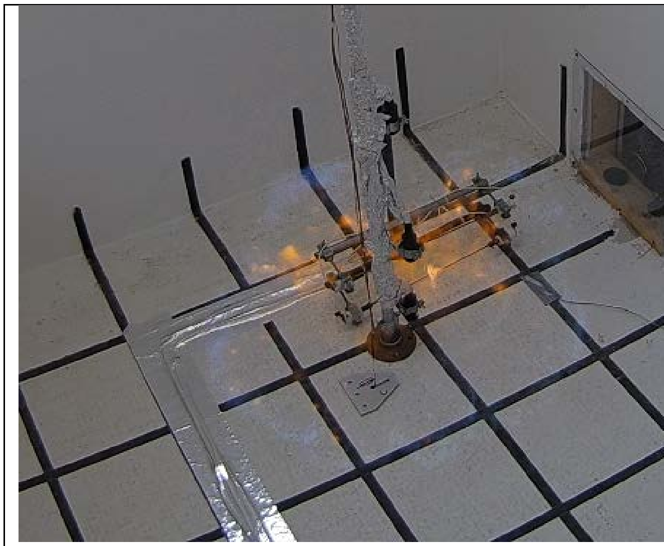


Figure 344 – MS_08 Temperatures at Locations A, B, C, and D

Figure 345 shows several frames from the videos of the test. Ignition started at Location A 1-inch level. Flames within the mixed volume of room air and propane endured for approximately 2 seconds. Flaming continued inside the indoor unit due to the remaining propane and ignition of the indoor unit filters. The unit was still operable after the test, but the filters were replaced to continue testing.

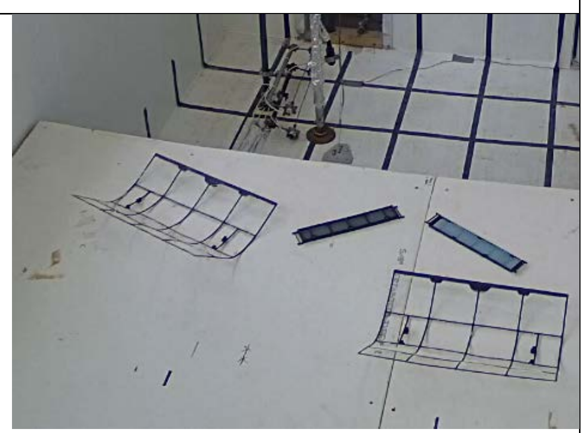
The videos showed no evidence of a liquid pool of propane on the floor.



Ignition at Location A

Maximum size of flaming

Flames continued due to propane trapped in the unit



Filters burned and melted

Figure 345 – MS_08: Frames of flaming from videos

Test MS_09 (329 g; Fan On; with Igniters)

Test MS_09 was performed with ignition sources. There was no ignition of a propane-air mixture because of the action of the fan to disperse concentrations to less than LFL.

Table 76 – MS_09 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	329	15.4	21.4	Return Bend of Evaporator Coil
Measured	327	15.5	21.2	

Figure 336 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. The action of the fan resulted in nearly complete uniform mixing within the test room at 5 minutes after the start of the discharge. Final concentrations stabilized close to the estimated well-mixed value of 0.39%. The discharge solenoid closed at 15.5 seconds. All measured concentrations were less than LFL at 60 seconds after the start of the discharge. The peak in concentrations between 45 and 70 seconds occurs first at the 48 inch level (same as the initial peak) because this sensor is directly in the exhaust flow of the wall mounted unit. This data shows that some amount of propane was trapped inside the wall unit and not exhausted until later.

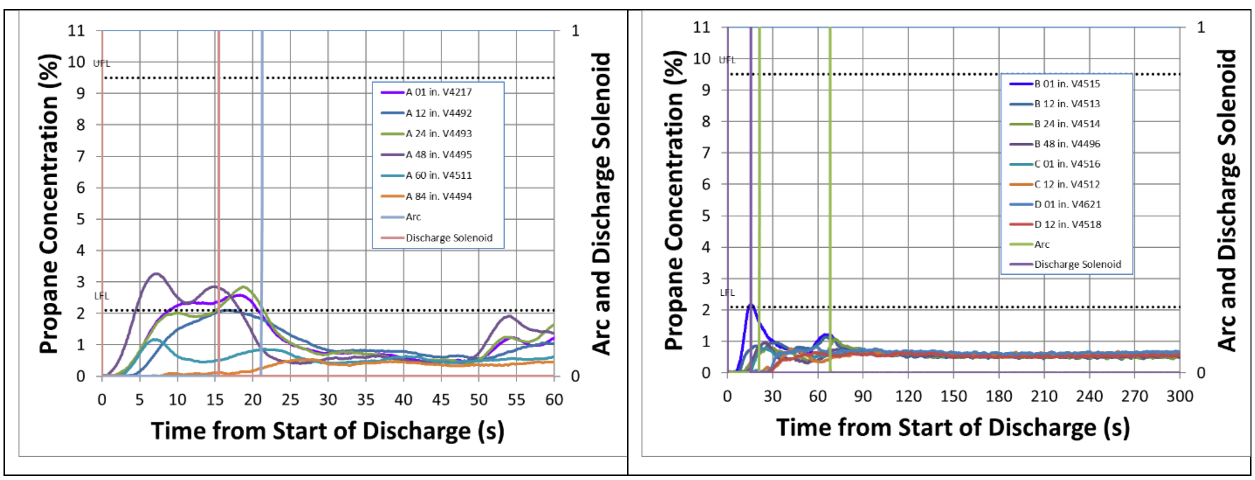


Figure 346 – MS_09 Concentrations

Figure 337 concentrates on the first 60 seconds of this test. The action of the fan reduced measured concentrations to less than LFL in 22 seconds. At the time the arc igniter was energized (21.2 s), concentrations at the 1-inch level were less than LFL

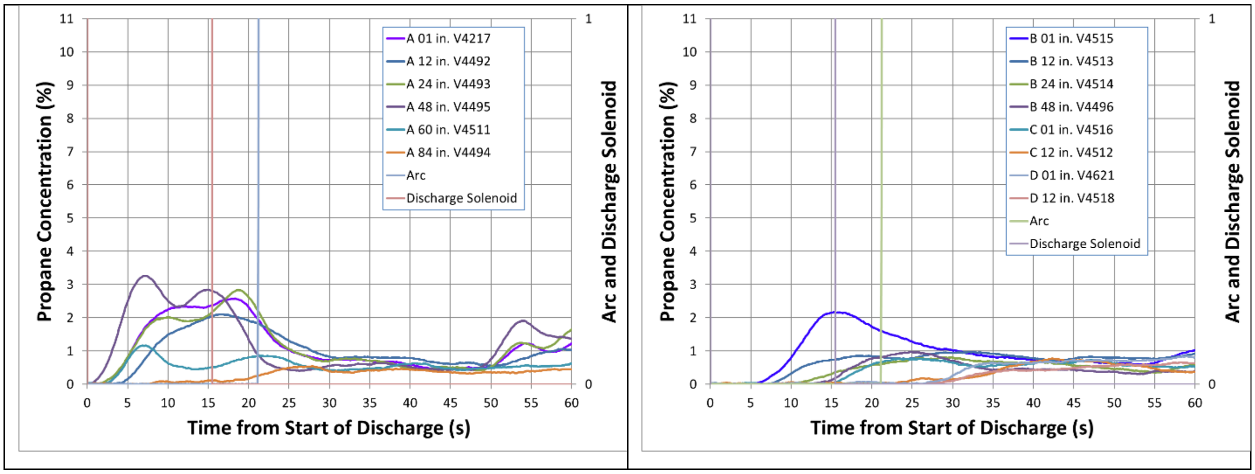


Figure 347 – MS_09 Concentrations and fan behavior

Figure 348 shows the mass flow rate and total mass flow.

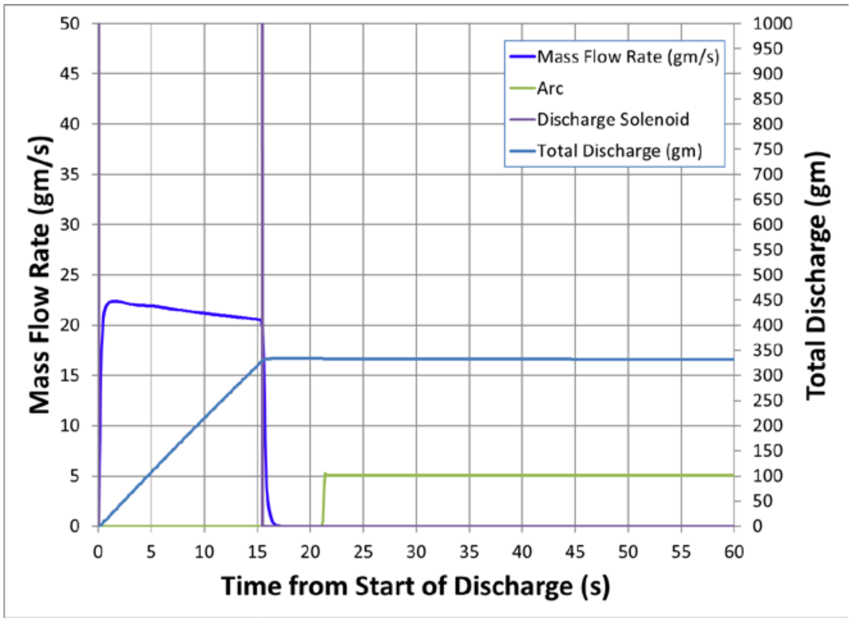


Figure 348 – MS_09 Mass Flow

Figure 349 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

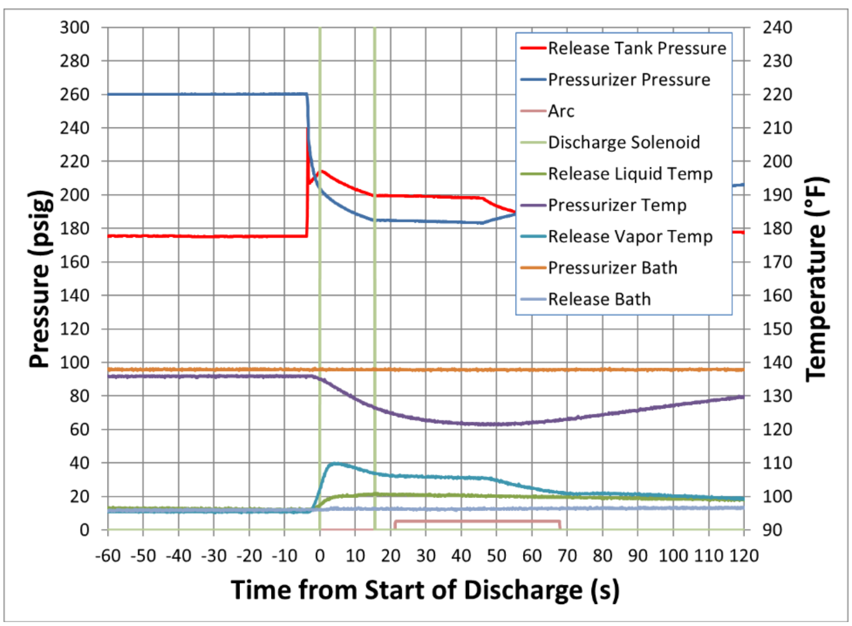


Figure 349 – MS_09 Pressurizer and Release Tank Pressure and Temperatures

Test MS_10 (650 g; Fan On; with Igniters)

Test MS_10 was performed with ignition sources, but there was no resulting ignition. The associated test without ignition sources is MS_03. This test involved release at a return bend of the evaporator coil with the fan operating continuously at 468 CFM. The key parameters and results of this test are summarized in the following table. At 40 seconds after the start of the discharge all sensors recorded less than LFL concentrations.

Table 77 – MS_10 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	650	30.4	21.4	Return Bend of Evaporator Coil	0.78	Calculated if well Mixed in whole room
Measured	649	33.6	19.3		2.3 2.1	Location A 12-inch Location B 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 350 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. The action of the fan resulted in nearly complete uniform mixing within the test room at 5 minutes after the start of the discharge. Final concentrations stabilized close to the estimated well-mixed value of 0.78%. The discharge solenoid closed at 33.6 seconds and all measured concentrations were less than LFL 6.4 seconds later (39.3 seconds after the start of the discharge).

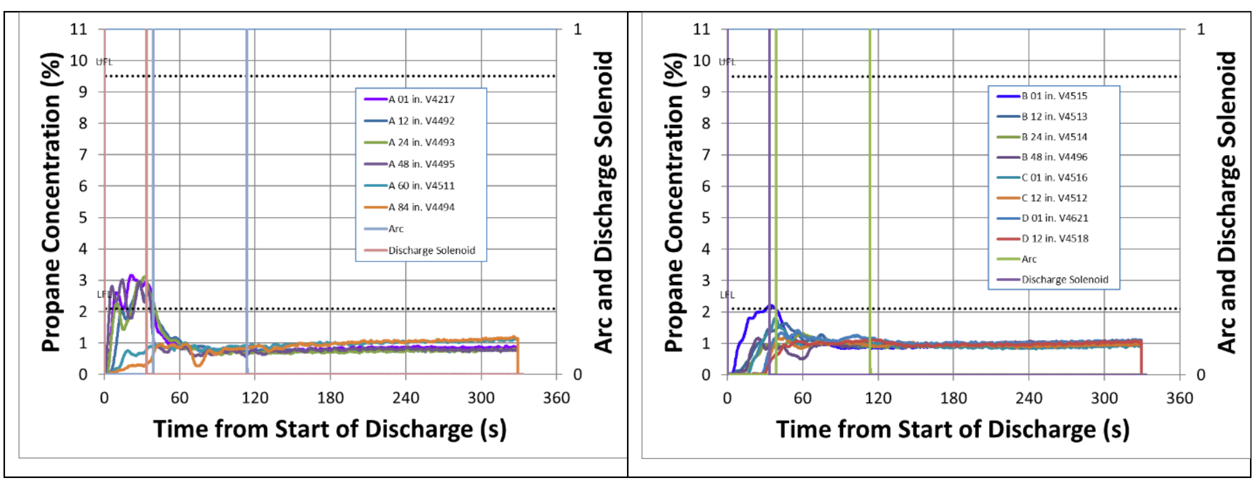


Figure 350 – MS_10 Concentrations

Figure 351 compares the concentrations at the 1-inch level at locations A and B for the pre-test and ignition tests (MS_03 and MS_10). Since there was no ignition the data for both tests is shown. Both tests show concentrations below LFL within 40 seconds of the start of the discharge due to the action of the unit fan.

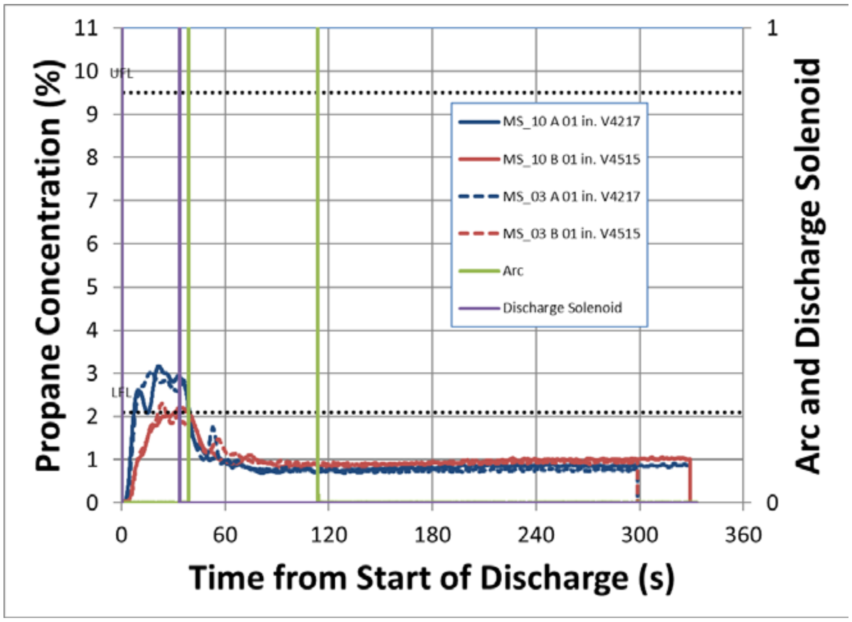


Figure 351 – MS_03 and MS_10 Concentration Comparison

Figure 352 shows the mass flow rate and total mass flow. The drop in mass flow during the discharge is due to the pressurizer tank loss of nearly all of its mass of liquid and a resulting drop in pressure to saturation pressure in the discharge tank.

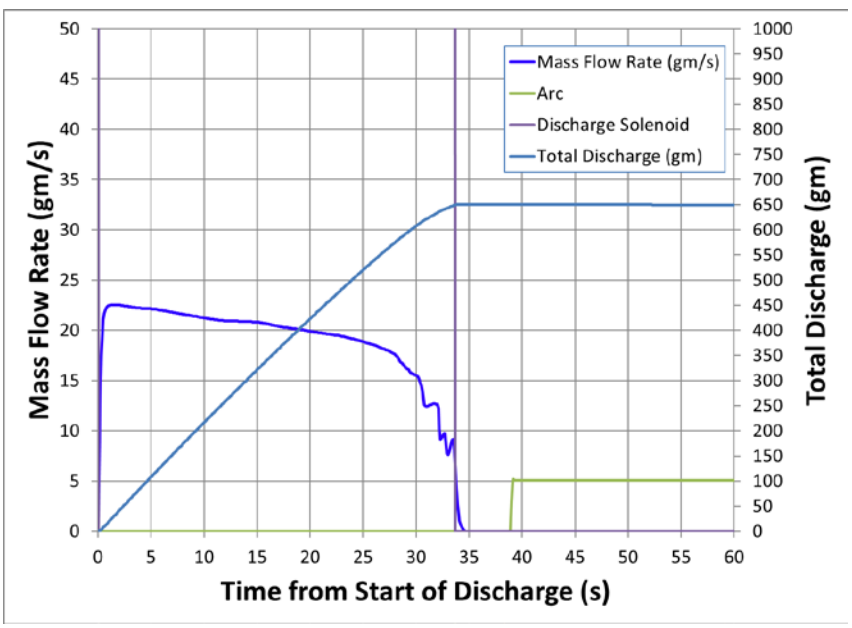


Figure 352 – MS_10 Mass Flow

Figure 353 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. Another indication of draining the pressurizer tank is the release tank pressure. At the end of the discharge, the figure shows release tank pressure returning to the pre-test value meaning that the pressurizer did not have sufficient mass to raise the pressure above saturation pressure in the release tank.

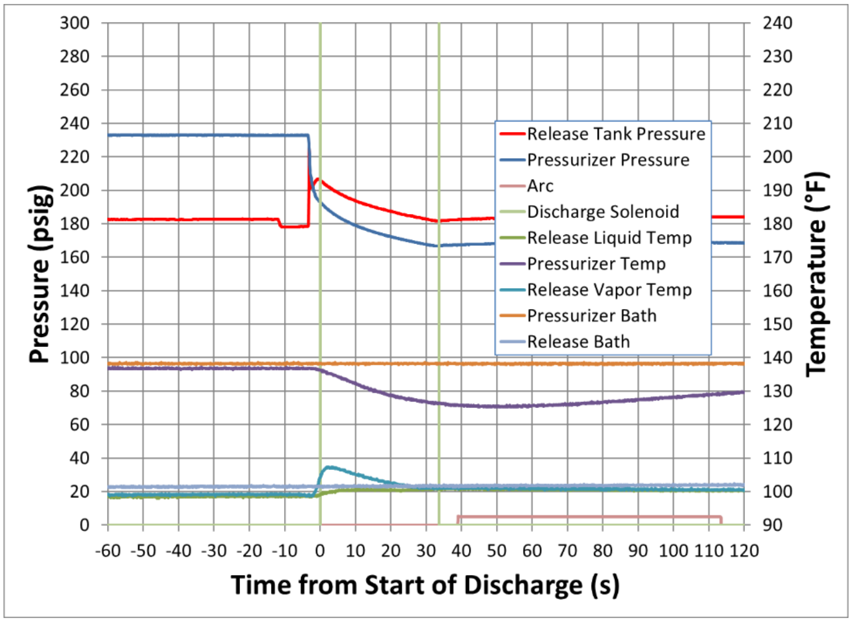


Figure 353 – MS_10 Pressurizer and Release Tank Pressure and Temperatures

Test MS_11 (329 g; Fan Off; with Igniters)

Test MS_11 was performed with ignition sources and resulted in ignition at arc location A with a slightly delayed ignition at location B.

Table 78 – MS_11 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	329	15.4	21.4	Return Bend of Evaporator Coil
Measured	327	13.2	24.8	

Figure 191 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time (18.2 seconds) so the data has been chopped at 16.2 seconds to filter out the effects of combustion on the oxygen sensors used to measure propane concentration.

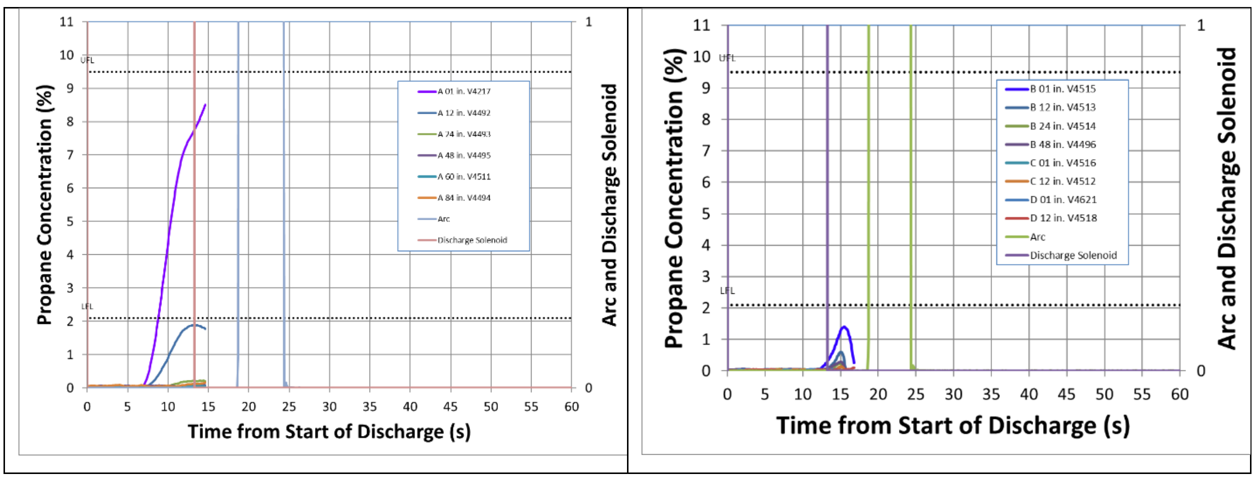


Figure 354 – MS_11 Concentrations

Figure 192 compares the concentrations at the 1-inch level at locations A and B for the pre-test and ignition tests (MS_01 and MS_11). The concentration data shown is deconvoluted to show an ignitable concentration existed location A 1-inch level (approximately 8.7% in the MS_01 pre-test). The MS_01 pre-test showed a concentration above LFL at location B 1-inch level of 2.3%. The MS_11 data does not show because the deconvoluted data had to be clipped at 16.8 seconds because of combustion product effects on the sensors. The MS_11 videos showed ignition occurred at location A as soon as the arcs with a slightly delayed ignition at location B.

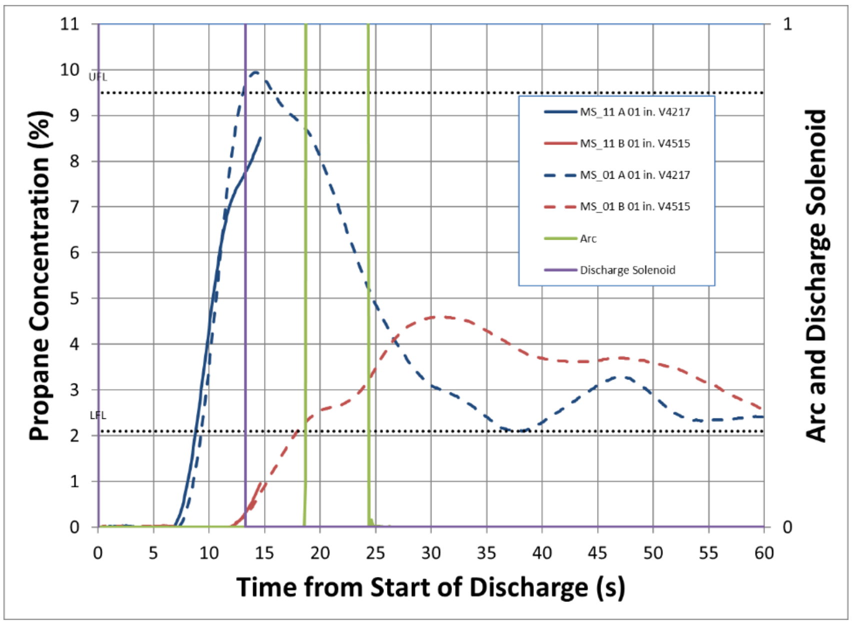


Figure 355 – MS_01 and MS_11 Concentration Comparison

Figure 193 shows the mass flow rate and total mass flow.

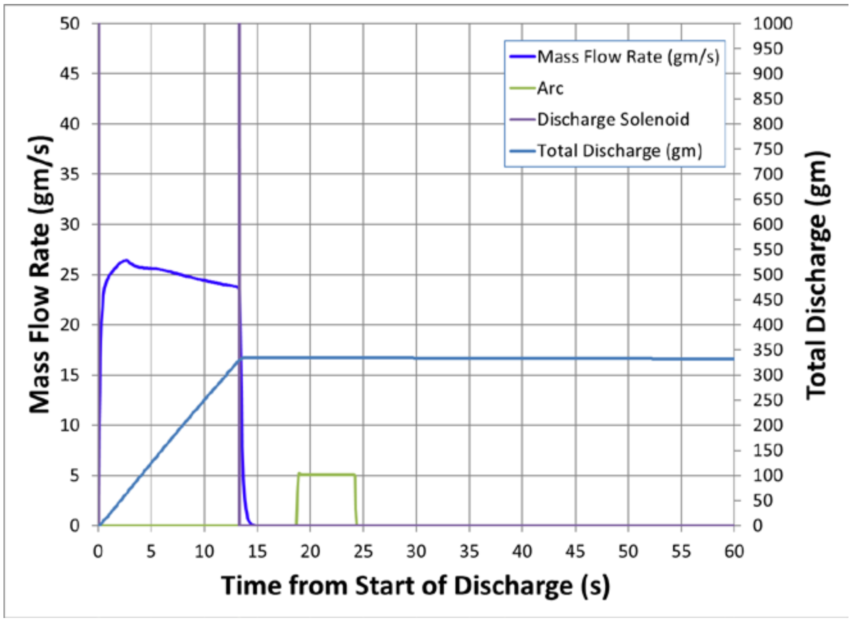


Figure 356 – MS_11 Mass Flow

Figure 194 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

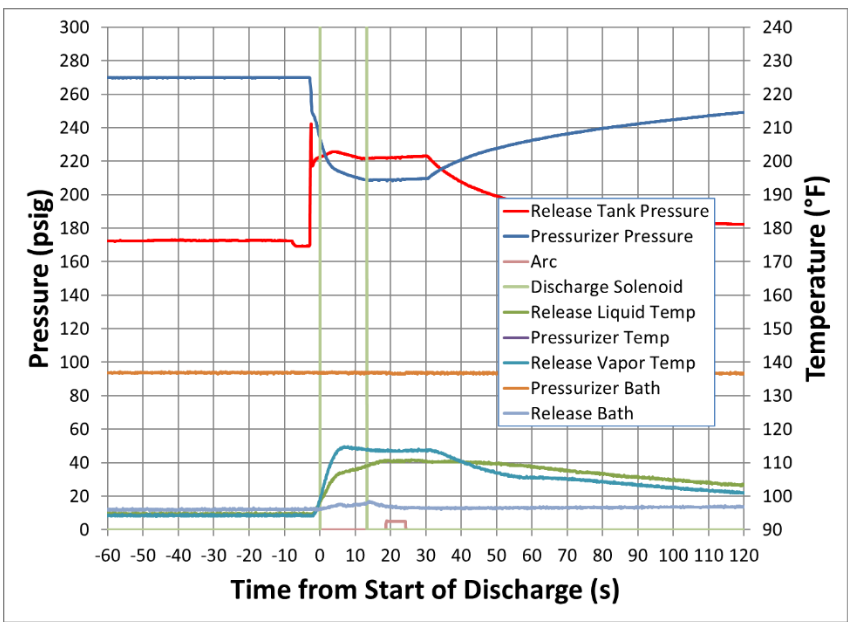


Figure 357 – MS_11 Pressurizer and Release Tank Pressure and Temperatures

Figure 195 shows the temperatures developed at the various locations following ignition. Location A shows the highest temperatures occurred at floor level followed by buoyant plume rising to the ceiling level. Location B and C showed highest temperatures at the low levels followed by the buoyant effect at higher levels. Location D showed the largest temperature increases from the buoyant plume and slight increases at the 18-inch level and below.

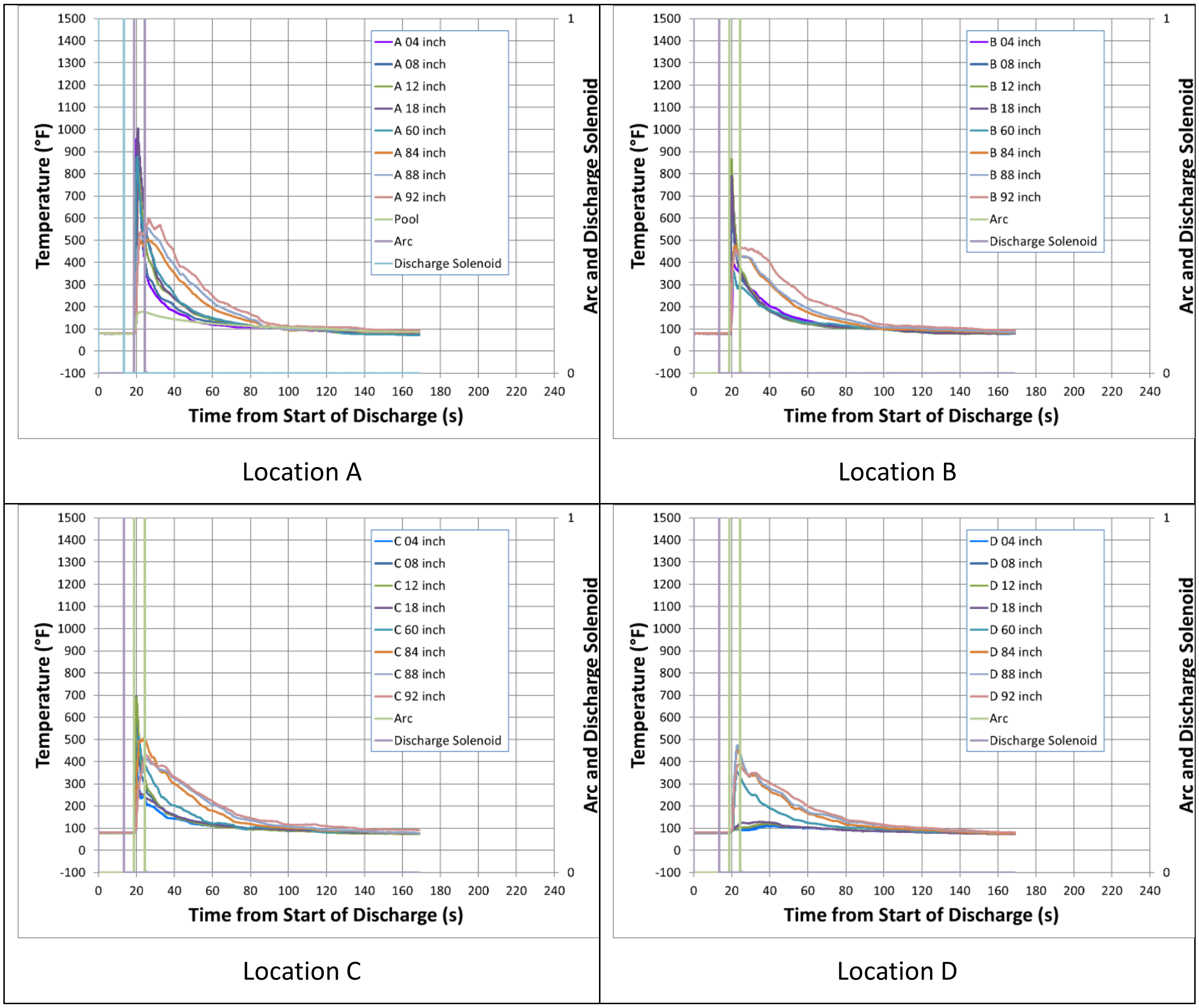


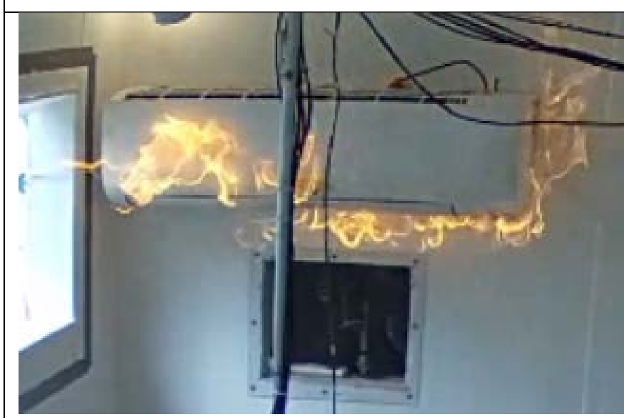
Figure 358 – MS_11 Temperatures at Locations A, B, C, and D

The videos showed ignition at Location A 1-inch level followed by a separate ignition at Location B 1-inch level. Flames within the mixed volume of room air and propane endured for approximately 2 seconds. Flaming continued inside the indoor unit due to the remaining propane and ignition of the indoor unit filters. The flames were suppressed with a water spray. The unit was replaced before testing was continued due to damage as shown in Figure 199.

The videos showed no evidence of a liquid pool of propane on the floor.

Ignition at Location A and B

Maximum size of flaming



Flames continued due to propane trapped in the unit

Front panel warped from heat and black smoke from burning fan assembly

Figure 359 – MS_11: Frames of flaming from videos

Test MS_12 (650 g; 15 s Fan Delay)

Test MS_12 was performed without ignition sources to measure propane concentrations. The associated test with ignition sources is MS_13. This test involved release at a return bend of the evaporator coil. The key parameters and results of this test are summarized in the following table. At 7 minutes after the start of the discharge, sensors at locations A, B, C, and D recorded concentrations slightly above the LFL of 2.1%.

Table 79 – MS_12 Summary

	Discharge Amount (g)	Duration of Discharge (Seconds)	Discharge Rate (g/s)	Leak Location	Concentration at 5 seconds after Discharge Completion (%)	
Planned	650	30.4	21.4	Return Bend of Evaporator Coil	0.78	Calculated if well Mixed in whole room
Measured	648	29.6	21.9		2.8 4.0	Location A 1-inch Location C 1-inch

Per procedure, the discharge was stopped after the target discharge amount was observed. Data recording continued for a minimum of 2.5 minutes after the discharge was completed. The unit fan was started at 15 seconds after the start of the discharge.

Figure 360 shows propane concentrations (deconvoluted) from the start of the discharge to the end of data recording at locations A, B, C and D. The action of the fan resulted in nearly complete uniform mixing within the test room at 4.5 minutes after the start of the discharge. Final concentrations stabilized close to the estimated well-mixed value of 0.78%. The discharge solenoid closed at 29.6 seconds. All measured concentrations were less than LFL 108 seconds after the start of the discharge.

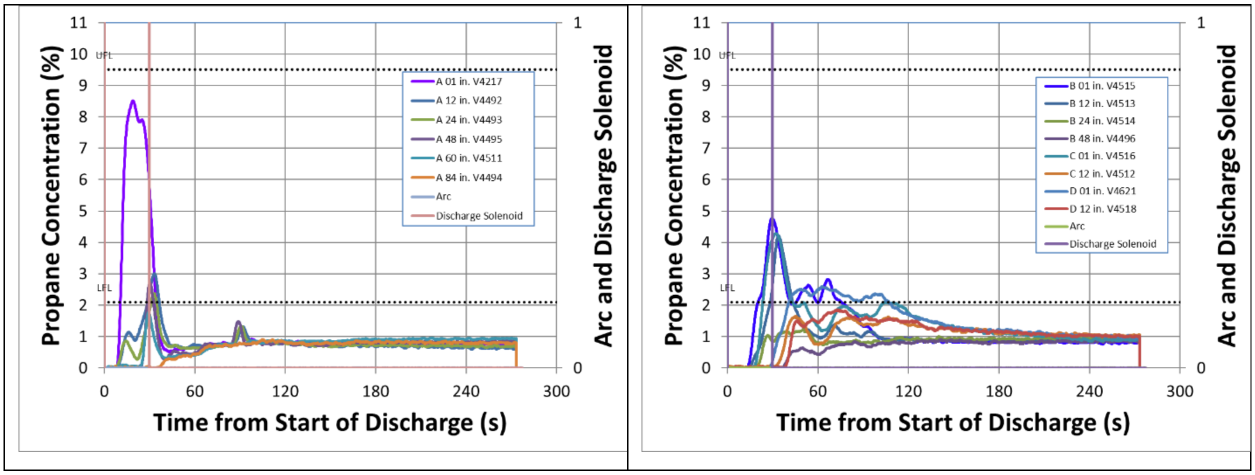


Figure 360 – MS_12 Concentrations

Figure 361 concentrates on the first 60 seconds of this test. The fan start command was given at 15 seconds after the start of the discharge. The fan was observed to require 10 seconds to come up to full speed and fully deploy the flaps on the bottom of the unit (fan discharge). The figure shows a sharp decline at location A 1-inch level following the fan achieving full speed. Locations B, C, and D at the 1-inch level show the sweeping action of this air flow as the concentrations at floor level are pushed away from location A and toward locations B, C, and D

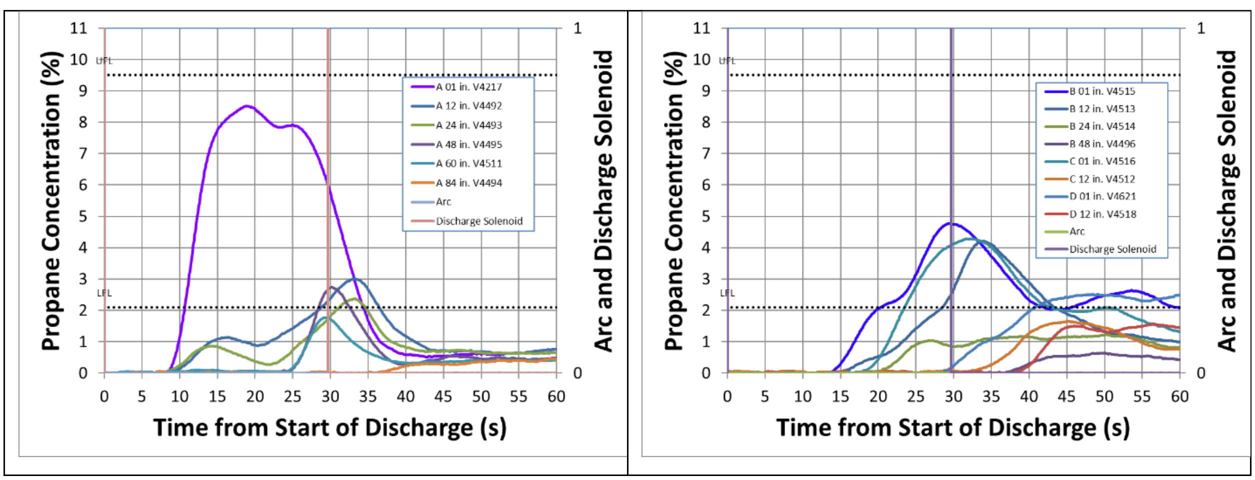


Figure 361 – MS_12 Concentrations and fan behavior

Figure 362 shows the mass flow rate and total mass flow. The mass flow rate signal shows a relatively slow drop to zero after the discharge solenoid closed. This was due to compression of the small amount of vapor in the liquid in the mass flow meter and downstream tubing.

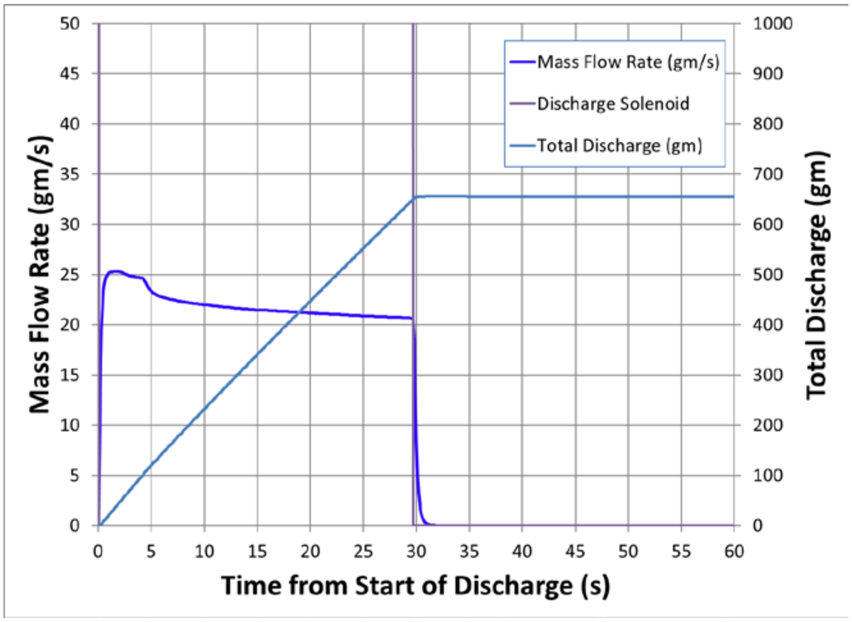


Figure 362 – MS_12 Mass Flow

Figure 363 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures. In this test, the pressurizer and release tank were placed in series at time -70 seconds and does not show on the figure below.

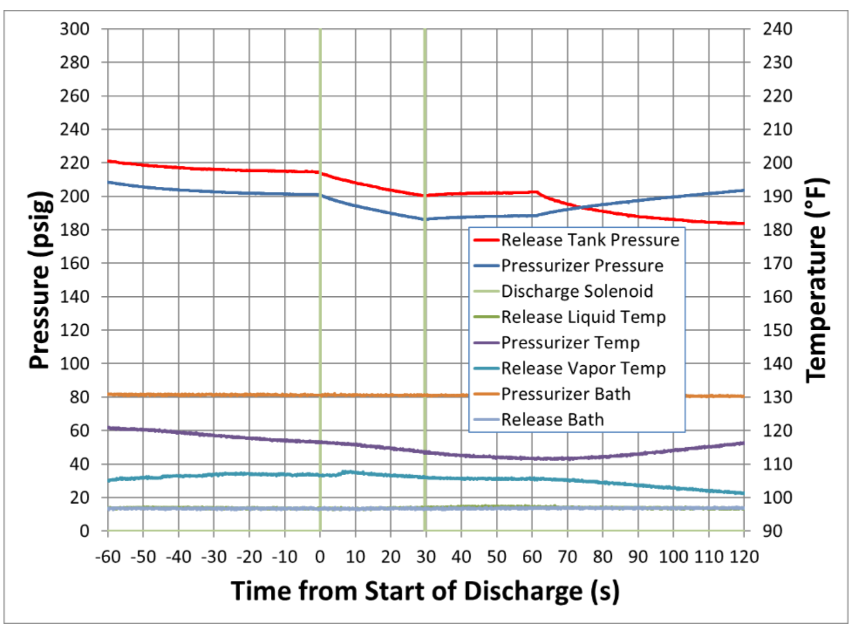


Figure 363 – MS_12 Pressurizer and Release Tank Pressure and Temperatures

Test MS_13 (650 g; 15 s Fan Delay; with Igniters)

Test MS_13 was performed with ignition sources and resulted in ignition at arc location B and none at location A. There was a delayed ignition of a liquid pool of propane just below the unit on the floor.

Table 80 – MS_13 Summary

	Discharge Amount (g)	Duration of Discharge (seconds)	Discharge Rate (g/s)	Leak Location
Planned	650	30.4	21.4	Return Bend of Evaporator Coil
Measured	647	30.0	21.6	

Figure 364 shows the deconvoluted concentrations measured up to the point that combustion products caused a false measure of propane concentration. Deconvolution looks back 2 seconds from the ignition time (35.6 seconds) so the data has been chopped at 33.2 seconds to filter out the effects of combustion on the oxygen sensors used to measure propane concentration.

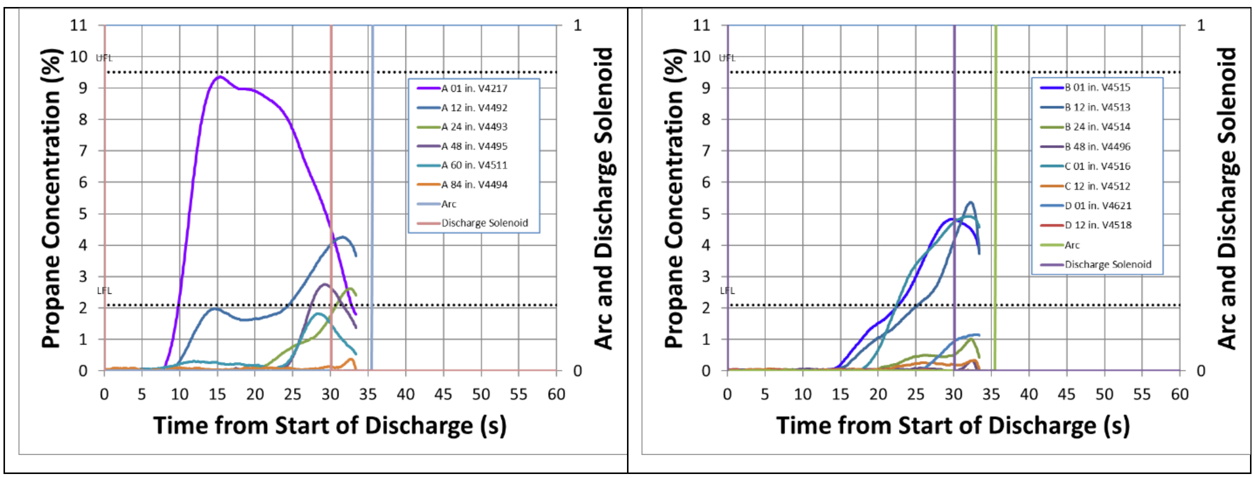


Figure 364 – MS_13 Concentrations

Figure 192 compares the concentrations at the 1-inch level at locations A, B, and C for the pre-test and ignition tests (MS_12 and MS_13). The action of the fan caused the concentration at location A to quickly drop below the LFL by the time the igniters were energized. Locations B and C pre-test data showed ignitable concentrations at ignition time of 3.6% and 3.8%, respectively. The igniters were placed at locations A and B.

The figure also shows the repeatability of the data between the pre-test and ignition tests.

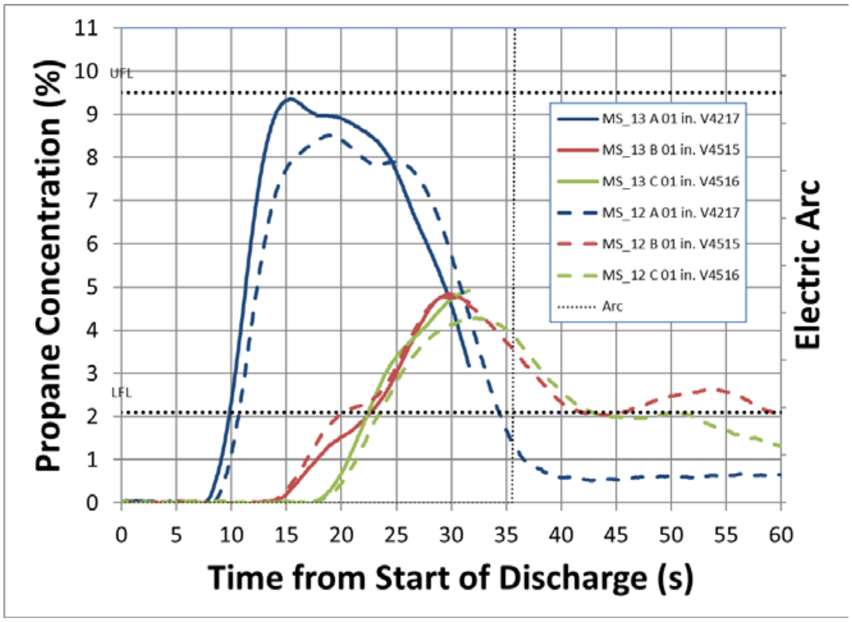


Figure 365 – MS_12 and MS_13 Concentration Comparison

Figure 366 shows the mass flow rate and total mass flow.

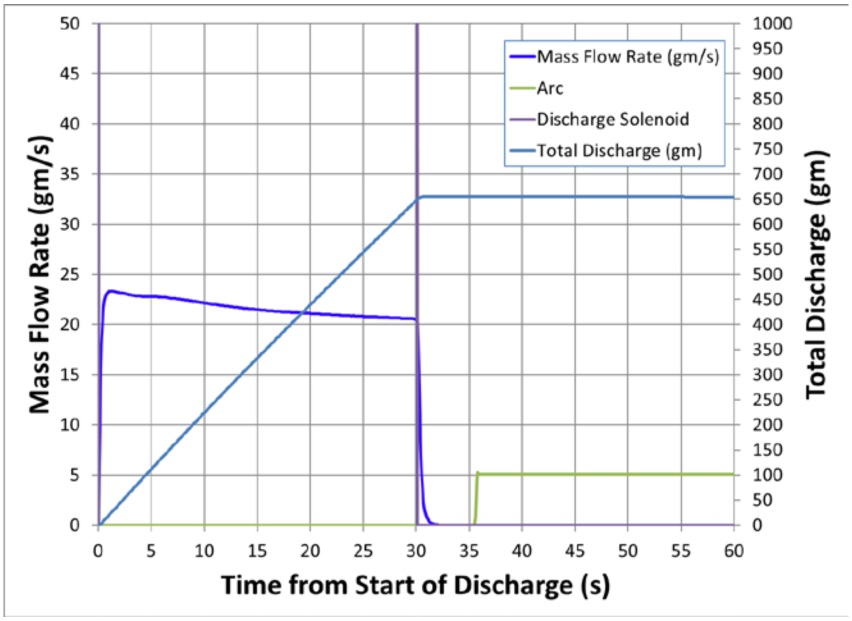


Figure 366 – MS_13 Mass Flow

Figure 367 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

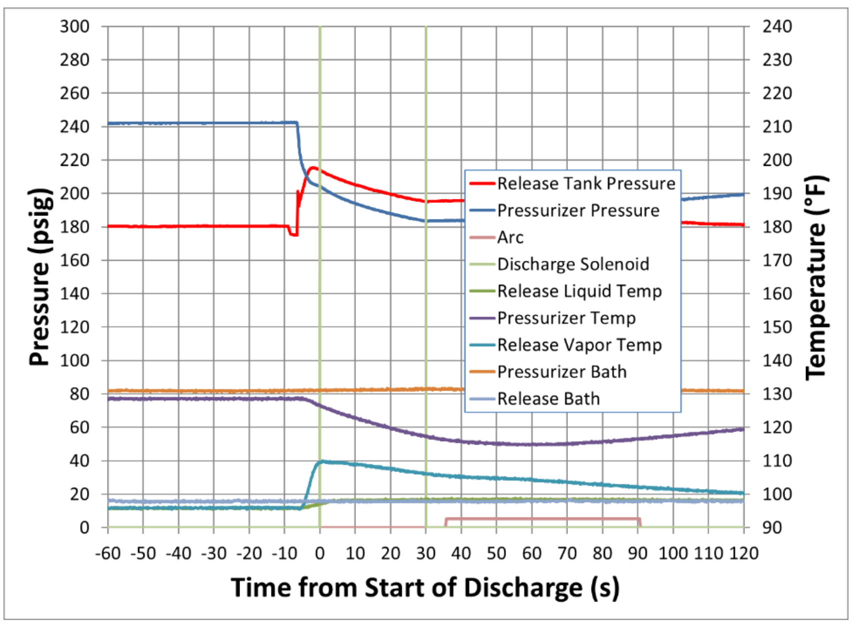


Figure 367 – MS_13 Pressurizer and Release Tank Pressure and Temperatures

Figure 368 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at location B where flames initiated. Location A showed an increase in temperature peaking at about 44 seconds due to delayed ignition of the nearby pool of liquid propane. The spikes in temperature around 130 seconds are due to ignition and continued flaming of the internal components of the indoor unit. Suppression activities with water spray were initiated from outside of the test room at 90 seconds after the start of discharge. When this proved insufficient, the suppression began inside the test room at 140 seconds and the flames were extinguished.

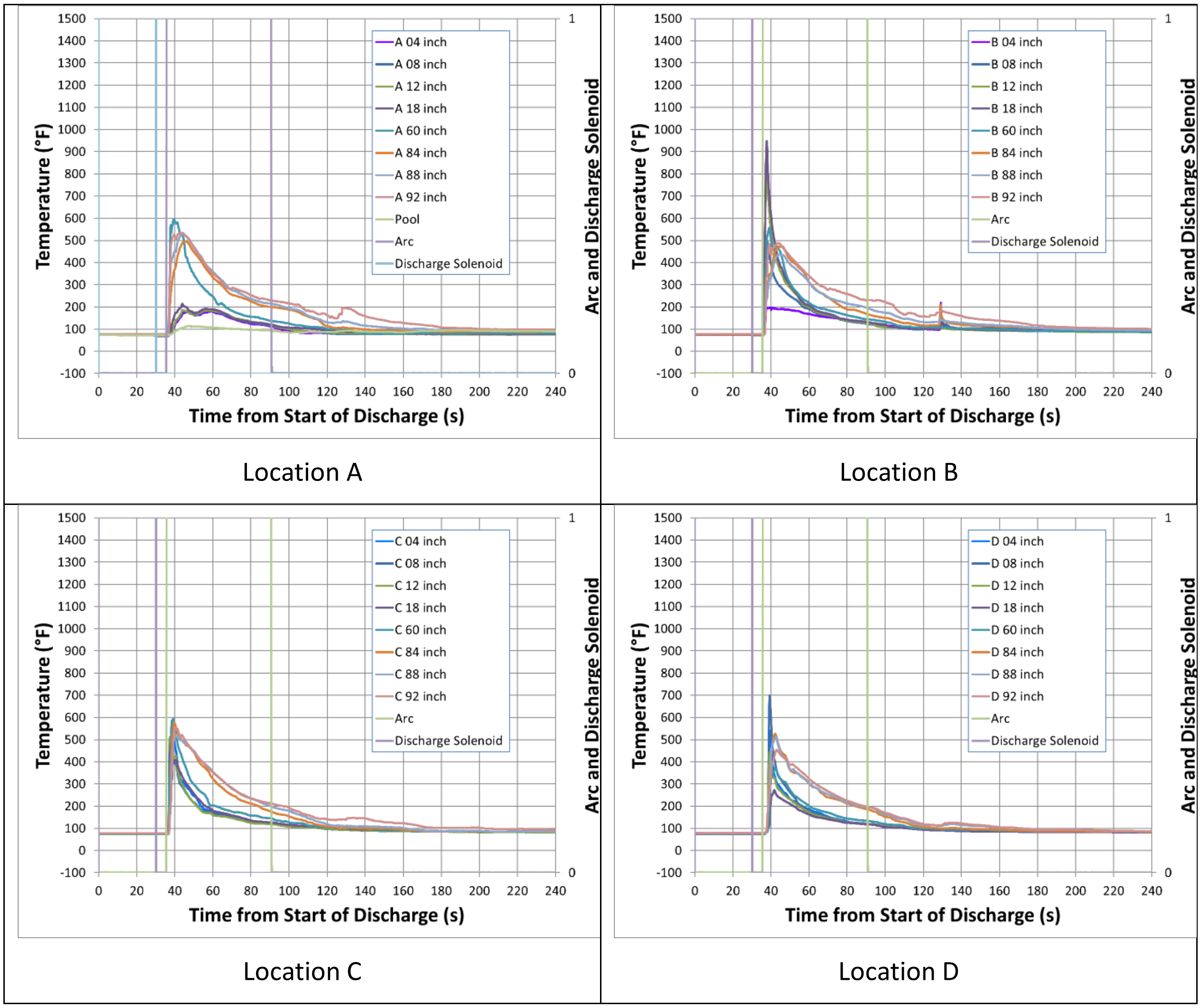


Figure 368 – MS_13 Temperatures at Locations A, B, C, and D

The videos showed ignition at Location B 1-inch level. The ignition was too faint to see on the video, but the frames shown in Figure 369 show the visible flames spreading from location B. Flames within the mixed volume of room air and propane endured for approximately 2 seconds. Flaming continued inside the indoor unit due to the remaining propane and ignition of the indoor unit components. The flames were suppressed with a water spray.

The videos showed some evidence of a liquid pool of propane on the floor below the unit. This pool was not ignited until after a piece of burning cheesecloth had fallen into the pool.

Ignition at Location B

Maximum size of flaming

Flames continued due to propane trapped in the unit

Liquid pool of propane ignited by a fallen piece of burning cheesecloth

Figure 369 – MS_13: Frames of flaming from videos

Appendix D Three Door Reach-In Cooler Test Data and Summary

This appendix summarizes the tests with the three-door reach in cooler.

The following table summarizes all tests with the three-door reach-in cooler. The sections that follow describe each test in detail.

Temperatures are color coded according to the following legend:

Range
< 0°F
0 – 105 °F
105 – 400 °F
400°F and higher

Table 81 – Three-Door Reach-in Cooler Tests

												Raw Video Times HH:MM:SS									Maximum Concentrations, Location, and Time Relative to Start of Discharge			Deconvoluted Concentrations, Location, and Time Relative to Start of Discharge			
Test Code	Date	Purpose	Condenser Fan State	Planned Discharge (g)	Planned Discharge Rate (g/s)	Planned Duration (MM:SS)	Measured Mass (g)	Measured Rate (g/s)	Measured Duration (MM:SS)	Discharge Location	Discharge Opening	Door Open Start	Door Open	Ignition	Max Pressure (mmHg)	Max Temp (°F)	Max Temp Location	Max Ceiling Temp (°F)	Number of Vents Burst /Melted	Result	Location	Max Conc. (%)	Max Conc. Time (s)	Location	Max Decon. (%)	Max Decon. Time (s)	Analysis File
RI_01	20-Jun-2018	Concentration	Off	150	0.224	11:10	159	0.235	11:16	Evap. Return	0.026 in. Cap. Tube	15:08:02	15:08:08	NA							Inside 04 in.	3.2	714	A 2 in.	3.6	735	RI_01_2018-06-20-1452 Analysis.xlsx
RI_02	20-Jun-2018	Concentration	Off	355	0.530	11:10	357	0.531	11:12	Evap. Return	0.026 in. Cap. Tube	15:55:46	15:55:50								Inside 04 in.	7.5	719	A 2 in.	8.8	717	RI_02_2018-06-20-1540 Analysis.xlsx
RI_03	21-Jun-2018	Concentration	On	355	0.530	11:10	347	0.530	10:55	Evap. Return	0.026 in. Cap. Tube	10:51:14	10:51:18								Inside 30 in.	6.8	706	Inside 30 in.	7.0	700	RI_03_2018-06-21-1035 Analysis.xlsx
RI_04	21-Jun-2018	Concentration	Off	71	0.224	05:17	71	0.229	05:12	Evap. Return	0.026 in. Cap. Tube	11:33:27	11:33:30								Inside 04 in.	1.7	369	Inside 04 in.	1.9	368	RI_04_2018-06-21-1122 Analysis.xlsx
RI_05	22-Jun-2018	Ignition	Off	71	0.224	05:17	72	0.229	05:17	Evap. Return	0.026 in. Cap. Tube	10:18:46	10:18:49	10:18:56	0.0	110	A-08	83	0/0	Local Ignition at arcs	Inside 04 in.	1.6	354	Inside 04 in.	1.8	353	RI_05_2018-06-22-1008 Analysis.xlsx
RI_06	22-Jun-2018	Ignition	Off	92	0.224	06:51	96	0.234	06:52	Evap. Return	0.026 in. Cap. Tube	10:57:20	10:57:23	10:57:24	0.0	718	A-08	100	0/0	Ignition	Inside 30 in.	1.9	445	Inside 30 in.	2.1	444	RI_06_2018-06-22-1043 Analysis.xlsx
RI_07	22-Jun-2018	Concentration	Off	114	0.224	08:29	116	0.227	08:30	Evap. Return	0.026 in. Cap. Tube	11:29:06	11:29:09	NA							A 2 in.	2.3	571	A 2 in.	2.6	558	RI_07_2018-06-22-1116 Analysis.xlsx
RI_08	22-Jun-2018	Ignition	Off	114	0.224	08:29	115	0.227	08:29	Evap. Return	0.026 in. Cap. Tube	13:25:36	13:25:39	13:25:40	0.0	886	A-88	671	1/1	Ignition	NA						RI_08_2018-06-22-1312 Analysis.xlsx
RI_09	22-Jun-2018	Ignition	On	114	0.224	08:29	117	0.231	08:29	Evap. Return	0.026 in. Cap. Tube	14:06:49	14:06:52	NA	0.0	84	A-04	82	0/0	No Ignition	Inside 04 in.	2.6	542	Inside 04 in.	2.7	539	RI_09_2018-06-22-1354 Analysis.xlsx
RI_10	22-Jun-2018	Ignition	On	150	0.224	11:10	157	0.235	11:10	Evap. Return	0.026 in. Cap. Tube	14:44:01	14:44:04	14:44:04	0.0	919	A-18	378	3/0	Ignition	NA						RI_10_2018-06-22-1428 Analysis.xlsx
RI_11	22-Jun-2018	Ignition	Off	132	0.224	09:50	133	0.226	09:50	Evap. Return	0.026 in. Cap. Tube	15:34:02	15:34:05	15:34:09	0.0	855	A-18	370	3/1	Ignition							RI_11_2018-06-22-1520 Analysis.xlsx
RI_12	25-Jun-2018	Ignition	Off	150	0.224	11:10	150	0.226	11:06	Evap. Return	0.026 in. Cap. Tube	10:42:40	10:42:42	10:42:49	0.0	835	A-18	429	5/0	Ignition							RI_12_2018-06-25-1027 Analysis.xlsx
RI_13	25-Jun-2018	Concentration	Off	355	0.530	11:10	347	0.528	10:59	Evap. Return	0.026 in. Cap. Tube	14:56:32	14:56:35	NA							Inside 04 in.	8.7	710	A 2 in.	9.6	715	RI_13_2018-06-25-1440 Analysis.xlsx
RI_14	25-Jun-2018	Concentration	Off	150	0.224	11:10	154	0.234	11:00	Evap. Return	0.026 in. Cap. Tube	15:36:58	15:37:02								Inside 04 in.	3.7	707	Inside 04 in.	3.9	711	RI_14_2018-06-25-1521 Analysis.xlsx
RI_15	26-Jun-2018	Ignition	Off	150	0.224	11:10	154	0.231	11:09	Evap. Return	0.026 in. Cap. Tube	09:55:08	09:55:11	09:55:12	0.0	922	A-18	413	5/0	Ignition	NA						RI_15_2018-06-26-0939 Analysis.xlsx
RI_16	26-Jun-2018	Concentration	Off	150	0.224	11:10	150	0.225	11:09	Evap. Return	0.026 in. Cap. Tube	10:41:36	10:41:39	NA							Inside 04 in.	3.0	700	Inside 04 in.	3.3	699	RI_16_2018-06-26-1026 Analysis.xlsx
RI_17	26-Jun-2018	Concentration	Off	200	0.299	11:10	204	0.229	14:52	Evap. Return	0.026 in. Cap. Tube	11:49:17	11:49:23								Inside 04 in.	4.9	934	Inside 04 in.	5.0	929	RI_17_2018-06-26-1130 Analysis.xlsx
RI_18	26-Jun-2018	Ignition	Off	200	0.299	11:10	198	0.297	11:10	Evap. Return	0.026 in. Cap. Tube	13:58:34	13:58:37	13:58:37	0.0	1061	A-12	478	6/0	Ignition	NA						RI_18_2018-06-26-1343 Analysis.xlsx
RI_19	27-Jun-2018	Concentration	Off	397	0.593	11:10	403	0.598	11:15	Cond. Return	0.064 in. Cap. Tube	NA									Left Back	8.3	684	Left Back	8.5	680	RI_19_2018-06-27-1009 Analysis.xlsx
RI_20	27-Jun-2018	Ignition	Off	397	0.593	11:10	400	0.597	11:10	Cond. Return	0.064 in. Cap. Tube	Arc Time 11:23:58			0.0	1292	B-04	298	4/1 + Door	Ignition	NA						RI_20_2018-06-27-1108 Analysis.xlsx
RI_37	12-Jul-2018	Ignition	On	397	0.593	11:10	392	0.586	11:10	Cond. Return	0.064 in. Cap. Tube	Arc Time 10:02:02			0.1	77	A-04	73	0/0	No Ignition	Pan	1.4	664	V4495decon	1.5	602	RI_37_2018-07-12-0946 Analysis.xlsx

Notes:

- The times recorded for the raw video are from the date/time stamp (time portion only) in the video.
- Temperatures are recorded in the cases where ignition occurred.
- Propane concentrations are recorded in cases where the igniters were not used except for RI_05 and RI_06.
- Tests RI_05 and RI_06 (ignition tests) do record concentrations because the ignition did not seem to affect the sensors. Evidence of ignition was visible only on the infrared camera.
- Refer to the main body of the report for the description of sensor locations.

Videos for each test are stored separately. The correspondence of channel number to camera view is as follows:

Video Channel	Camera Location
2	East Wall Upper
3	Northeast Floor Corner
4	South Wall Center
6	East Side Vents
7	West Side Vents
9	Test Marquee and Clock
10	IR Camera West Wall
11	West Wall Upper

High speed camera videos are stored in the same folder for each test. High speed cameras were used where ignition was expected. The following table matches the test number with the high speed camera video:

High Speed Cameras		
Test	**Floor Level**	**High Level**
RI_08	CIMG3363.MOV	CIMG3364.MOV
RI_11	CIMG3366.MOV	Not Done
RI_15	CIMG3368.MOV	CIMG3369.MOV
RI_18	CIMG3369.MOV	CIMG3370.MOV
RI_20	CIMG3370.MOV	CIMG3371.MOV

Note: The cameras assigned file names automatically. Some filenames are identical and are stored separately. For example CIMG3444.MOV appears twice on the list above, but they contain different video.

Test RI_01 (3-Door Cooler; 150 gram; Internal Release)

Test RI_01 was performed without ignition sources in order to measure propane concentrations prior to the conduct of an ignition test. The key parameters and results of this test are summarized in the following table. The ignition test did not immediately follow because the measured concentrations indicated that an overpressure event could occur.

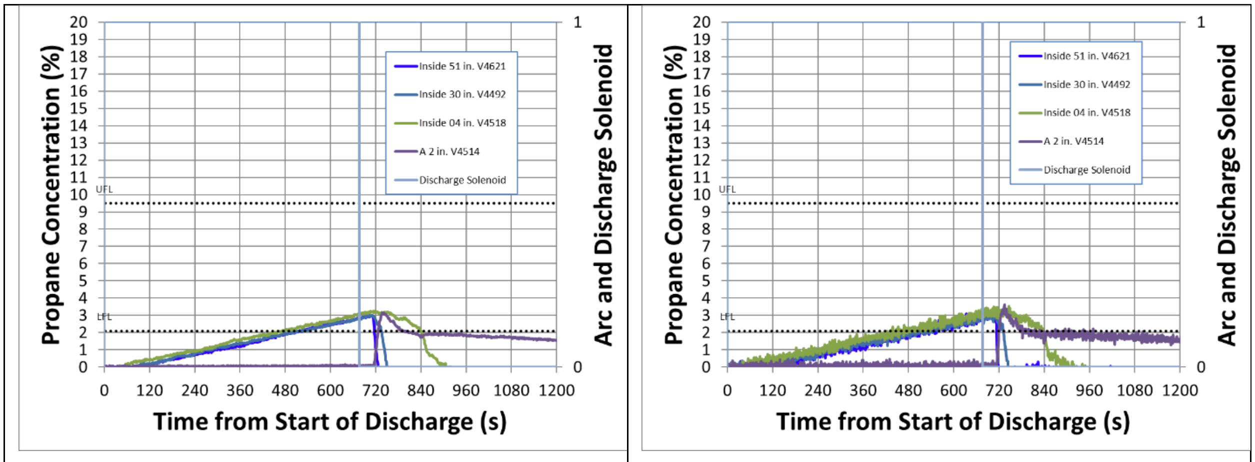
Table 82 – RI_01 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	150	11:10	0.224	Evaporator Return Bend	4.4	Well Mixed (Internal)
Measured	159	11:16	0.235		3.2	Internal
					3.5	Internal Deconvoluted
					3.6	Electric Arc Location

Per procedure, all doors of the cooler remained closed for 30 seconds after completion of the release. The center door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2 minutes following the door opening.

Figure 370 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 51 inches. As the door opens the sensor at 51 inches decreases the fastest, followed by the 30 inch level, while the 4 inch sensor decreased at the slowest rate.

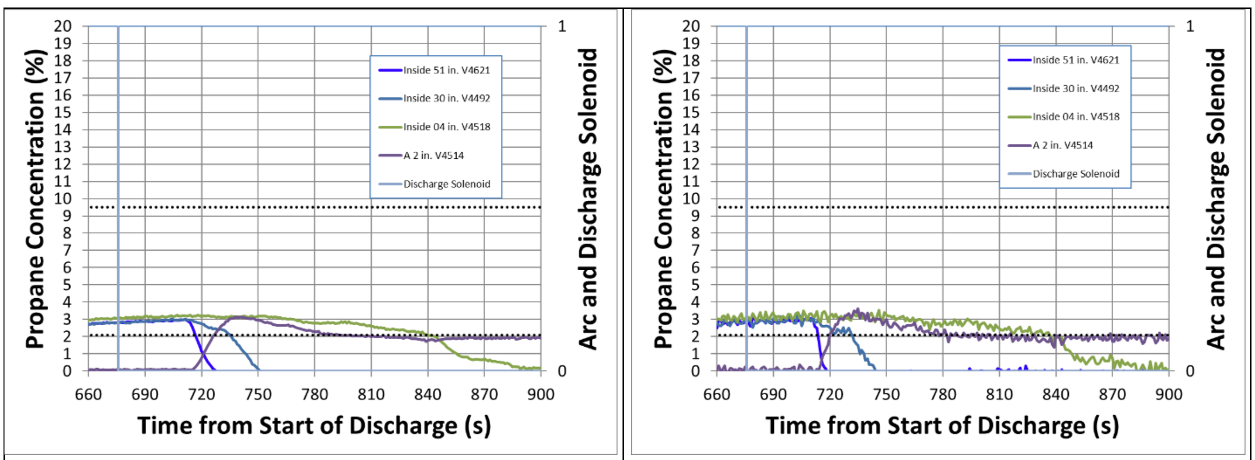
The sensor at the electric arc location (A 2 in.) shows a slight increase prior to the door opening, most likely due to door gasket leakage onto the floor near the cooler. This leakage accounts for the peak concentrations being less than the calculated well-mixed value. After the door is opened, the arc location increases to a value above the LFL of 2.1% and peaks at 3.2% (3.6% deconvoluted).



Concentrations	Deconvoluted Concentrations

Figure 370 – RI_01 Concentrations

Figure 371 focuses on the concentrations after completion of the discharge. The graphs show that the concentration at the arc location remains above the LFL for approximately 30 seconds. For reference, the door opening began at 690 seconds on these timelines.



Concentrations	Deconvoluted Concentrations

Figure 371 – RI_01 Concentrations after Discharge Completion

Figure 372 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

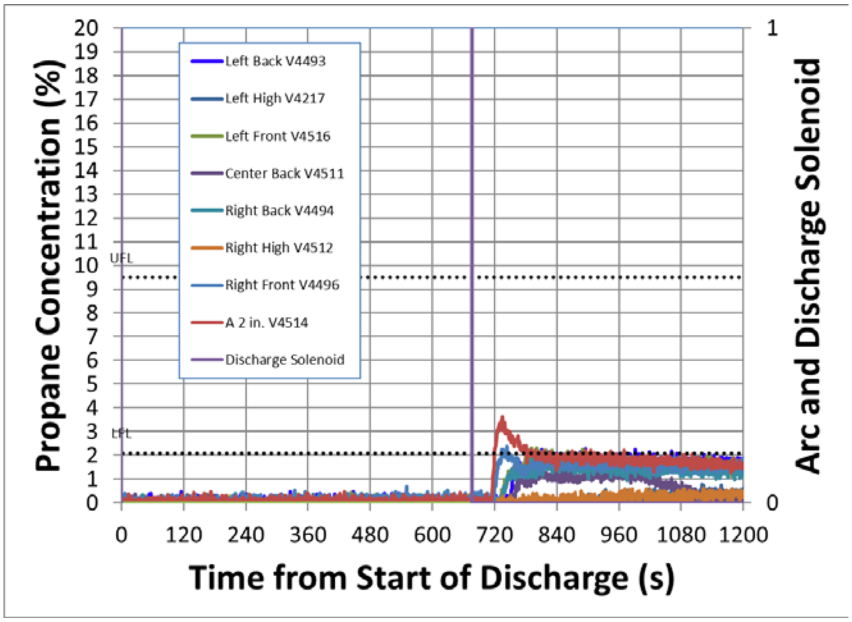


Figure 372 – RI_01 Concentrations at 8 locations surrounding cooler

Figure 373 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to integrate the total mass release.

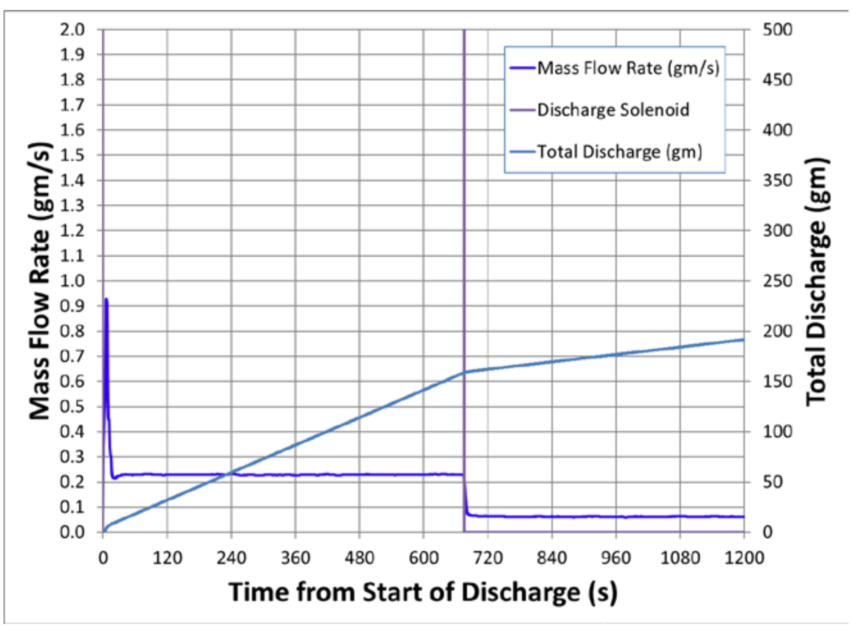


Figure 373 – RI_01 Mass Flow

Figure 374 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced prior to test RI_17. Release pressure is approximately equal to pressurizer pressure during the discharge when the two tanks are cross-connected.

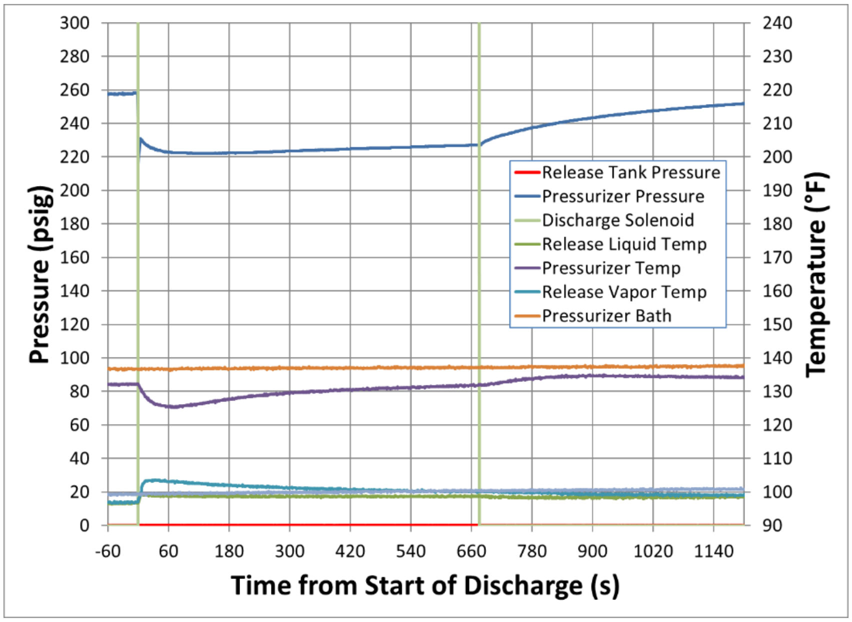


Figure 374 – RI_01 Pressurizer and Release Tank Pressure and Temperatures

Test RI_02 (3-Door Cooler; 355 gram; Internal Release)

Test RI_02 was performed without ignition sources. The interior leak was at an evaporator return bend. The interior fans were not operating during this test. The purpose was to demonstrate the effect of the fan on propane concentration. The key parameters and results of this test are summarized in the following table.

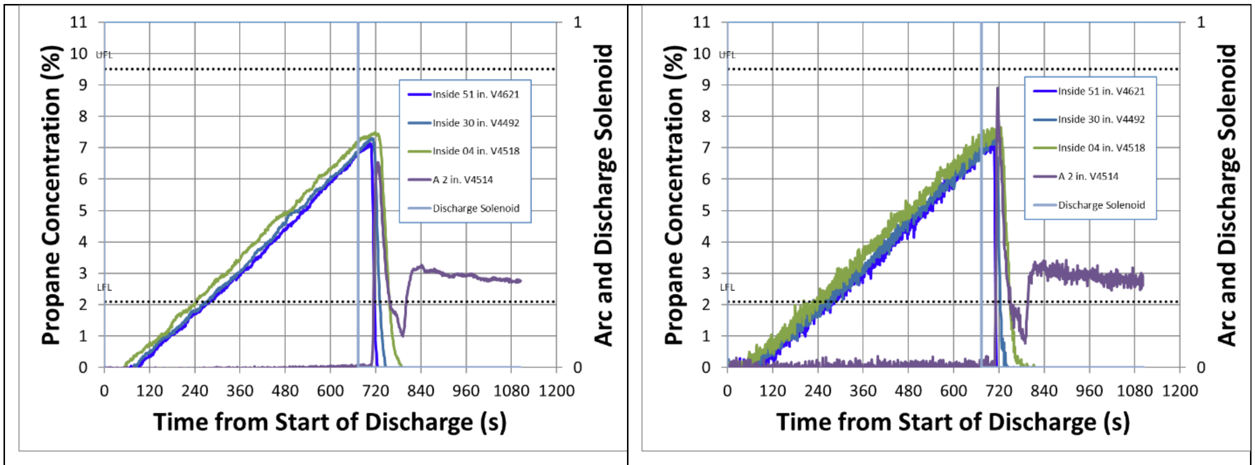
Table 83 – RI_02 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	355	11:10	0.530	Evaporator Return Bend	10.8 0.4	Well Mixed (Internal) Test Room
Measured	357	11:12	0.531		7.5 7.9 8.9	Internal Internal Deconvoluted Electric Arc Location

Per procedure, the discharge was stopped after 11 minutes and 10 seconds. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 375 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 51 inches. As the door opens the sensor at 51 inches decreases the fastest, followed by the 30 inch level, while the 4 inch sensor decreased at the slowest rate.

The concentration at the electric arc location (A 2 in.) shows a slight increase prior to the door opening, most likely due to door gasket leakage onto the floor near the cooler. This leakage accounts for the peak concentrations being less than the calculated well-mixed value. After the door is opened, the arc location increases to a value above the LFL of 2.1% and peaks at 6.5% (8.9% deconvoluted).

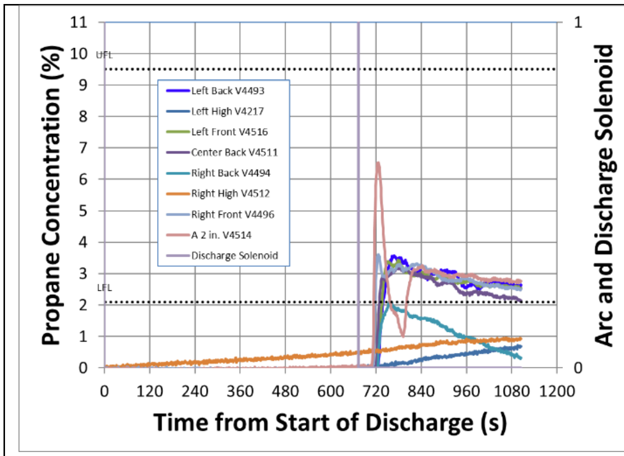


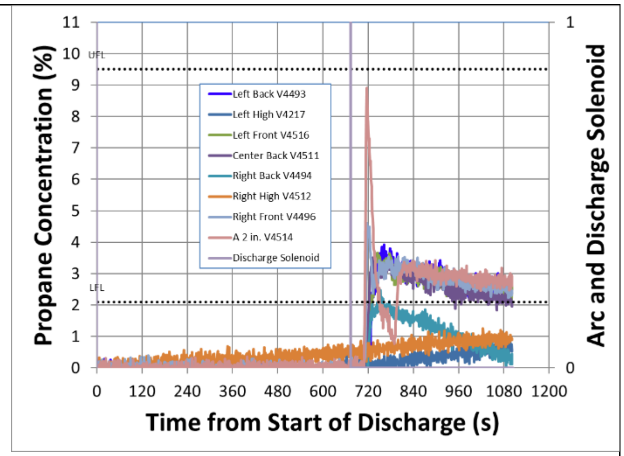
Concentrations	Deconvoluted Concentrations

Figure 375 – RI_02 Internal Concentrations

Figure 376 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording at the 8 locations specified in by 2-89 CDV. Observations of this test include the following:

- The data show the concentration at location A 2-inches peaked at 8.9% (deconvoluted) immediately after the door was opened
- The Right-side High sensor (externally attached to the unit) showed a steady increase from the start of the discharge to the end of data recording. This sensor did not show evidence of drift in tests before or after this test. Both High sensors were near incandescent lights at the ceiling level and showed steadily increasing sensor temperatures. It appears that uneven heating of the electro-chemical media contributed to this effect. All other sensors showed relatively constant temperatures.
- All external concentrations settled at a level above LFL at the end of data recording. The one exception was the Right-side Back which was located close to the test room exterior door. This same effect was observed in later tests (e.g. RI_13). The suspect cause is leakage through the exterior door weather seal.





Concentrations	Deconvoluted Concentrations

Figure 376 – RI_02 Concentrations

Figure 377 shows concentration measurements at other locations in the test room. The concentration at location B 2-inches settled to the same level as the location A 2-inch sensor. The sensor at location A-8 inches settle to a level just under 2% indicating the formation of a room-wide flammable layer three minutes after the cooler door was opened.

The time scale in Figure 377 has been narrowed to show the wave-like action as the high concentration propane/air mixture poured out of the cooler.

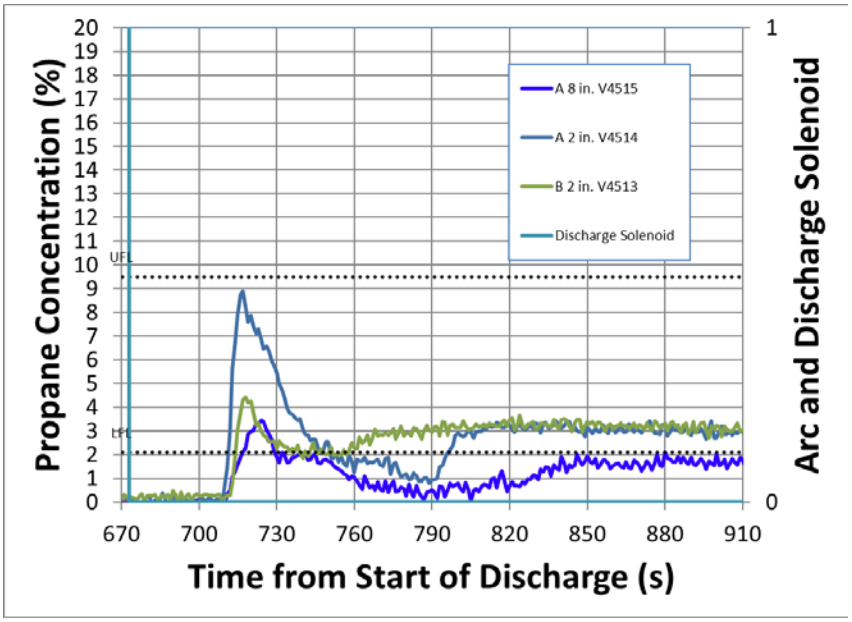


Figure 377 – RI_02 Other Concentrations

Figure 378 shows the change in temperature at location A after the door opening. Temperatures at the 4, 8, 12, and 18 inch heights showed a drop from the air leaving the cooler (cooled by evaporation of liquid propane). There was no effect at the 60-inch height and above.

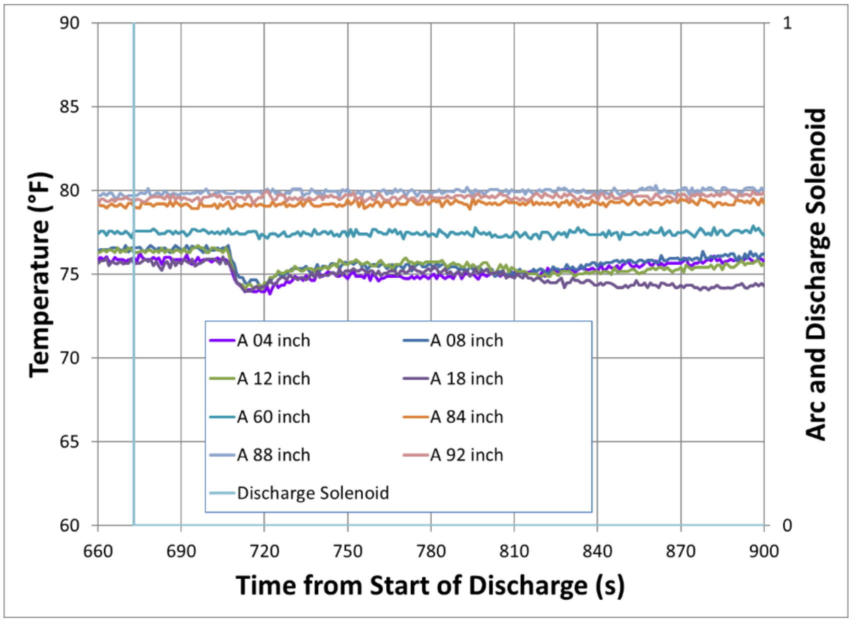


Figure 378 – RI_02 Temperature effect after door opening

Figure 379 shows similar but less intense drops in temperature as the cooled propane/air mixture migrated throughout the test room at floor level.

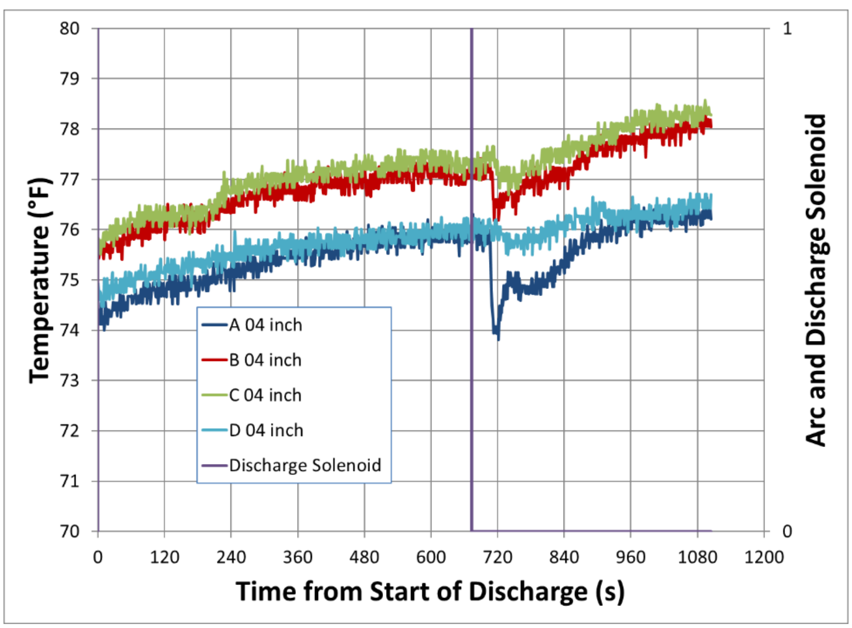


Figure 379 – RI_02: Temperatures at the 4-inch level

Figure 380 shows the mass flow rate and total mass flow. After approximately one minute flow was stabilized and maintained through the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

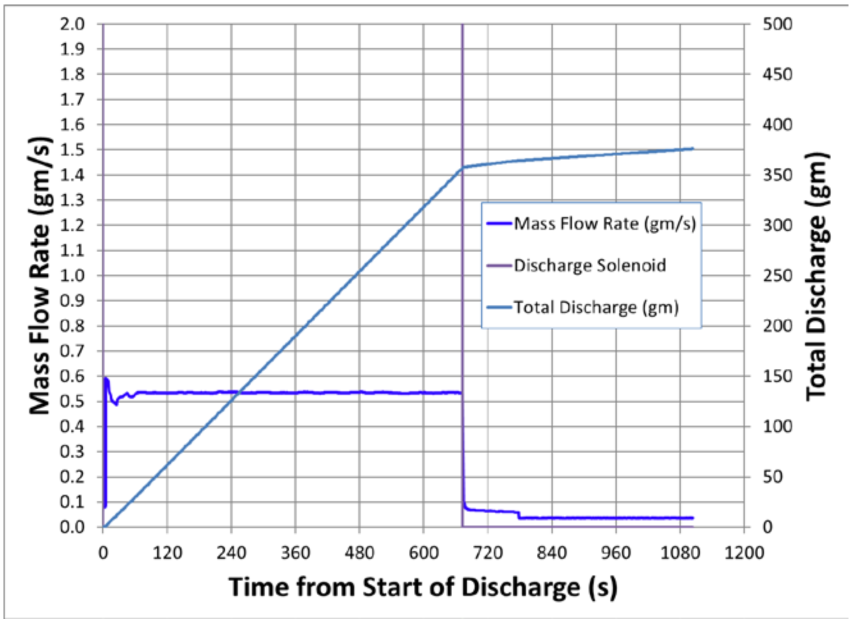


Figure 380 – RI_02 Mass Flow

Figure 381 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. The release tank pressure transmitter had failed prior to this test and was replaced prior to test RI_17. Release pressure is approximately equal to pressurizer pressure during the discharge when the two tanks are cross-connected.

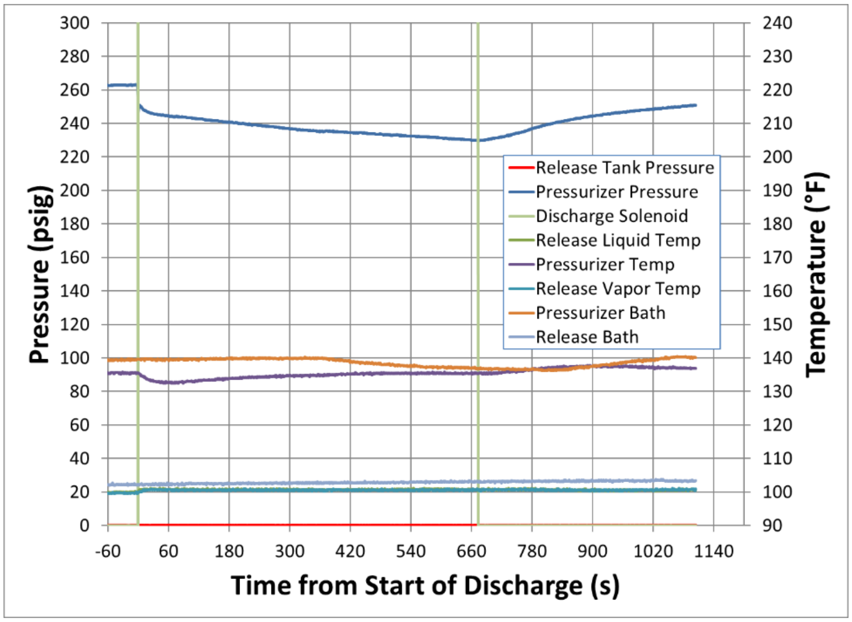


Figure 381 – RI_02 Pressurizer and Release Tank Pressure and Temperatures

Test RI_03 (3-Door Cooler; 355 gram; Internal Release; Fans on)

Test RI_03 was performed without ignition sources. The interior leak was at an evaporator return bend. The interior and exterior (condenser) fans were operating during this test. The purpose was to demonstrate the effect of the fan on propane concentration after the door was opened. The key parameters and results of this test are summarized in the following table.

Table 84 – RI_03 Summary

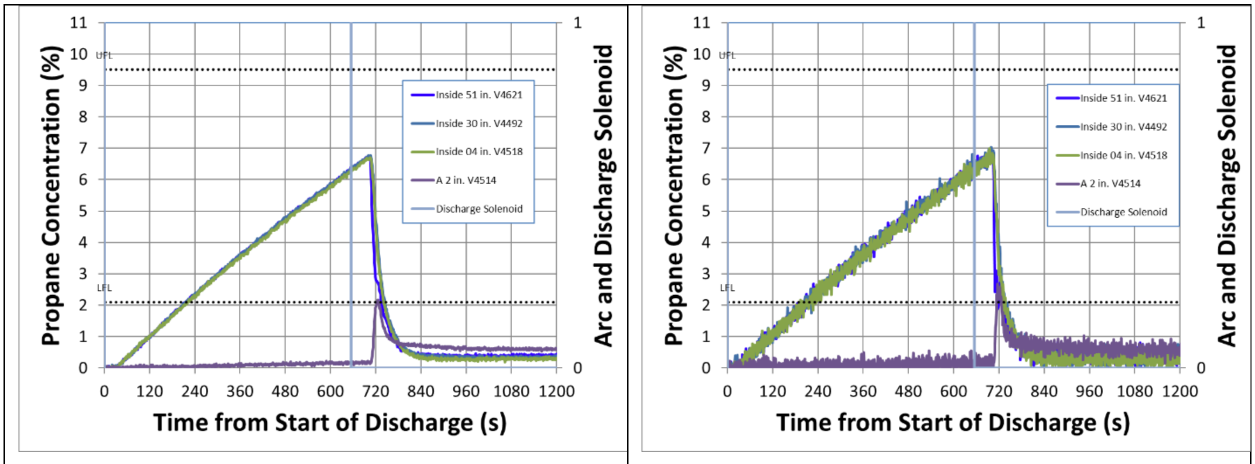
	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	355	11:10	0.530	Evaporator Return Bend	10.8 0.4	Well Mixed (Internal) Test Room
Measured	347	10:55	0.530		6.8 7.0 2.8	Internal Internal Deconvoluted Electric Arc Location

Per procedure, the discharge was stopped after 11 minutes and 10 seconds. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 382 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The action of the evaporator fans resulted in uniform mixing throughout the height of the cooler. The rate of concentration decrease after the door opened is nearly identical regardless of the height.

The concentration at the electric arc location (A 2 in.) shows a slight increase prior to the door opening, most likely due to door gasket leakage onto the floor near the cooler. This leakage accounts for the peak concentrations being less than the calculated well-mixed value. After the door is opened, the arc location increases to a value above the LFL of 2.1% and peaks at 6.5% (8.9% deconvoluted).

At the end of data recording concentrations are close to the well-mixed estimate of 0.4%.

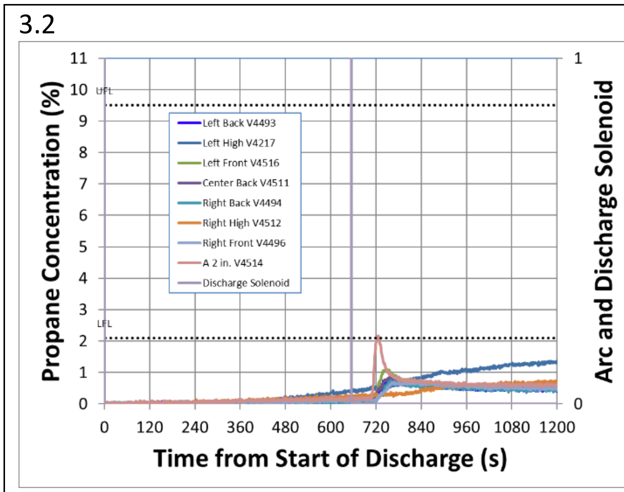


Concentrations	Deconvoluted Concentrations

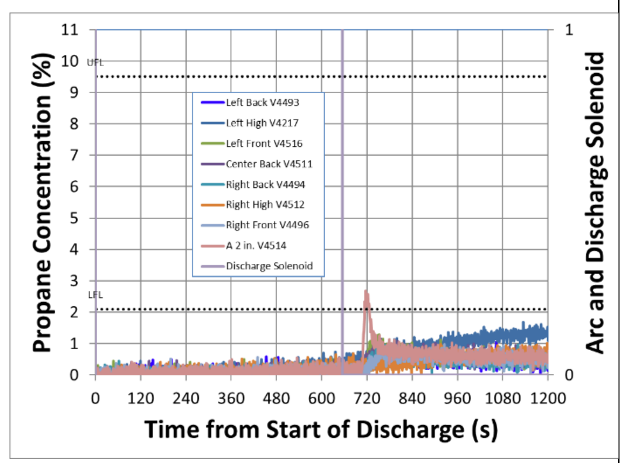
Figure 382 – RI_03 Internal Concentrations

Figure 383 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording at the 8 locations specified in by 2-89 CDV. Observations of this test include the following:

- The data show the concentration at location A 2-inches peaked at 2.8% (deconvoluted) immediately after the door was opened. No other measurement exceeded the LFL.
- Both Right-side and Left-side High sensors (externally attached to the unit) showed a steady increase in concentration from the start of the discharge to the end of data recording. Both High sensors were near incandescent lights at the ceiling level and showed steadily increasing sensor temperatures. Further investigation is needed to determine if uneven heating of the electro-chemical media contributed to this effect. All other sensors showed relatively constant temperatures.
- At the end of data recording concentrations, excepting the Left-side High sensor, are close to the well-mixed estimate of 0.4%.



Concentrations



Deconvoluted Concentrations

Figure 383 – RI_03 Concentrations

Figure 384 shows concentration measurements at other locations in the test room. There was a brief period of time (~15 seconds) when both concentrations at location A were above LFL. The concentration at location B did not exceed LFL.

At the end of data recording all three sensors settled close to the well-mixed concentration of 0.4%.

The time scale in Figure 377 has been narrowed to show the wave-like action as the high concentration propane/air mixture poured out of the cooler. The action of the condenser fan reduced the size of this effect compared to that seen in test RI_02 (Figure 377).

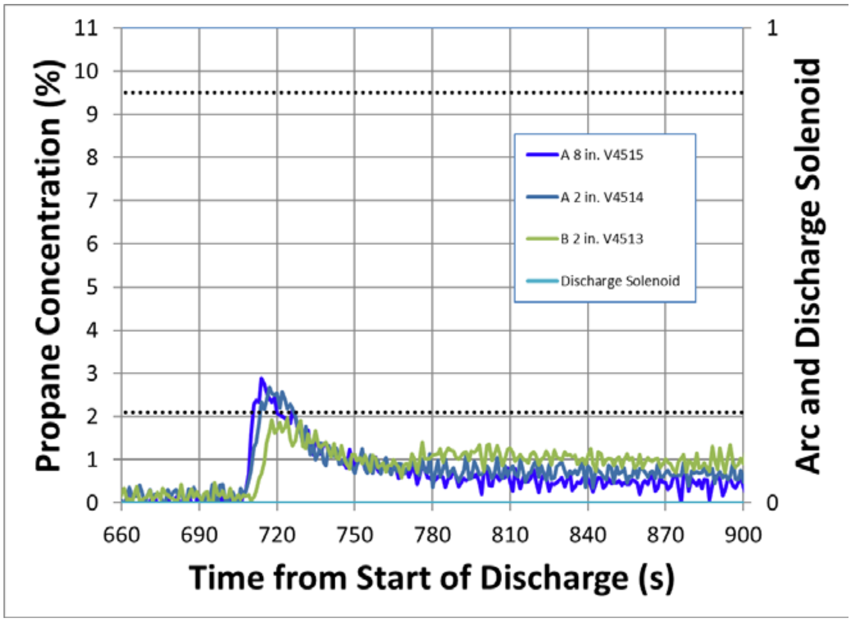


Figure 384 – RI_03 Other Concentrations

Figure 385 shows the change in temperature at location A after the door opening. Temperatures at the 4, 8, 12, 18 and 60 inch heights showed a drop from the air leaving the cooler (cooled by evaporation of liquid propane). These temperatures started increasing and the higher elevations started decreasing indicating the mixing action of the fans.

This effect was not observed at the other locations (B, C, and D).

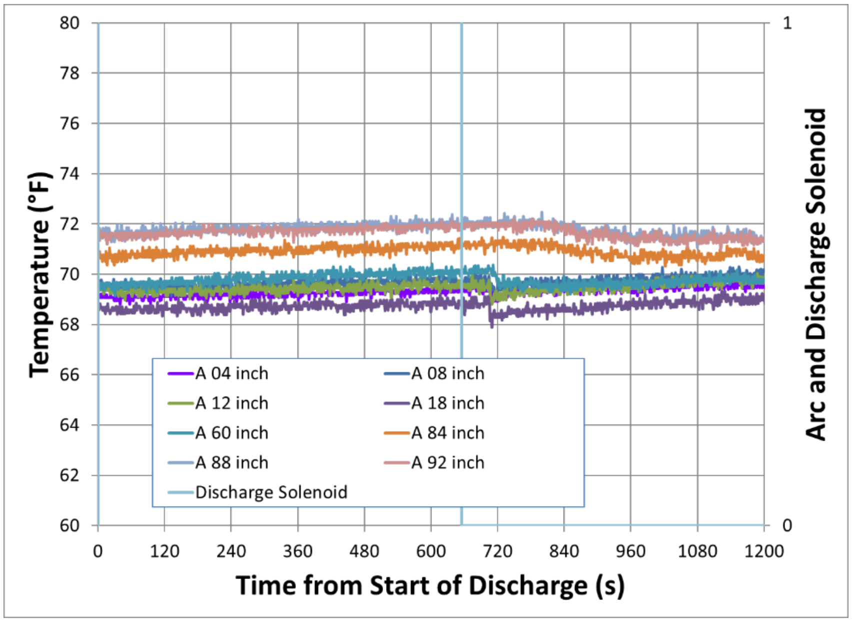


Figure 385 – RI_03 Temperature effect after door opening

Figure 387 shows the mass flow rate and total mass flow. After approximately one minute flow was stabilized and maintained through the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

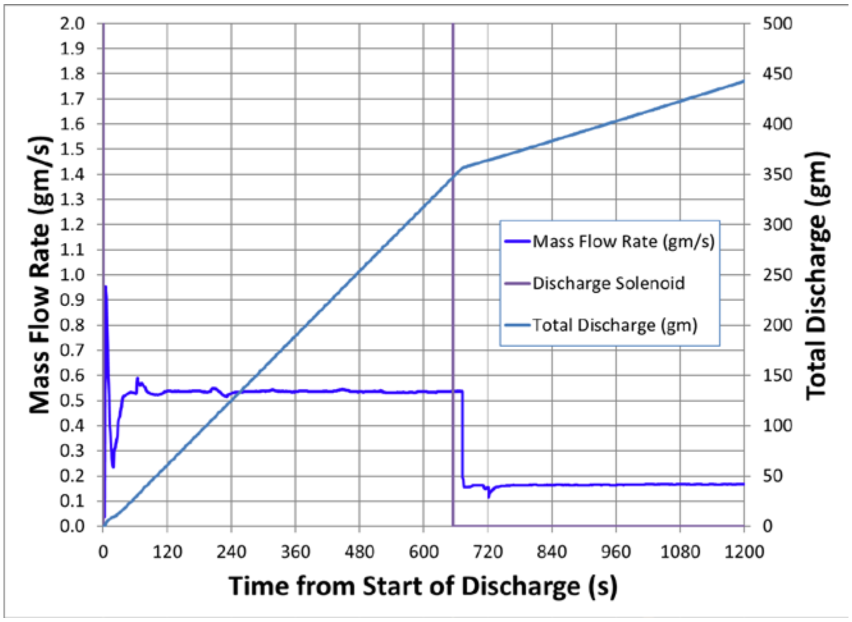


Figure 386 – RI_03 Mass Flow

Figure 387 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. The release tank pressure transmitter had failed prior to this test and was replaced prior to test RI_17. Release pressure is approximately equal to pressurizer pressure during the discharge when the two tanks are cross-connected.

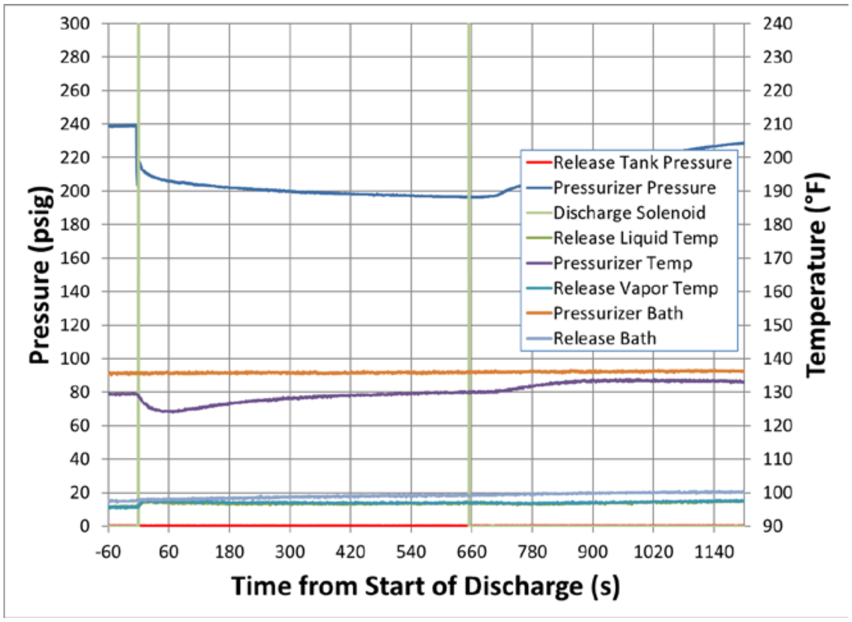


Figure 387 – RI_03 Pressurizer and Release Tank Pressure and Temperatures

Test RI_04 (3-Door Cooler; 71 gram; Internal Release)

Test RI_04 was performed without ignition sources in order to measure propane concentrations prior to the conduct of an ignition test. The key parameters and results of this test are summarized in the following table.

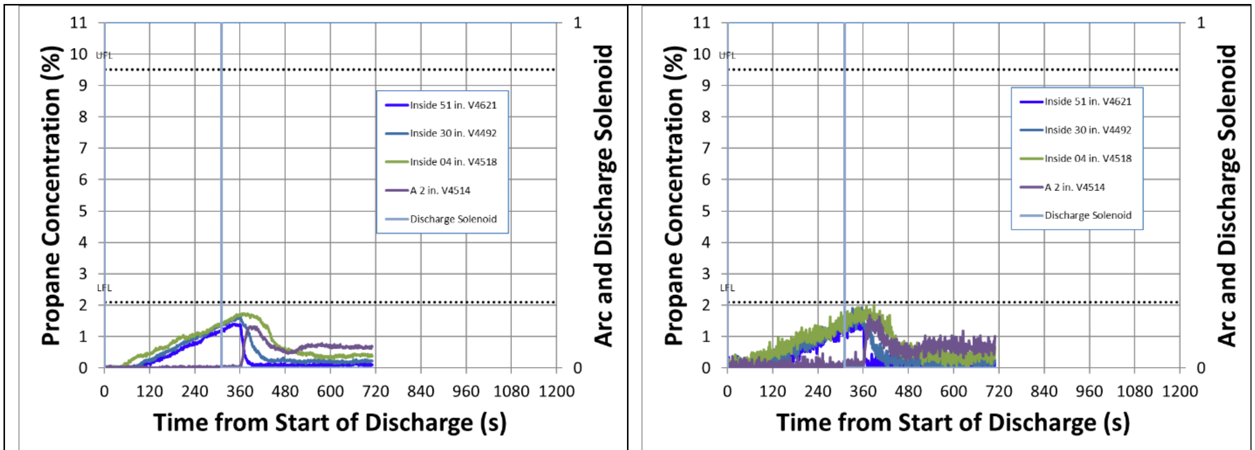
Table 85 – RI_04 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	71	5:17	0.224	Evaporator Return Bend	2.1	Well Mixed (Internal)
Measured	71	5:12	0.227		1.7	Internal
					2.0	Internal Deconvoluted
					1.6	Electric Arc Location

Per procedure, all doors of the cooler remained closed for 30 seconds after completion of the release. The center door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2 minutes following the door opening.

Figure 388 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 51 inches. As the door opens the sensor at 51 inches decreases the fastest, followed by the 30 inch level, while the 4 inch sensor decreased at the slowest rate.

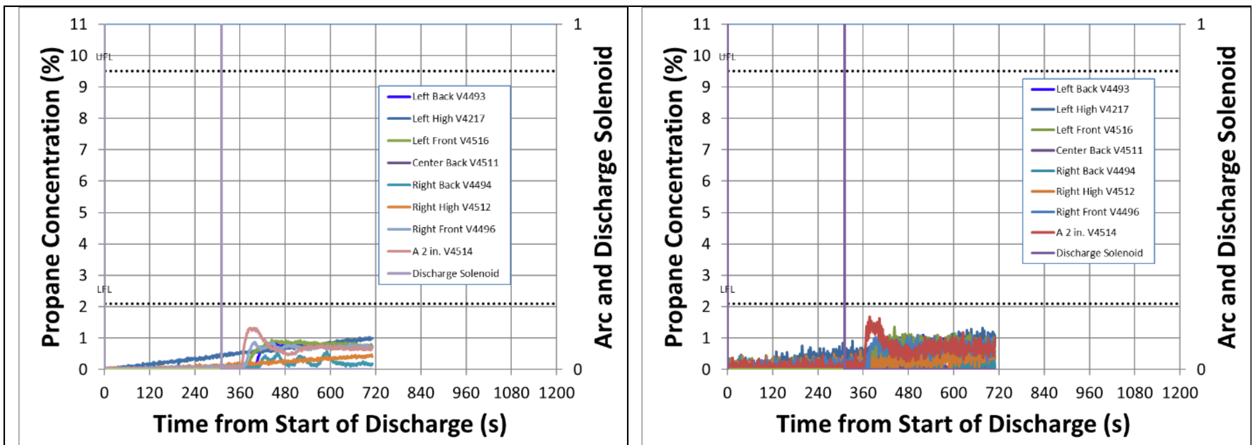
After the door is opened, the sensor at the electric arc location (A 2 in.) increases to a value of 1.7%, slightly below the LFL of 2.1%.



Concentrations	Deconvoluted Concentrations

Figure 388 – RI_04 Concentrations

Figure 389 shows the measured concentrations at the eight locations specified by 2-89 CDV. Similar to the effect noted in test RI_02, the trend in the Left High and Right High sensor is an effect of uneven heating of the sensor media due to a nearby incandescent light.



Concentrations	Deconvoluted Concentrations

Figure 389 – RI_04 Concentrations at 8 locations surrounding cooler

Figure 390 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to integrate the total mass release.

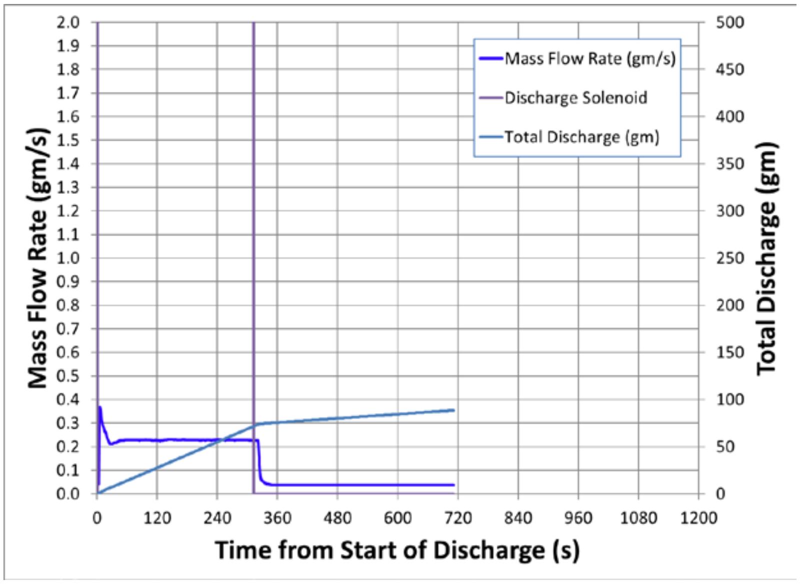


Figure 390 – RI_04 Mass Flow

Figure 391 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced prior to test RI_17. Release pressure is approximately equal to pressurizer pressure during the discharge when the two tanks are cross-connected.

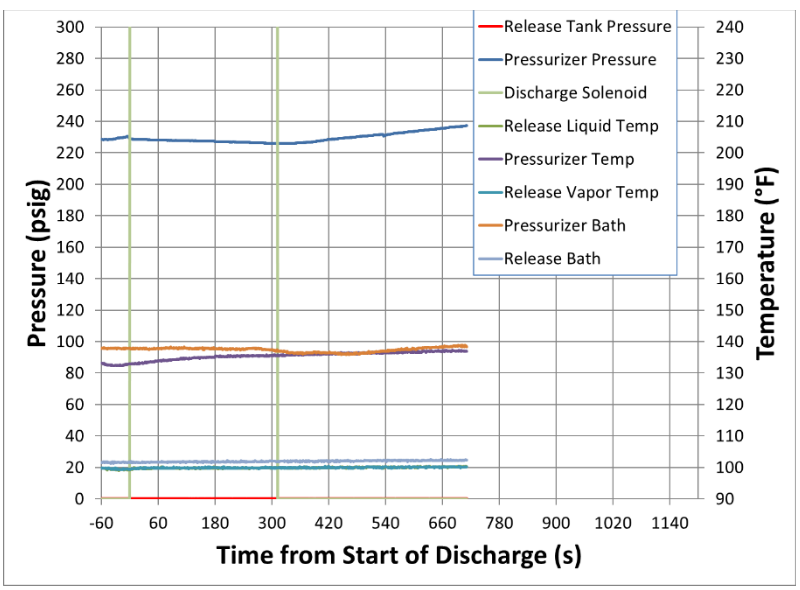


Figure 391 – RI_04 Pressurizer and Release Tank Pressure and Temperatures

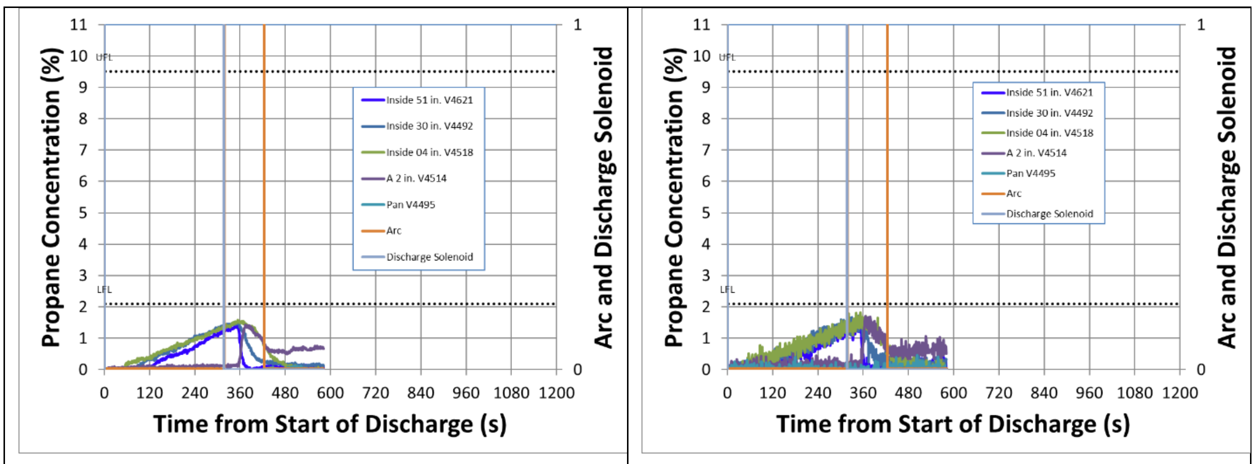
Test RI_05 (3-Door Cooler; 71 gram; Internal Release, with Arc Igniters)

Test RI_05 was performed with ignition sources. There was some flaring observed at the electric arc in location A, but no ignition of a volume of propane-air mixture above the LFL. The key parameters and results of this test are summarized in the following table.

Table 86 – RI_05 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	71	5:17	0.224	Evaporator Return Bend
~~Measured~~	72	5:17	0.229	

Figure 392 shows the concentrations measured in the cabinet interior and the sensor at location A, 2-inch level. There is no indication that combustion interfered with concentration measurement.



Concentrations	Deconvoluted Concentrations

Figure 392 – RI_05 Concentrations

Figure 393 shows the measured concentrations at the eight locations specified by 2-89 CDV. No sensor recorded a concentration above the LFL.

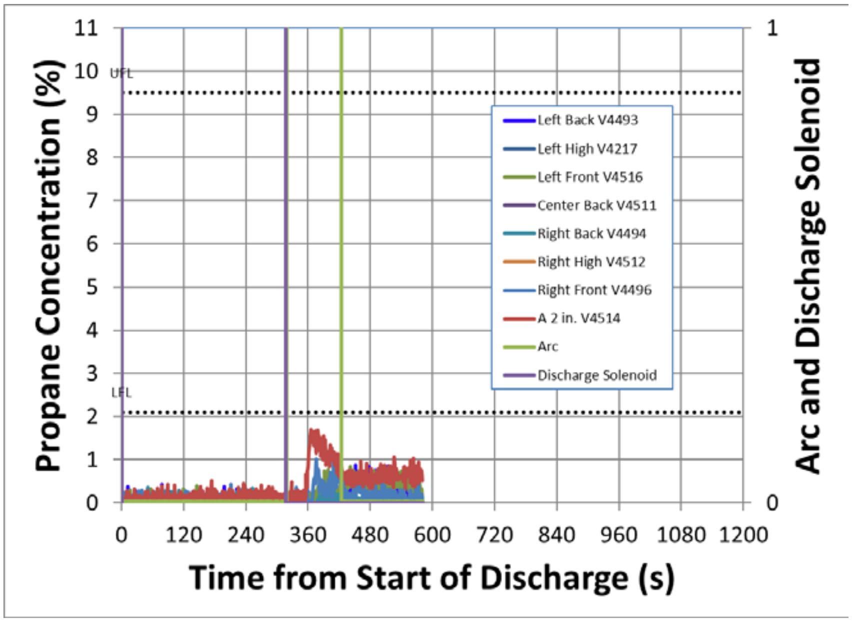


Figure 393 – RI_05 Concentrations at 8 locations surrounding cooler

Figure 394 compares the concentrations at the interior sensor (4 inch level) in tests RI_04 and RI_05 to show that concentrations were similar to within a few tenths of a percent.

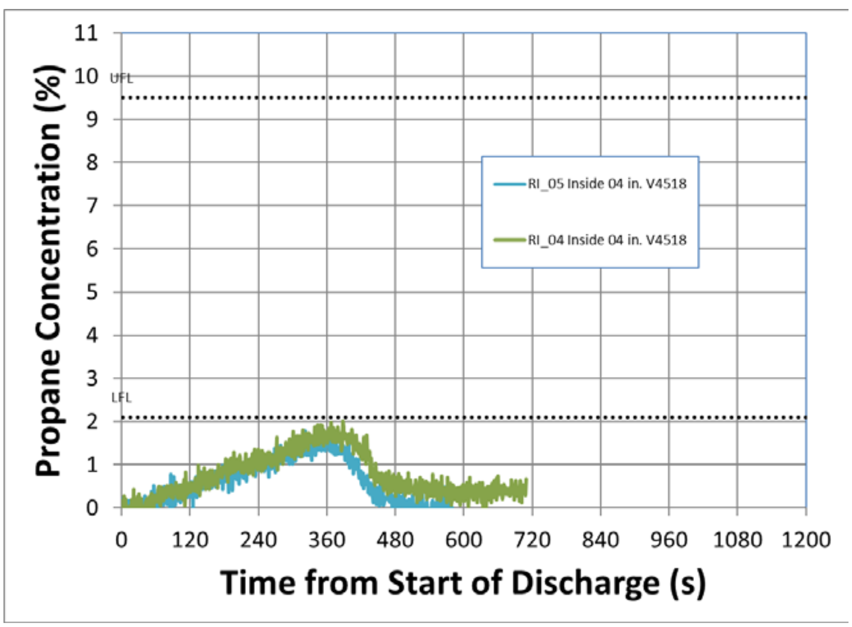


Figure 394 – RI_05 to RI_04 Concentration Comparison

Figure 395 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

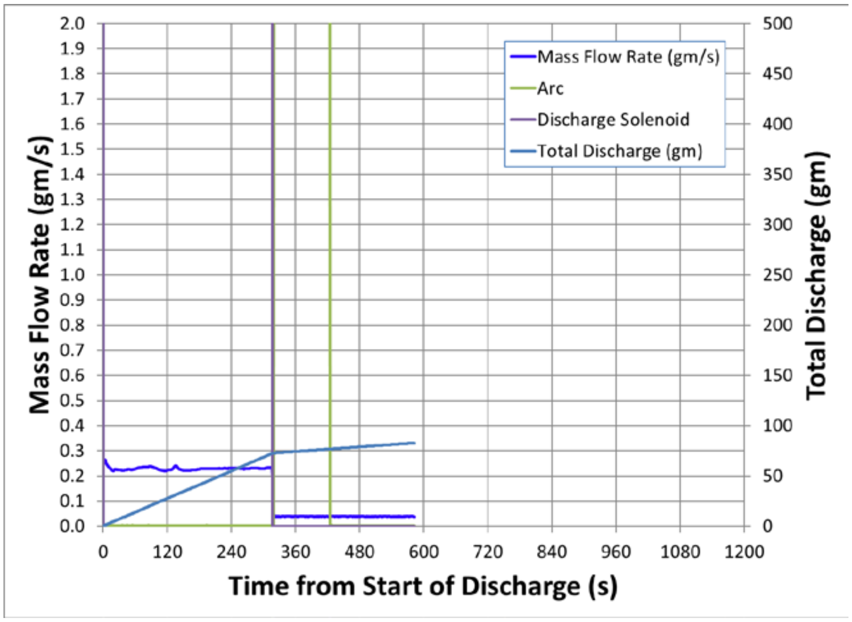


Figure 395 – RI_05 Mass Flow

Figure 396 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

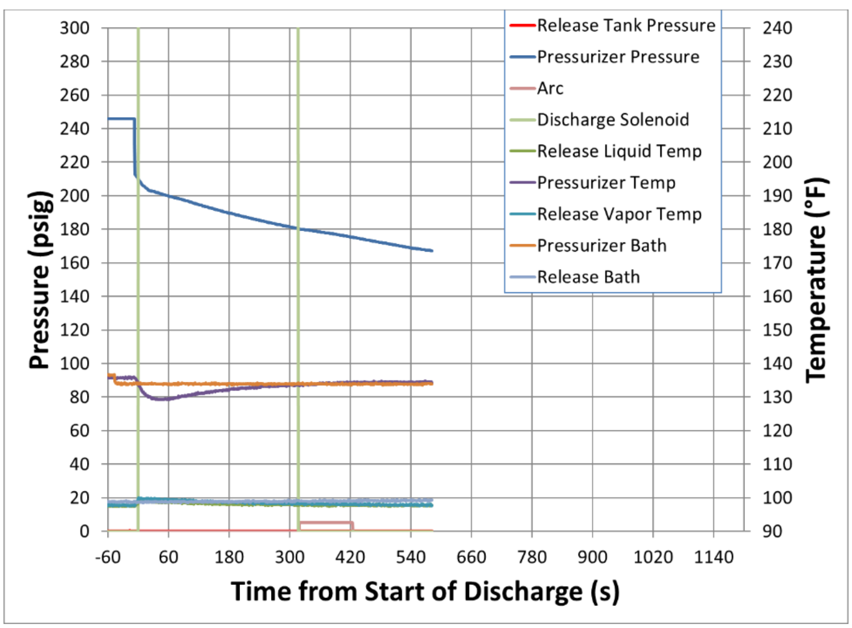


Figure 396 – RI_05 Pressurizer and Release Tank Pressure and Temperatures

Figure 397 shows the temperatures developed at the location A following energizing the electric arcs. There were notable temperature increases at the 18-inch level and below due to the flaring at the arc. Locations B,C, and D did not show any increases in temperature.

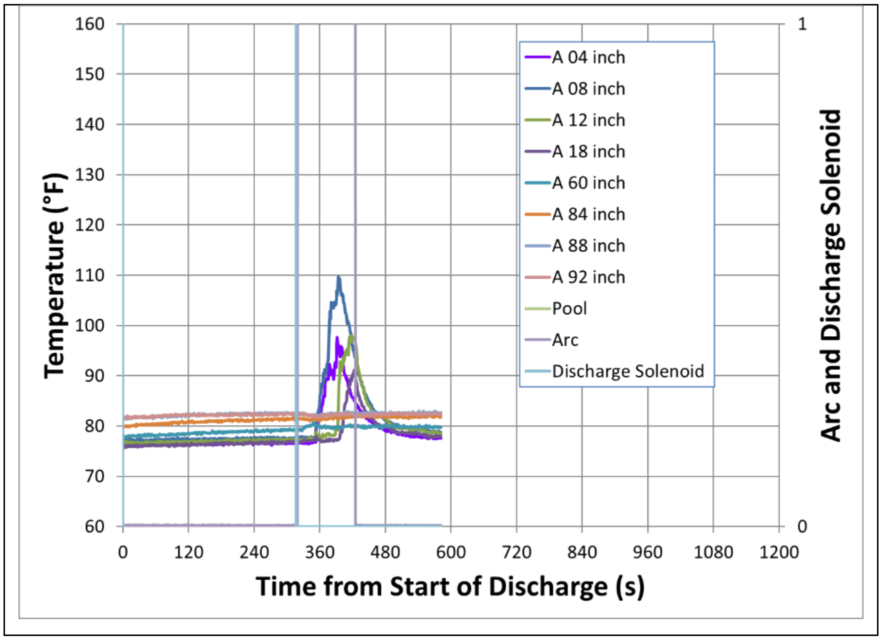


Figure 397 – RI_05 Temperatures at Location A

The infrared camera captured flaring at the electric arc as shown in Figure 398. This effect was not visible in the other cameras except as a disturbance in the shape of the electric arc.

Figure 398 – RI_05 Small flaring at the location A electric arc.

Test RI_06 (3-Door Cooler; 92 gram; Internal Release, with Arc Igniters)

Test RI_06 was performed with ignition sources and resulted in ignition at the arc location. The key parameters and results of this test are summarized in the following table.

Table 87 – RI_06 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	92	6:51	0.224	Evaporator Return Bend
Measured	96	6:52	0.234	

Figure 399 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration. The combustion event was small and did not cause an effect on the oxygen sensors.

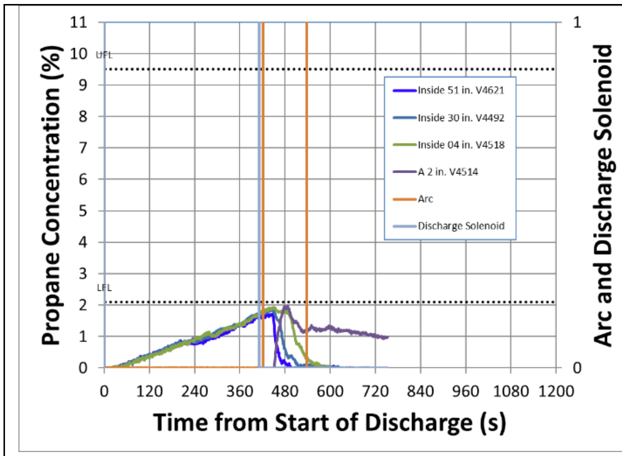
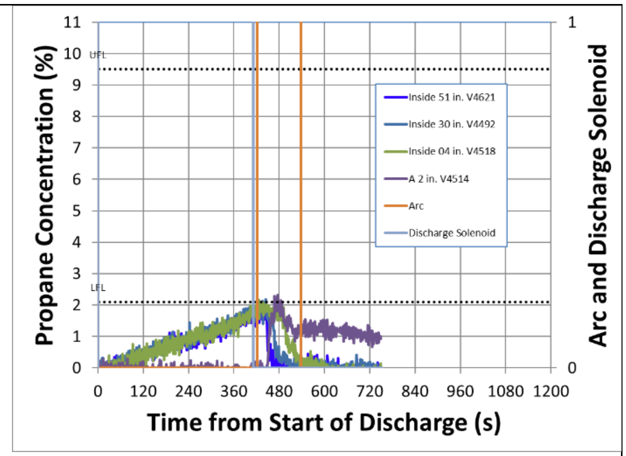
	
Concentrations	Deconvoluted Concentrations

Figure 399 – RI_06 Concentrations

Figure 400 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

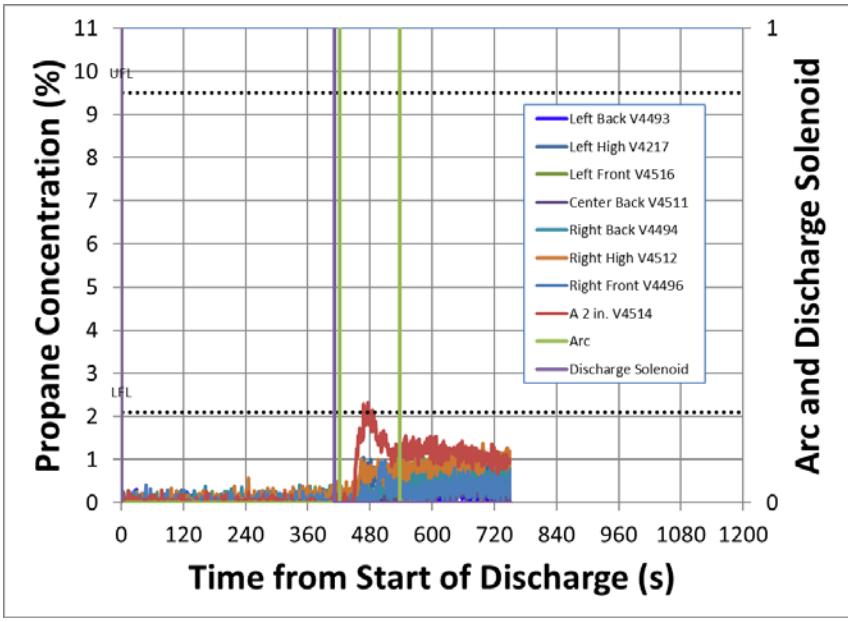


Figure 400 – RI_06 Concentrations at 8 locations surrounding cooler

Figure 401 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

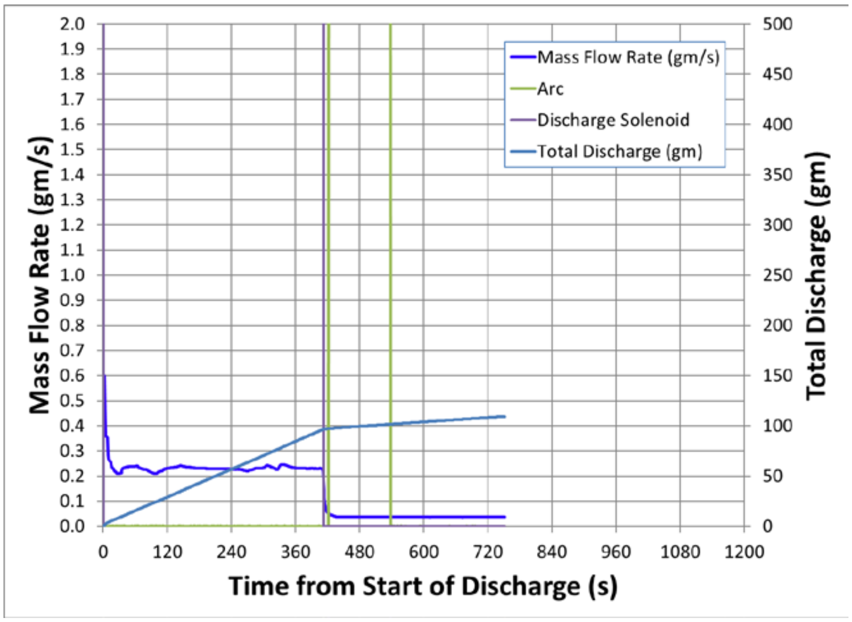


Figure 401 – RI_06 Mass Flow

Figure 402 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

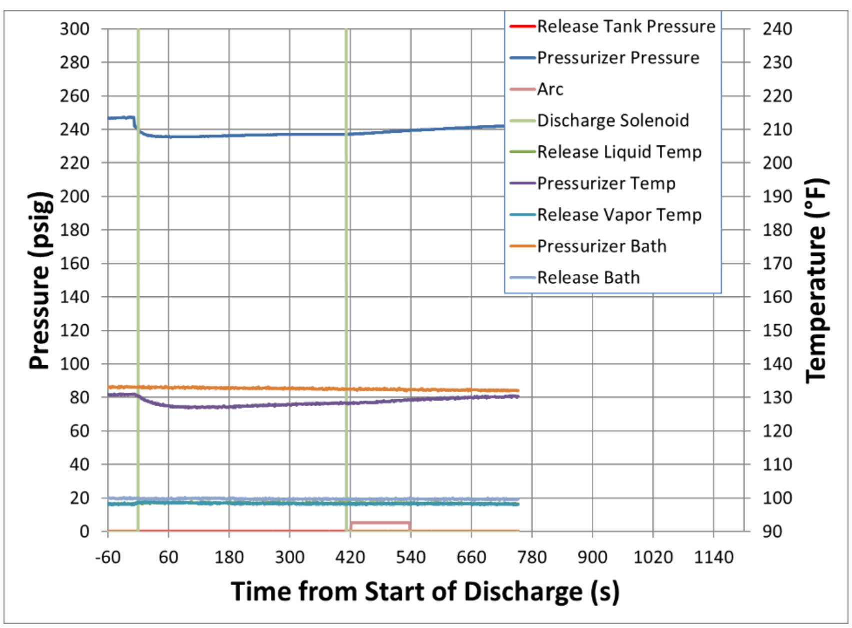


Figure 402 – RI_06 Pressurizer and Release Tank Pressure and Temperatures

Figure 403 shows the temperatures developed at the various locations following ignition. The data shows the highest temperature at location A with very small temperature increases at locations B, C, and D. The data at location A shows three spikes in temperature which conforms with the video evidence of three separate ignition events separated by several seconds.

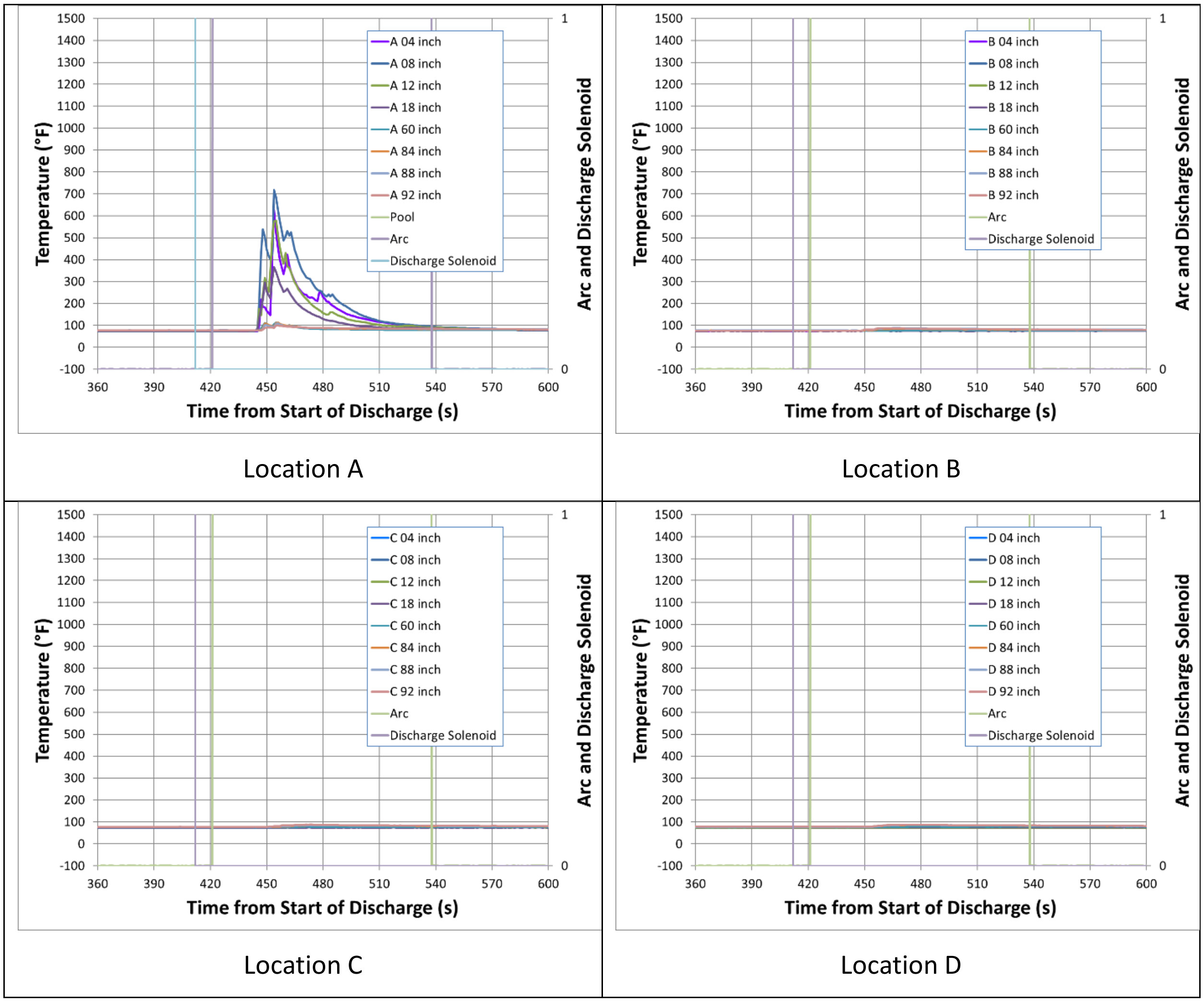


Figure 403 – RI_06 Temperatures at Locations A, B, C, and D

There were three separate ignitions in this test. None of these flares were easily visible in the color camera views. Figure 404 captures three frames in the infrared camera. The time stamps show the second flare occurred six seconds after the first, while the third flare was eight seconds after the second. There was no sustained flaming of a volume of gas between these frames.

It appears opening the cooler door released a volume of a flammable mixture, but flames were not large enough to travel back into the cooler. The turbulence of the flame swept away any ignitable mixture near the electric arcs. The process repeated twice as the cooler continued to spill out a flammable mixture toward the electric arcs.

Figure 404 – RI_06 Three separate ignitions visible in infrared, separated by a few seconds

Test RI_07 (3-Door Cooler; 114 gram; Internal Release)

Test RI_07 was performed without ignition sources in order to measure propane concentrations prior to the igniter test, RI_08 and RI_09. The key parameters and results of this test are summarized in the following table.

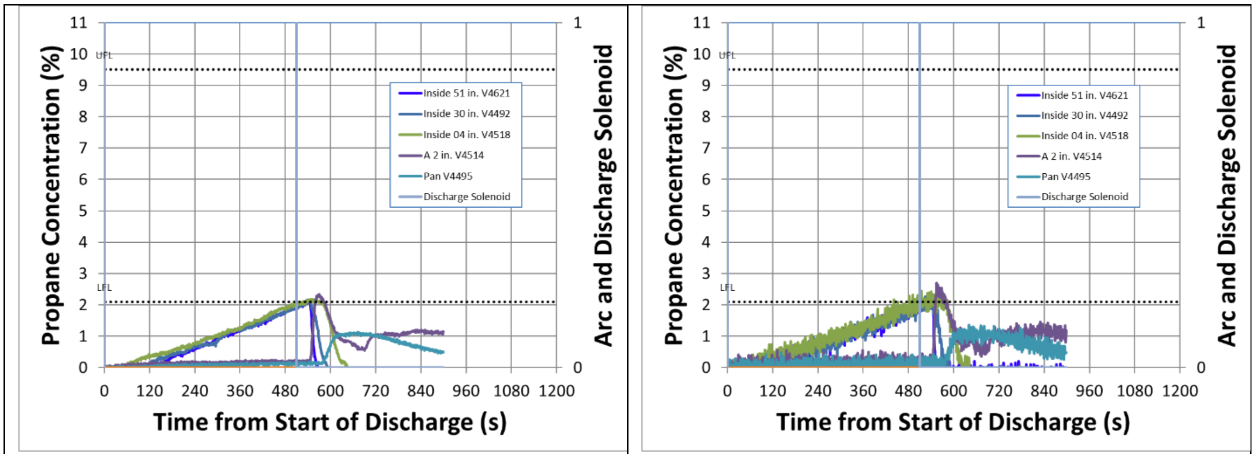
Table 88 – RI_07 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	114	8:29	0.224	Evaporator Return Bend	3.4 0.1	Well Mixed (Internal) Well Mixed (Whole Room)
Measured	116	8:30	0.227		2.3 2.7 2.7	Internal Internal Deconvoluted Electric Arc Location

Per procedure, all doors of the cooler remained closed for 30 seconds after completion of the release. The center door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2 minutes following the door opening.

Figure 405 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 51 inches. As the door opens the sensor at 51 inches decreases the fastest, followed by the 30 inch level, while the 4 inch sensor decreased at the slowest rate.

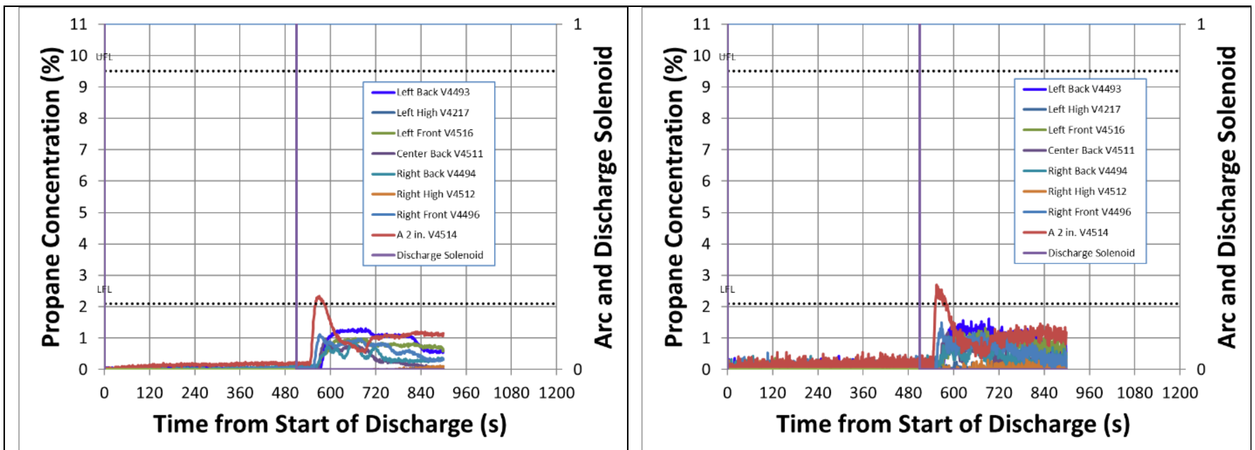
After the door is opened, the sensor at the electric arc location (A 2 in.) increases to a value of 2.7%, slightly above the LFL of 2.1%.



Concentrations	Deconvoluted Concentrations

Figure 405 – RI_07 Concentrations

Figure 406 shows the measured concentrations at the eight locations specified by 2-89 CDV. At the end of data recording the concentrations at the floor level sensors have stabilized to values above the well-mixed value (whole room) of 0.1%.



Concentrations	Deconvoluted Concentrations

Figure 406 – RI_07 Concentrations at 8 locations surrounding cooler

~~Figure 407~~ shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to integrate the total mass release.

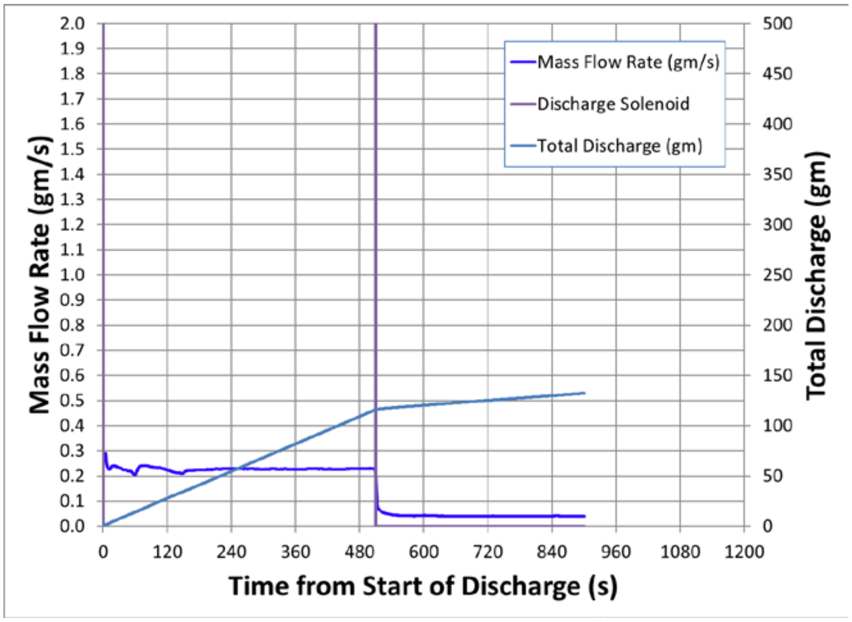


Figure 407 – RI_07 Mass Flow

Figure 408 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced prior to test RI_17. Release pressure is approximately equal to pressurizer pressure during the discharge when the two tanks are cross-connected.

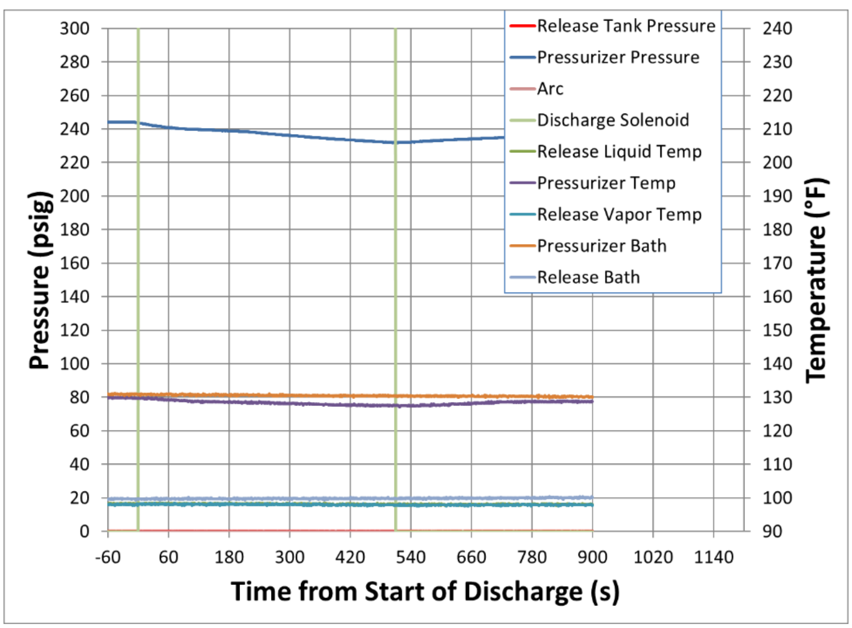


Figure 408 – RI_07 Pressurizer and Release Tank Pressure and Temperatures

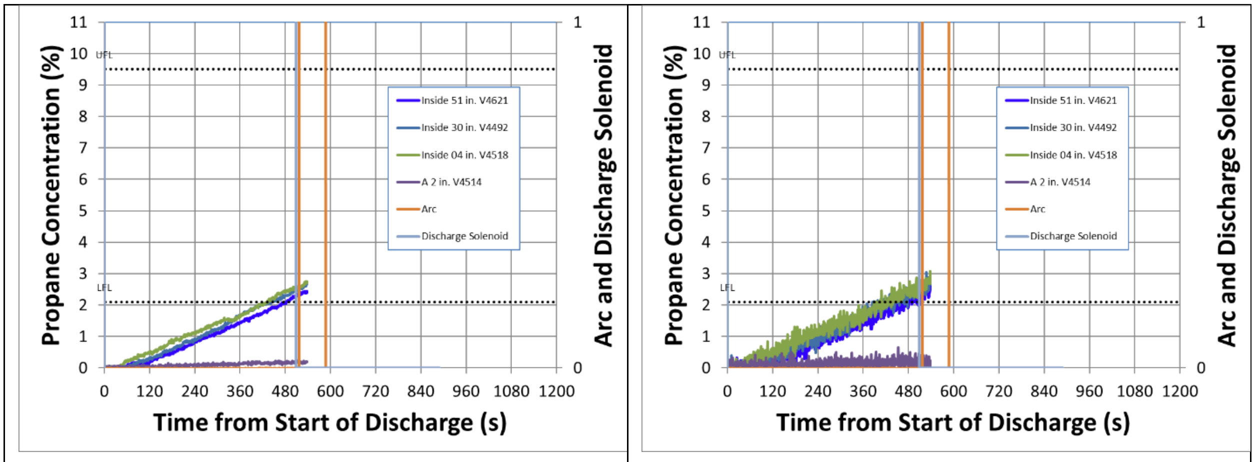
Test RI_08 (3-Door Cooler; 114 gram; Internal Release, with Arc Igniters)

Test RI_08 was performed with ignition sources and resulted in ignition at the arc location. The key parameters and results of this test are summarized in the following table.

Table 89 – RI_08 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	114	8:29	0.224	Evaporator Return Bend
Measured	115	8:29	0.227	

Figure 455 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations	Deconvoluted Concentrations

Figure 409 – RI_08 Concentrations

Figure 456 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets. This data is similar to that obtained in test RI_07 (see Figure 406).

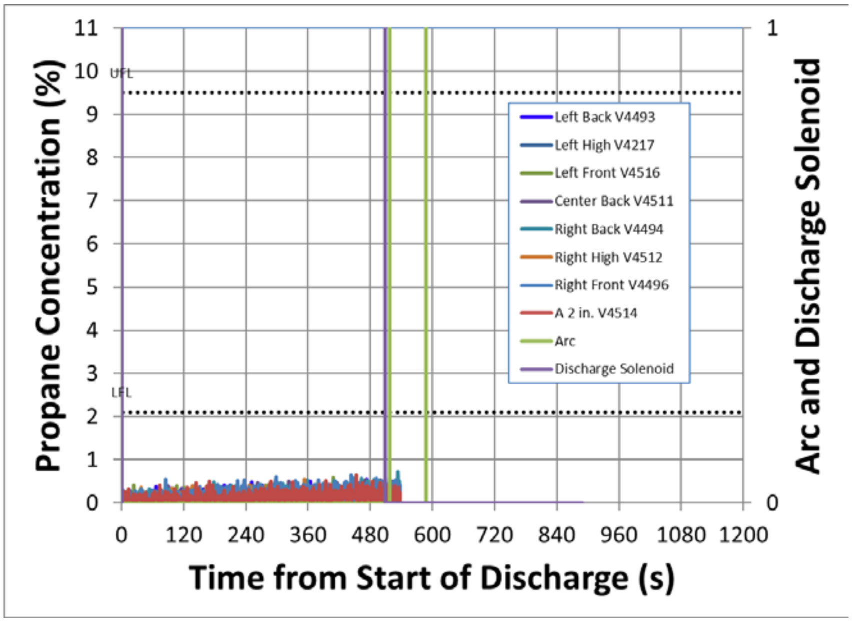


Figure 410 – RI_08 Concentrations at 8 locations surrounding cooler

Figure 411 compares the concentrations at the interior sensor (4 inch level) in tests RI_07 and RI_08 to show that concentrations were similar to within a few tenths of a percent.

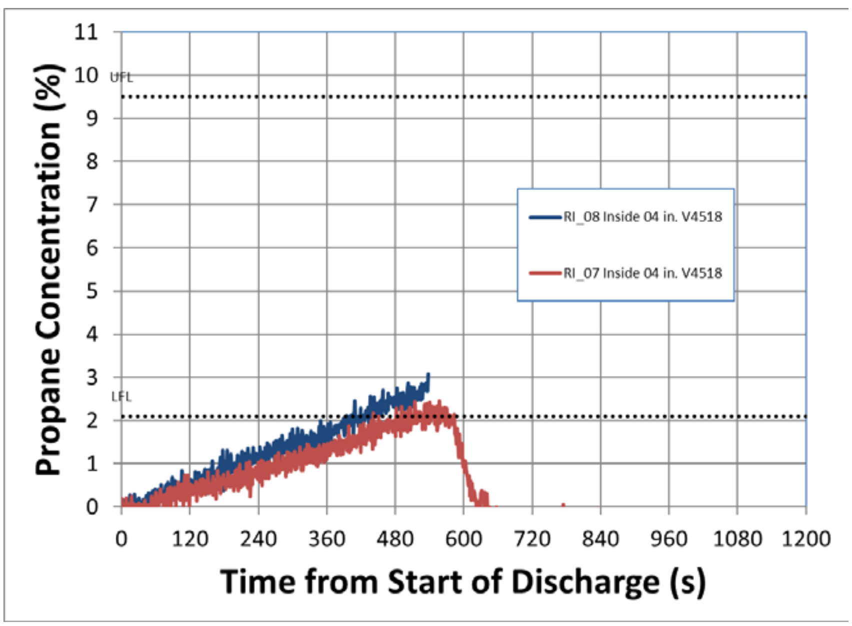


Figure 411 – RI_08 to RI_07 Concentration Comparison

Figure 412 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

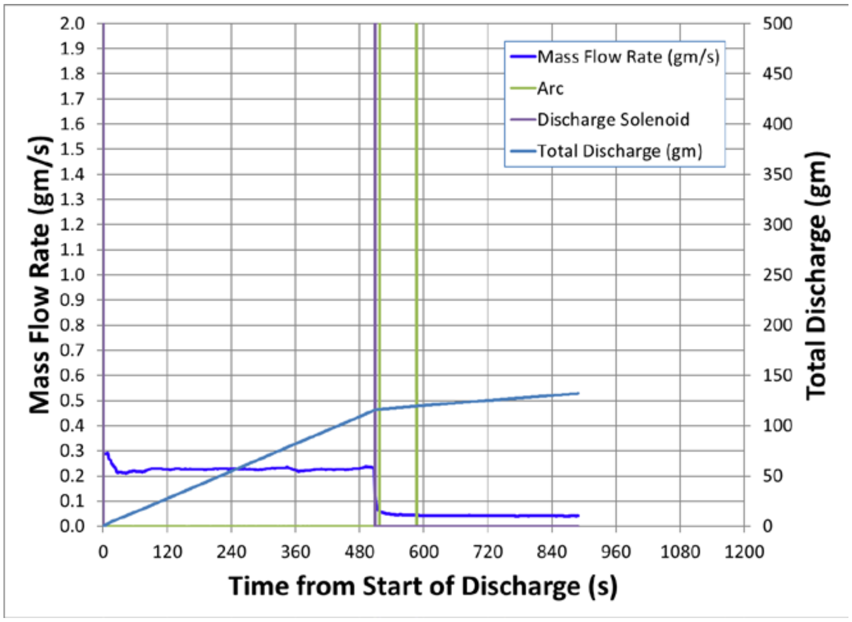


Figure 412 – RI_08 Mass Flow

Figure 413 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

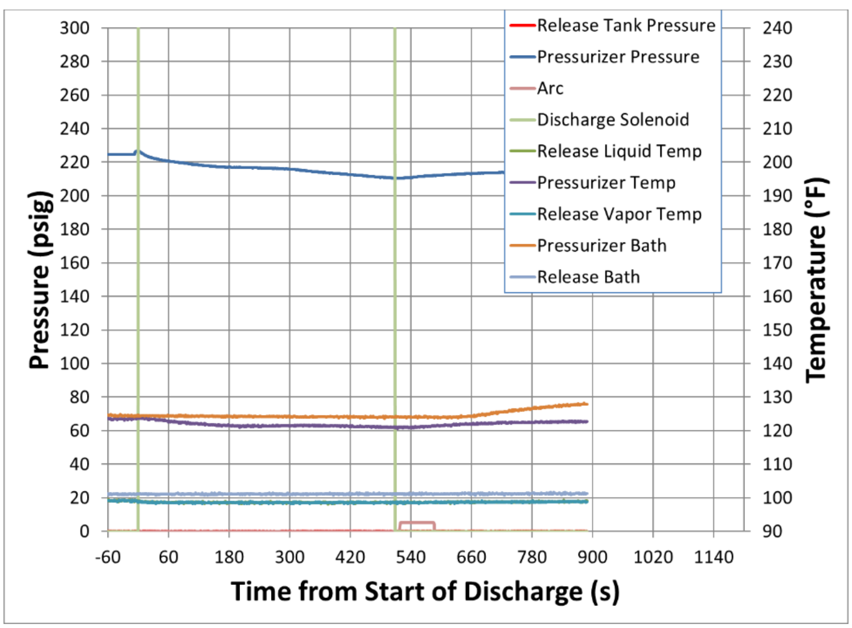


Figure 413 – RI_08 Pressurizer and Release Tank Pressure and Temperatures

Figure 414 shows the temperatures developed at the various locations following ignition. The data shows the highest temperature at location A at the 88 inch level near the ceiling. The temperatures at locations B, C, and D were much lower and confined to levels about 60 inches.

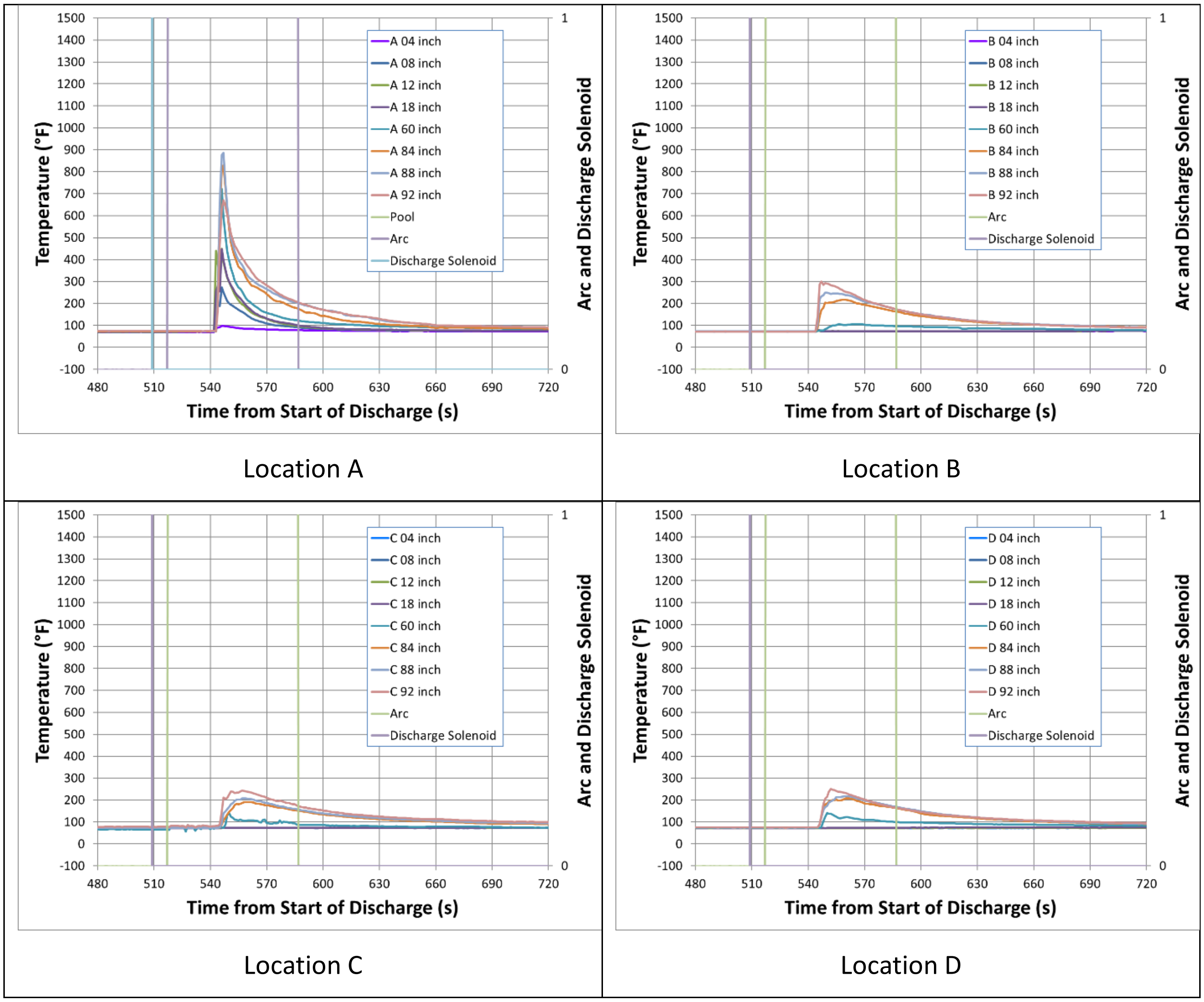


Figure 414 – RI_08 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 4 seconds. The pressure was sufficient to cause 1 of 6 deflagration vents to open another vent melted from the hot gas layer. The east side vents were shuttered during this test since a large deflagration was not expected.

The flames were almost entirely pre-mixed and blue in color. Figure 415 left-side shows the faint blue flame. The right side frame shows the fireball inside the cooler when the flames reached up to the level of the drip tray, just below the location (hidden) of the discharge capillary tube. After the fireball, pre-mixed flaming continued for another 2 seconds.

Figure 415 – RI_08 Ignition (left) and small fireball (right).

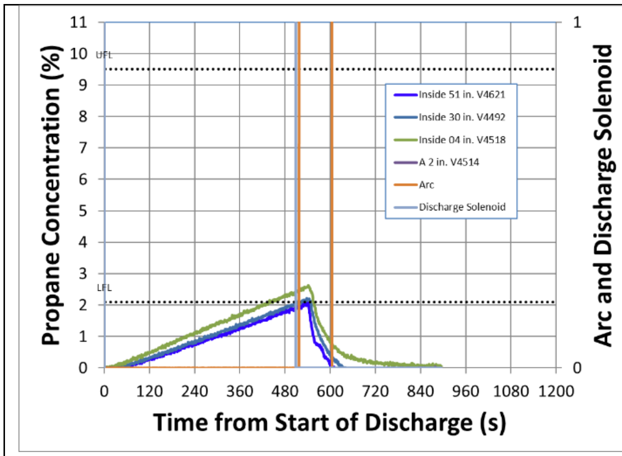
Test RI_09 (3-Door Cooler; 114 gram; Internal Release, with Arc Igniters)

Test RI_09 used similar parameters as test RI_08 with the exception that the evaporator and condenser fans and internal lighting were energized throughout the test. There was no ignition in this test. The key parameters and results of this test are summarized in the following table.

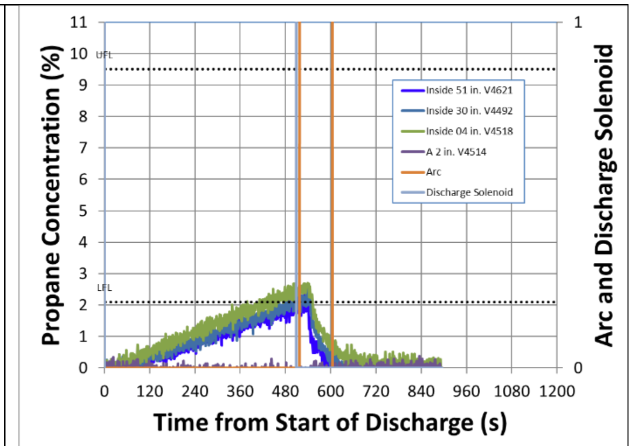
Table 90 – RI_09 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	114	8:29	0.224	Evaporator Return Bend
Measured	117	8:29	0.232	

Figure 416 shows the concentrations measured up to the end of data recording. The sensor at location A, 2-inch level did not measure a significant increase after the cooler door was opened. This shows that the action of the fans acted to quickly disperse concentrations from inside the cooler. Concentrations at all other sensors were less than LFL.



Concentrations



Deconvoluted Concentrations

Figure 416 – RI_09 Concentrations

Figure 417 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

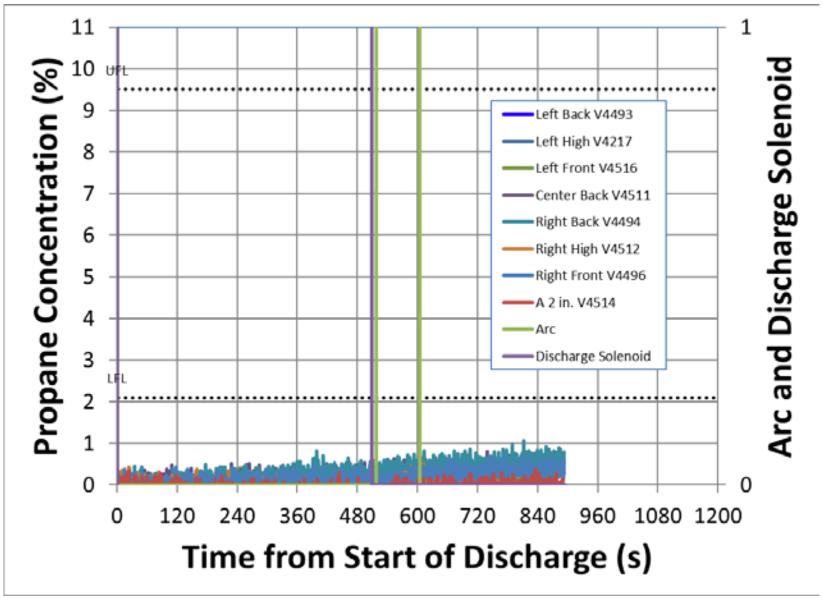


Figure 417 – RI_09 Concentrations at 8 locations surrounding cooler

Figure 418 compares the concentrations at the interior sensor (4 inch level) in tests RI_07 and RI_09 to show that concentrations were similar to within a few tenths of a percent. The significant difference is the rate of fall of concentration after the door is opened. RI_09 starts dropping immediately due to the action of the fans. In test RI_07, there is a delay before concentration begins to fall. This delay in RI_07 is due to emptying the propane-air mixture from the top down without much mixing. In test RI_09 there is mixing and dilution of the cooler contents as it is emptying.

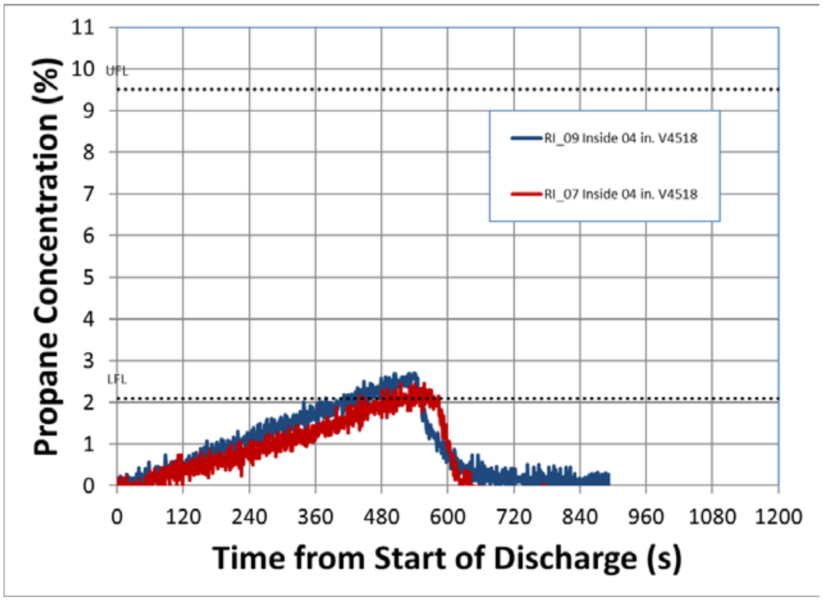


Figure 418 – RI_09 to RI_07 Concentration Comparison

Figure 419 compares the concentrations measured at the front, right and left locations at the cooler. Both these sensor are mounted 2 inches above the floor. The concentrations from RI_07 are larger than those in RI_09 showing that either the condenser fan, evaporator fans, or both have caused a reduction in the concentration spilling from the cooler's open door.

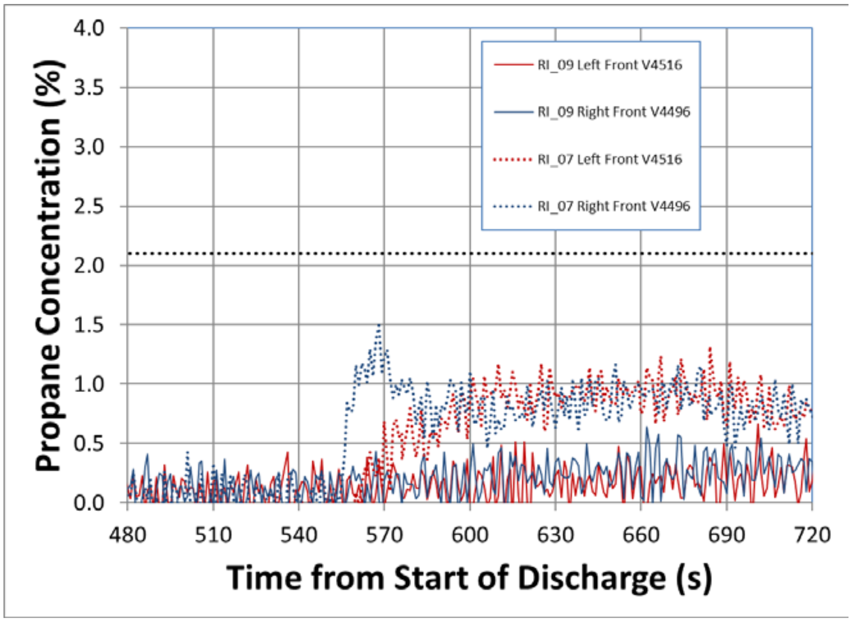


Figure 419 – RI_09 vs. RI_07 front concentration comparison

Figure 420 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

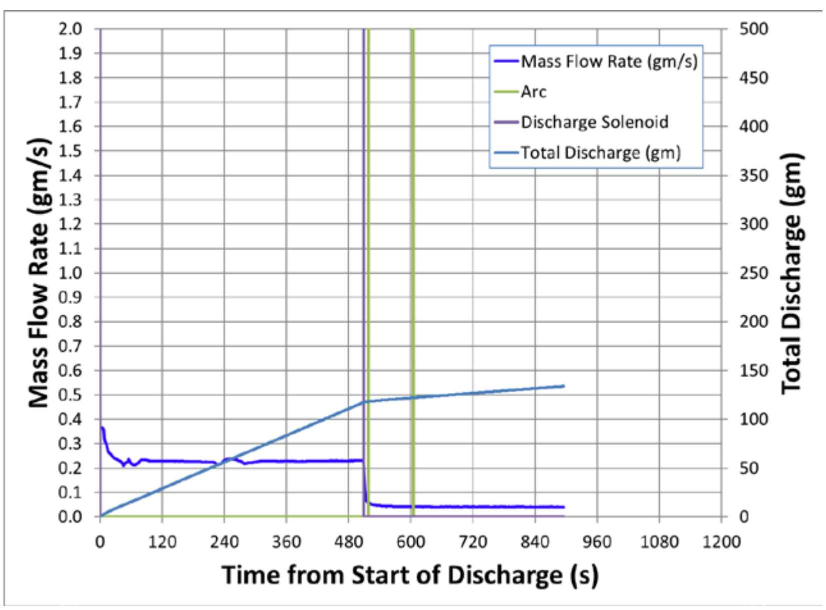


Figure 420 – RI_09 Mass Flow

Figure 421 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

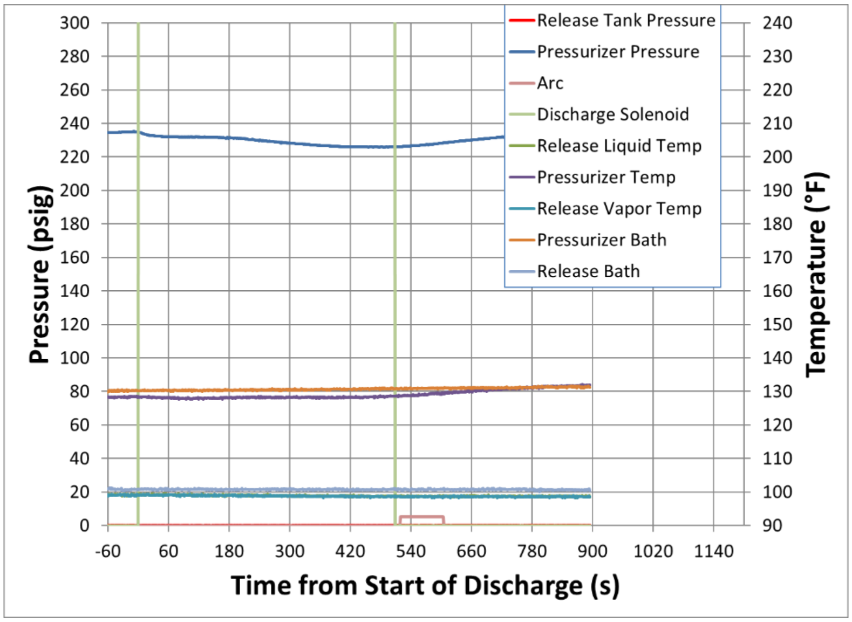


Figure 421 – RI_09 Pressurizer and Release Tank Pressure and Temperatures

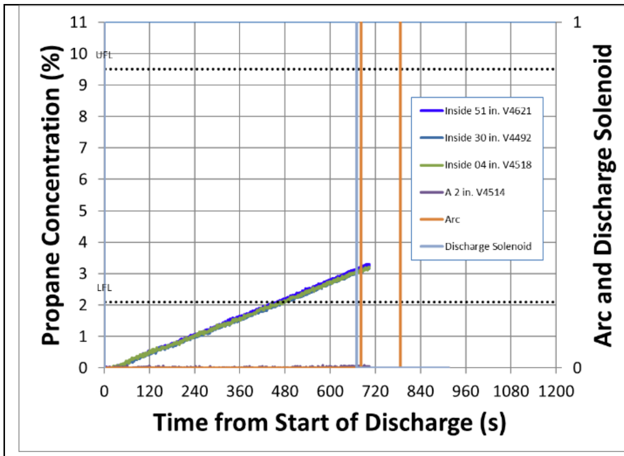
Test RI_10 (3-Door Cooler; 150 gram; Internal Release, with Arc Igniters)

Test RI_10 was performed with ignition sources and resulted in ignition at the arc location. The key parameters and results of this test are summarized in the following table.

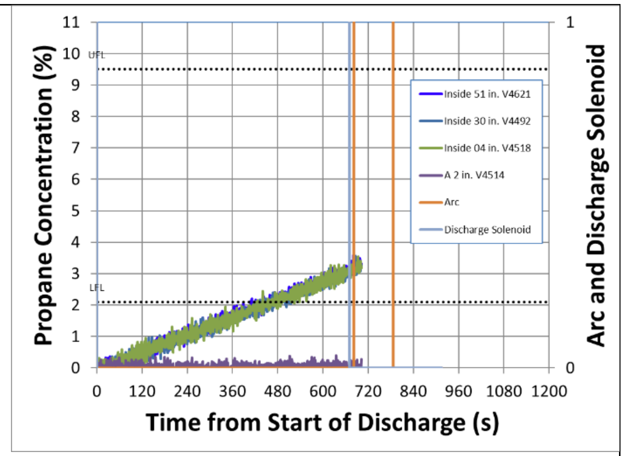
Table 91 – RI_10 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	150	11:10	0.224	Evaporator Return Bend
Measured	157	11:10	0.235	

Figure 422 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations



Deconvoluted Concentrations

Figure 422 – RI_10 Concentrations

Figure 423 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets. This data is similar to that obtained in test RI_01 (see Figure 376).

4.4

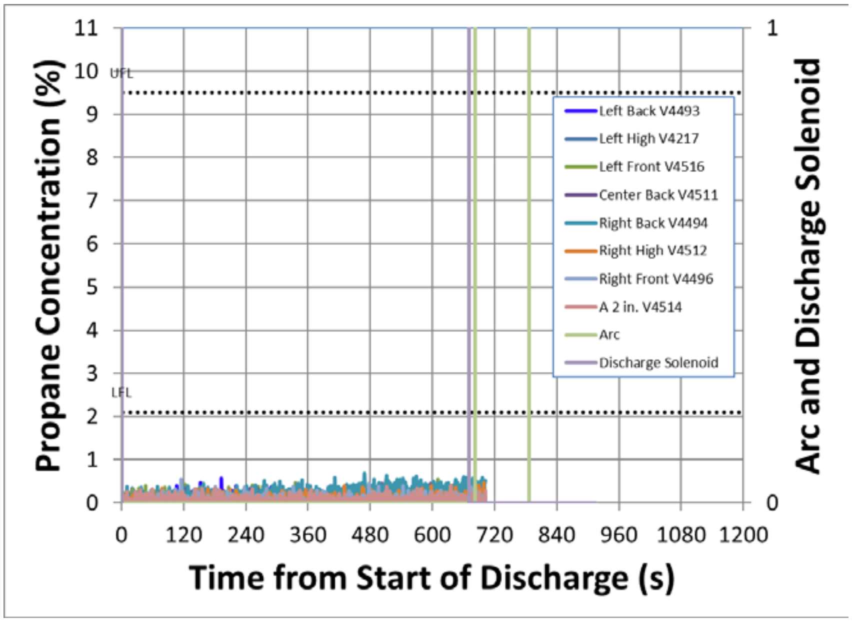


Figure 423 – RI_10 Concentrations at 8 locations surrounding cooler

Figure 424 compares the concentrations at the interior sensor (4 inch level) in tests RI_01 and RI_10 to show that concentrations were similar to within a few tenths of a percent. This data shows no change is leakage from the door gaskets.

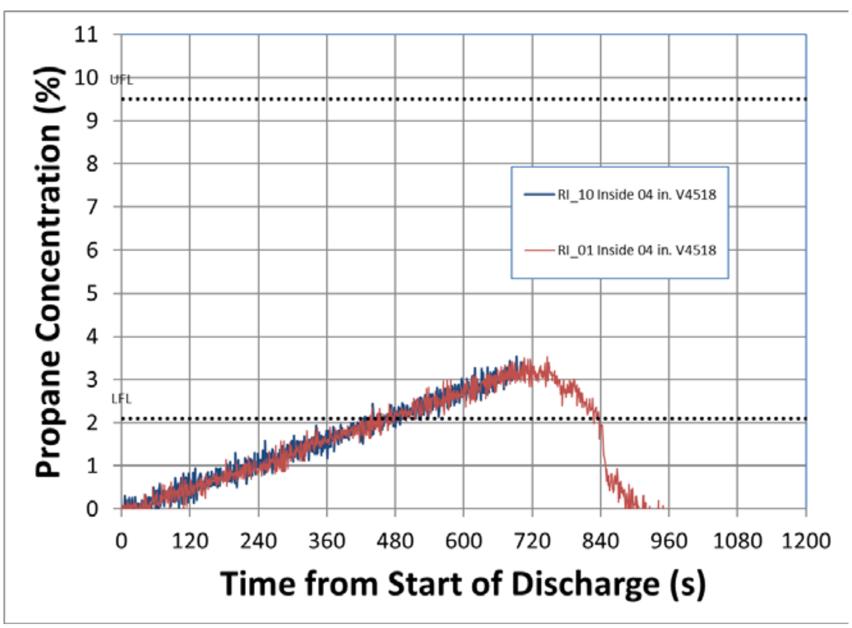


Figure 424 – RI_10 to RI_01 Concentration Comparison

Figure 425 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

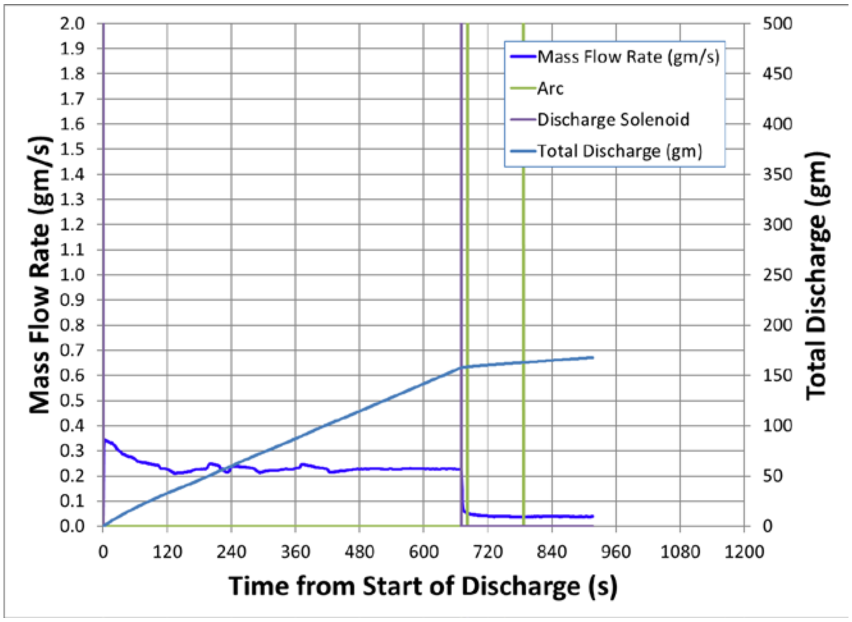


Figure 425 – RI_10 Mass Flow

Figure 426 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

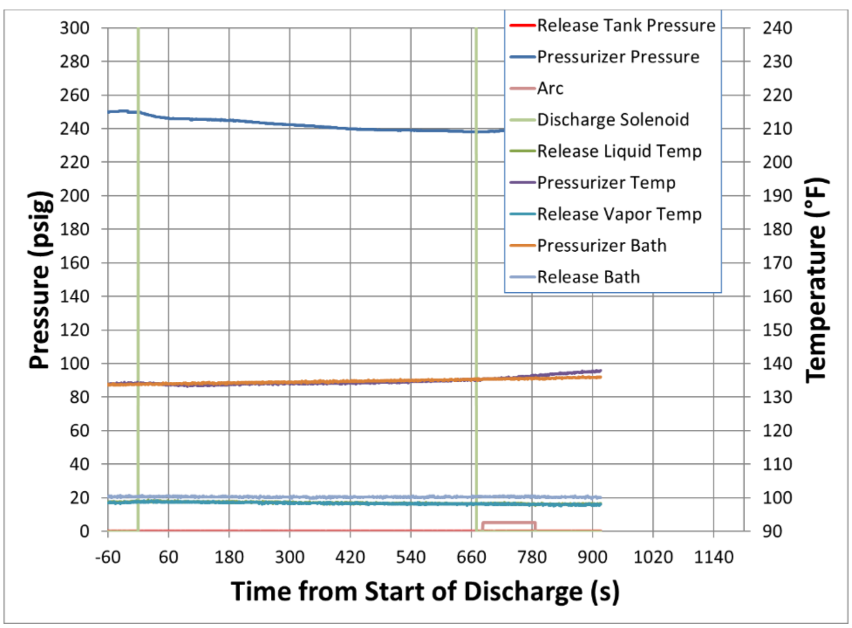


Figure 426 – RI_10 Pressurizer and Release Tank Pressure and Temperatures

Figure 427 shows the temperatures developed at the various locations following ignition. The data shows the highest temperature at location A at the 18 inch level close to the ignition source. Within a few seconds the highest temperatures were recorded at 4 inches below the ceiling (92 inches) due to buoyancy of the heated air. Locations B, C, and D showed small increases in temperature at the 18-inch level and below.

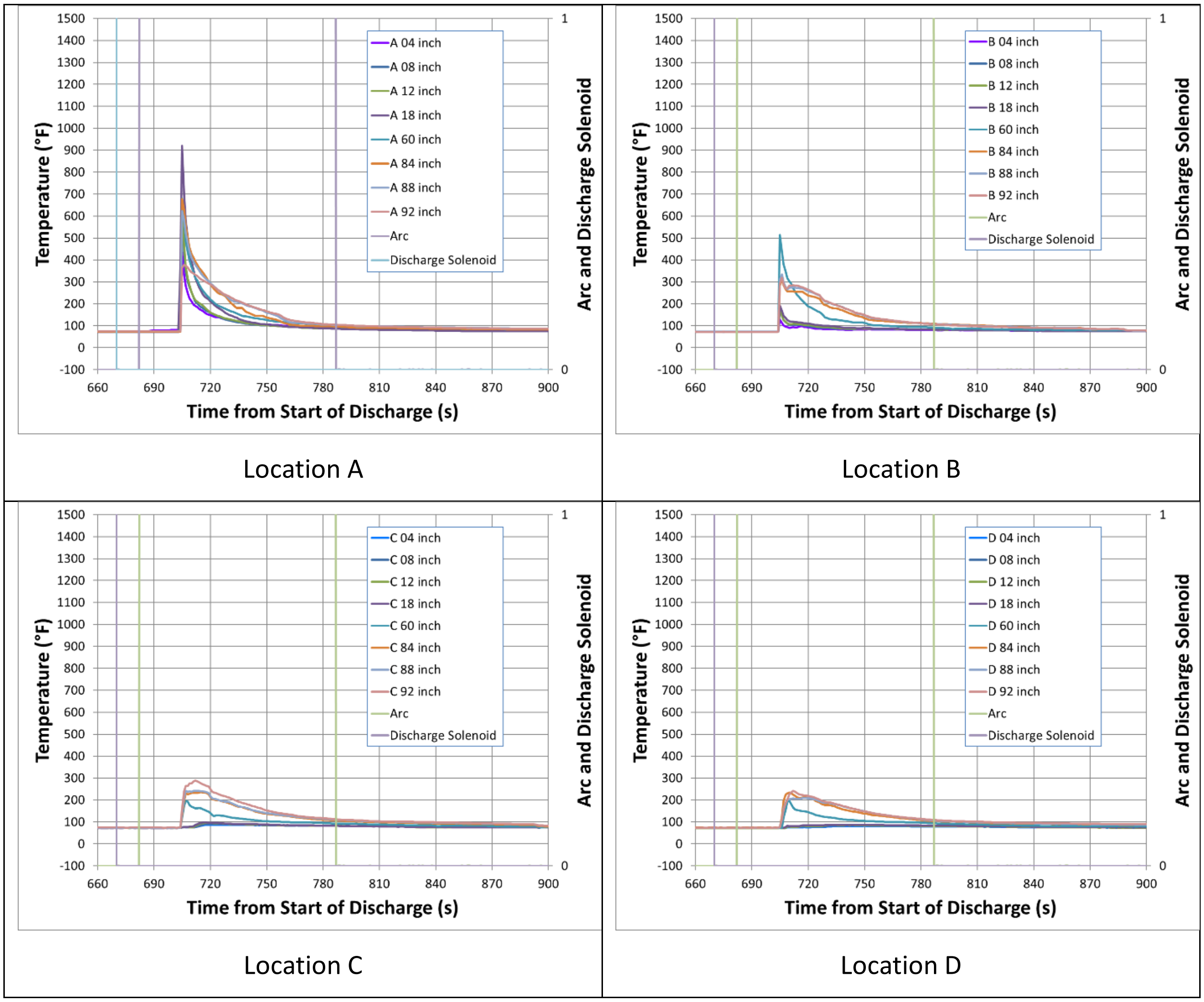


Figure 427 – RI_10 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 2 seconds. The deflagration pressure was sufficient to cause 3 of 6 deflagration vents to open. The deflagration also forced open the other two doors of the cooler as shown in Figure 461. The doors were thrown completely open. The left-hand door latched open and the right-hand door bounced and closed.

Figure 428 – RI_10 Deflagration showing doors forced open due to developed pressure.

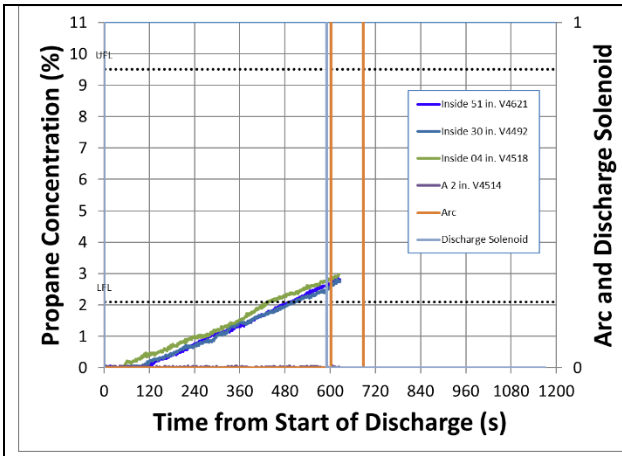
Test RI_11 (3-Door Cooler; 132 gram; Internal Release, with Arc Igniters)

Test RI_11 was performed with ignition sources and resulted in ignition at the arc location. The key parameters and results of this test are summarized in the following table. This test was conducted on the suspicion that door gasket damage may have occurred in the previous test.

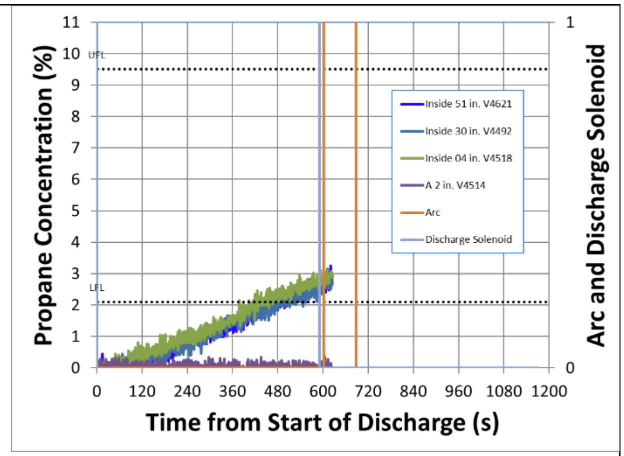
Table 92 – RI_11 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	132	09:50	0.224	Evaporator Return Bend
Measured	133	09:50	0.226	

Figure 429 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations



Deconvoluted Concentrations

Figure 429 – RI_11 Concentrations

Figure 430 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

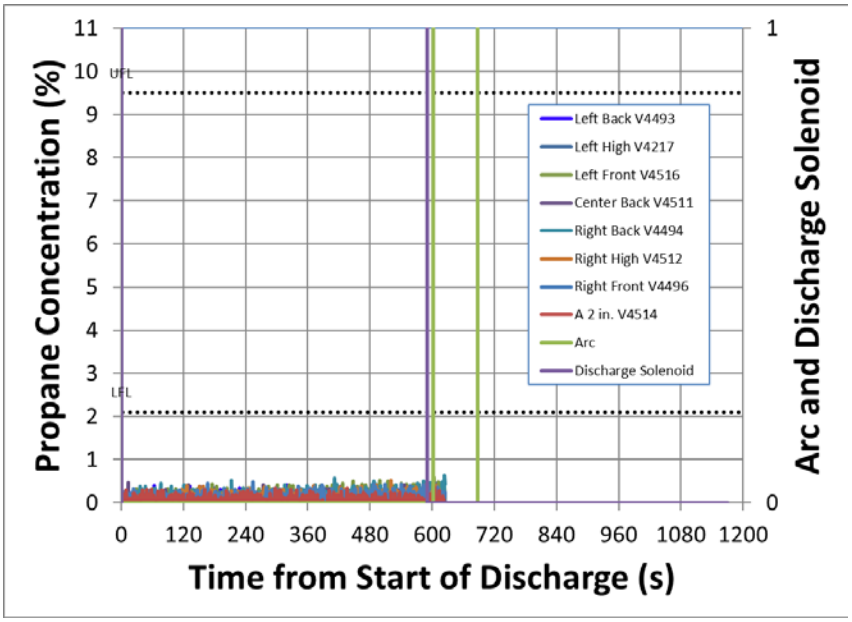


Figure 430 – RI_11 Concentrations at 8 locations surrounding cooler

Figure 431 compares the concentrations at the interior sensor (4 inch level) in tests RI_01 and RI_11 to show that concentration buildup were similar to within a few tenths of a percent. This data shows no change is leakage from the door gaskets. While RI_01 discharged 150g and RI_11 discharged 132g the buildup rates are nearly identical showing that the gasket seals performed as well as the first test.

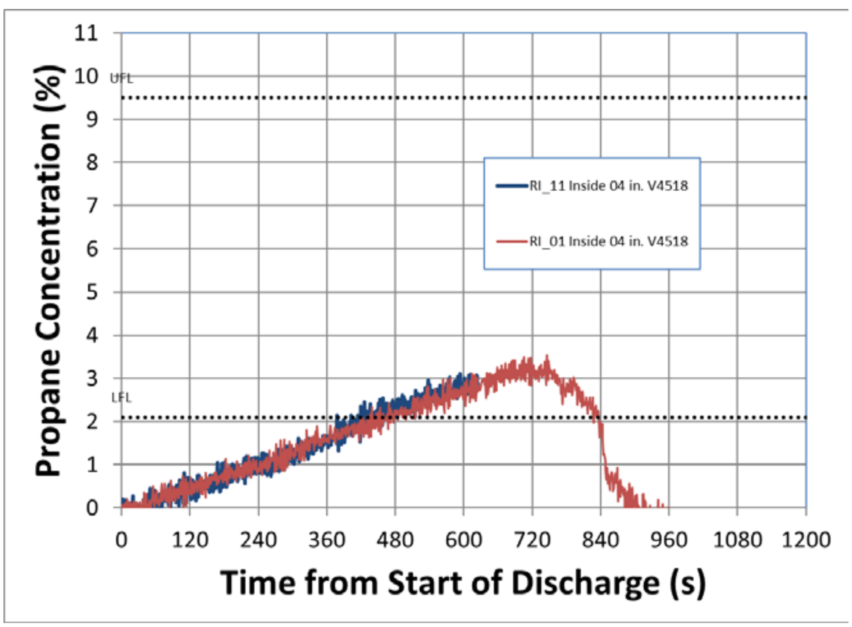


Figure 431 – RI_11 to RI_01 Concentration Comparison

Figure 432 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

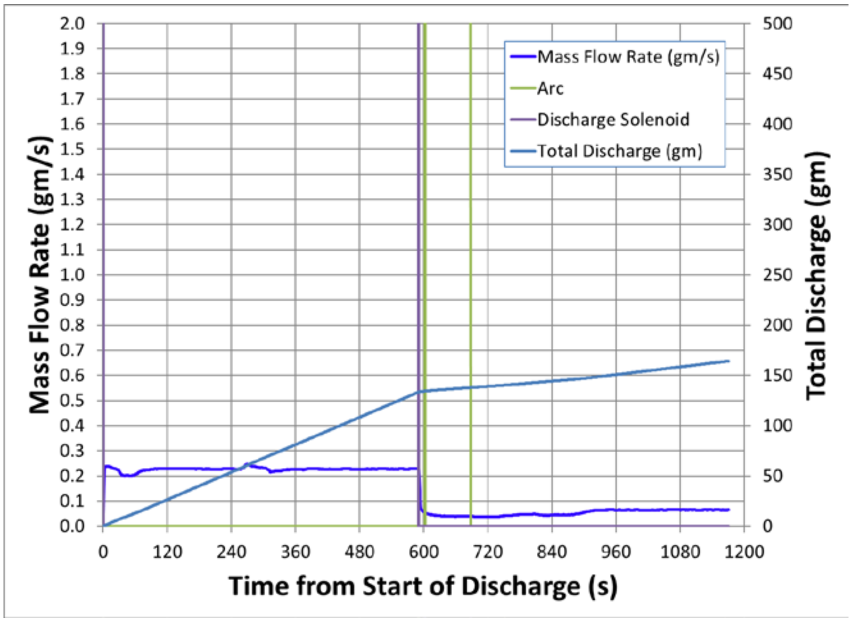


Figure 432 – RI_11 Mass Flow

Figure 433 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

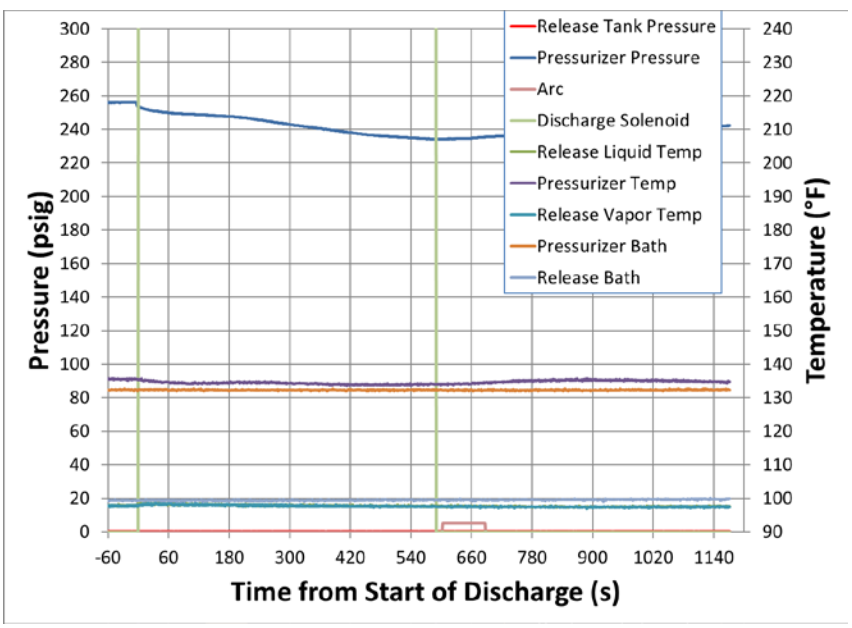


Figure 433 – RI_11 Pressurizer and Release Tank Pressure and Temperatures

Figure 434 shows the temperatures developed at the various locations following ignition. The data shows the highest temperature at location A at the 18 inch level close to the ignition source. Within a few seconds the highest temperatures were recorded at 4 inches below the ceiling (92 inches) due to buoyancy of the heated air. Locations B, C, and D showed small increases in temperature at the 18-inch level and below.

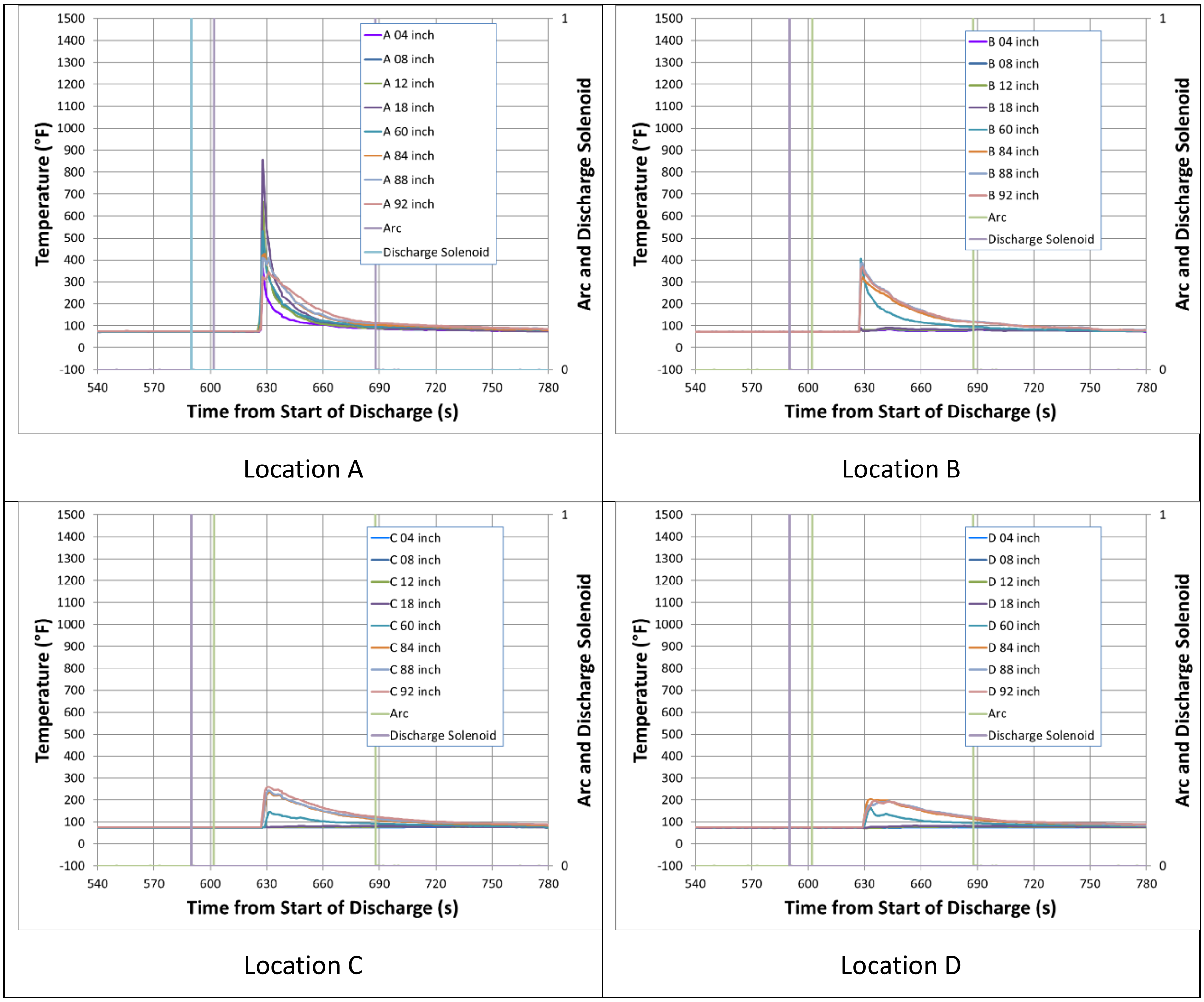


Figure 434 – RI_11 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 2 seconds. The deflagration pressure was sufficient to cause 3 of 6 deflagration vents to open. One additional vent melted open due to the hot gases. The deflagration also forced open the other two doors of the cooler as shown in Figure 435. Both doors were popped open about 2 inches by the fast, but small, deflagration shown in the right-hand image.

The high-speed camera showed the yellow fireball expanding from initiation to its largest size in 0.05 seconds.

Figure 435 – RI_11 Deflagration showing initial pre-mixed flame (left) and small deflagration (right)

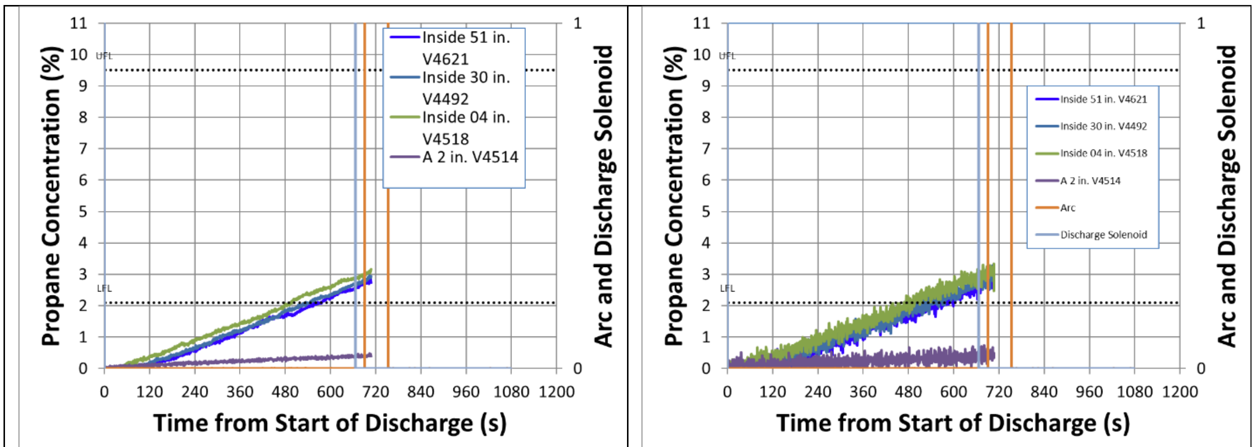
Test RI_12 (3-Door Cooler; 150 gram; Internal Release, with Arc Igniters)

Test RI_12 was performed with ignition sources and resulted in ignition at the arc location. The key parameters and results of this test are summarized in the following table.

Table 93 – RI_12 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	150	11:10	0.224	Evaporator Return Bend
Measured	150	11:06	0.226	

Figure 436 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations	Deconvoluted Concentrations

Figure 436 – RI_12 Concentrations

Figure 437 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets. This data is similar to that obtained in test RI_01 (see Figure 452).

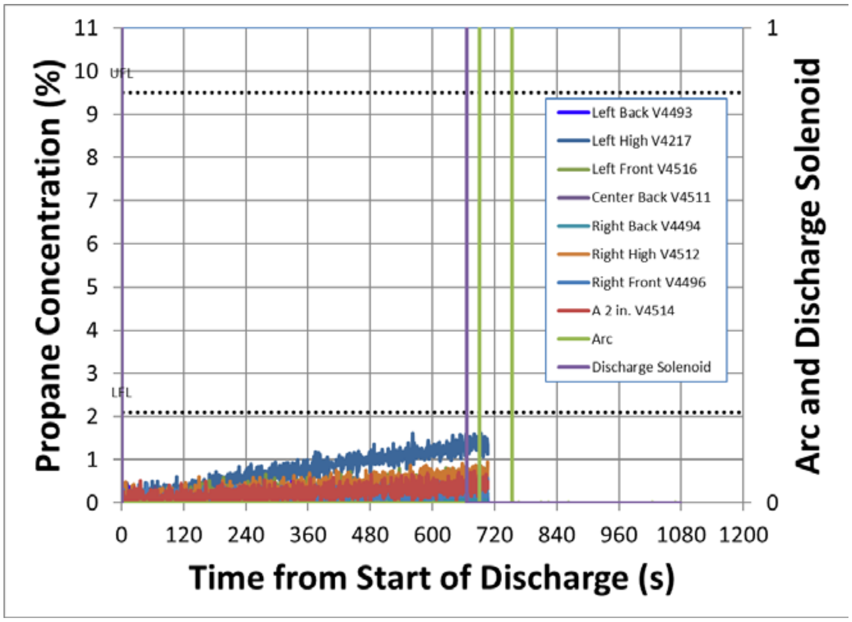


Figure 437 – RI_12 Concentrations at 8 locations surrounding cooler

Figure 438 compares the concentrations at the interior sensor (4 inch level) and the location A 2-inch sensor for tests RI_01 and RI_12 to show that concentrations were similar to within a few tenths of a percent. While within the repeatability range of these sensors, the data begins to show some gasket leakage. The inside concentration was slightly higher in test RI_01, while the outside (A-2 inch) is slightly lower.

This data indicated some door gasket leakage greater than what was observed in test RI_01. The center door gasket was inspected and showed some warping from the previous ignitions. This door gasket was replaced before continuing the test series.

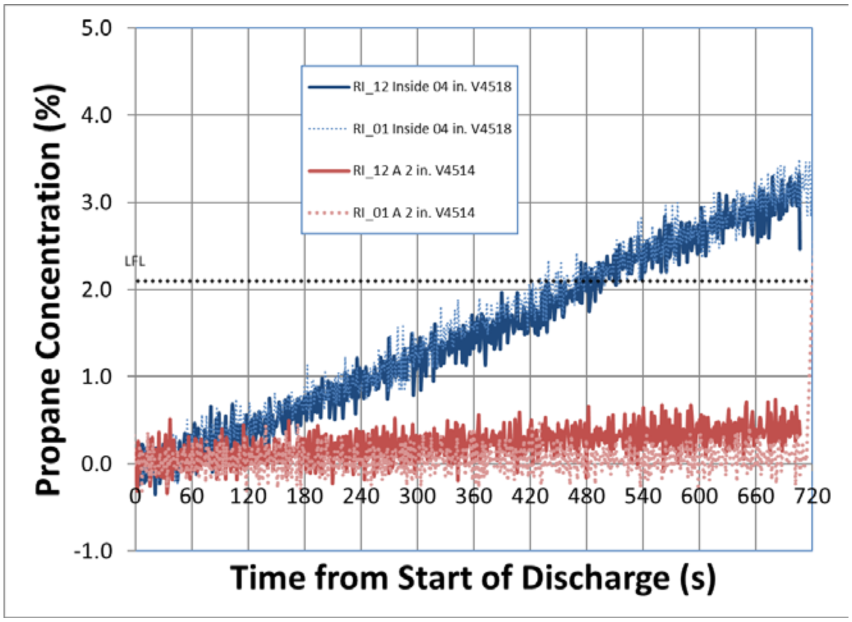


Figure 438 – RI_12 to RI_01 Concentration Comparison

Figure 439 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

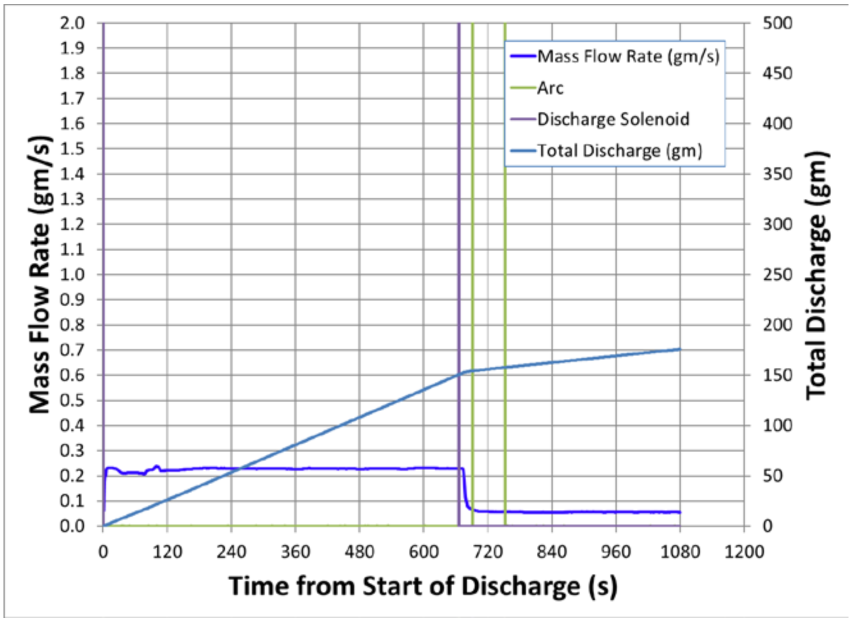


Figure 439 – RI_12 Mass Flow

Figure 440 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

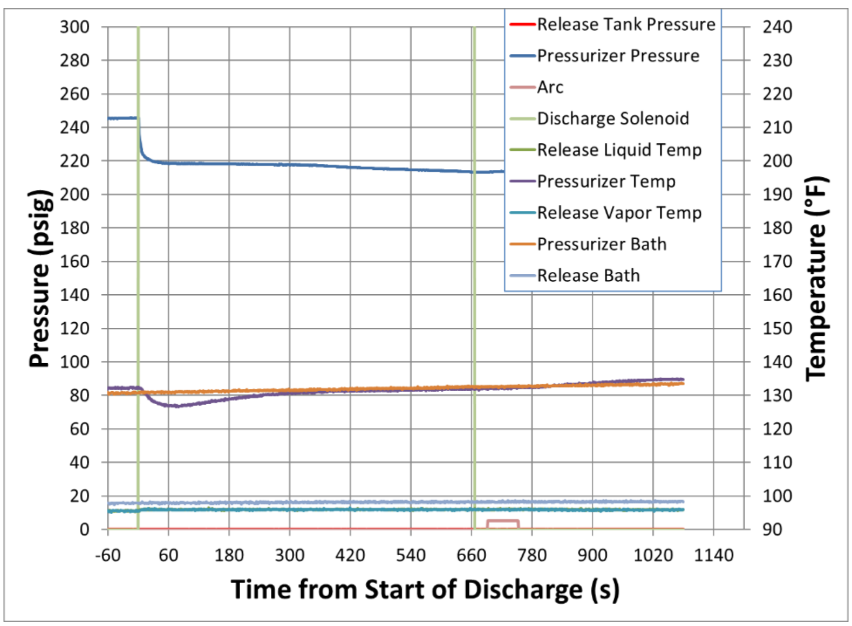


Figure 440 – RI_12 Pressurizer and Release Tank Pressure and Temperatures

Figure 441 shows the temperatures developed at the various locations following ignition. The data shows the highest temperature at location A at the 18 inch level close to the ignition source. Within a few seconds the highest temperatures were recorded at 4 inches below the ceiling (92 inches) due to buoyancy of the heated air. Locations B, C, and D showed small increases in temperature at the 18-inch level and below.

The peak temperature at location A 18-inch level is slightly smaller than recorded in test RI_10 (835°F vs. 910°F). This is another indication that the cooler door gaskets may have been damaged in earlier tests.

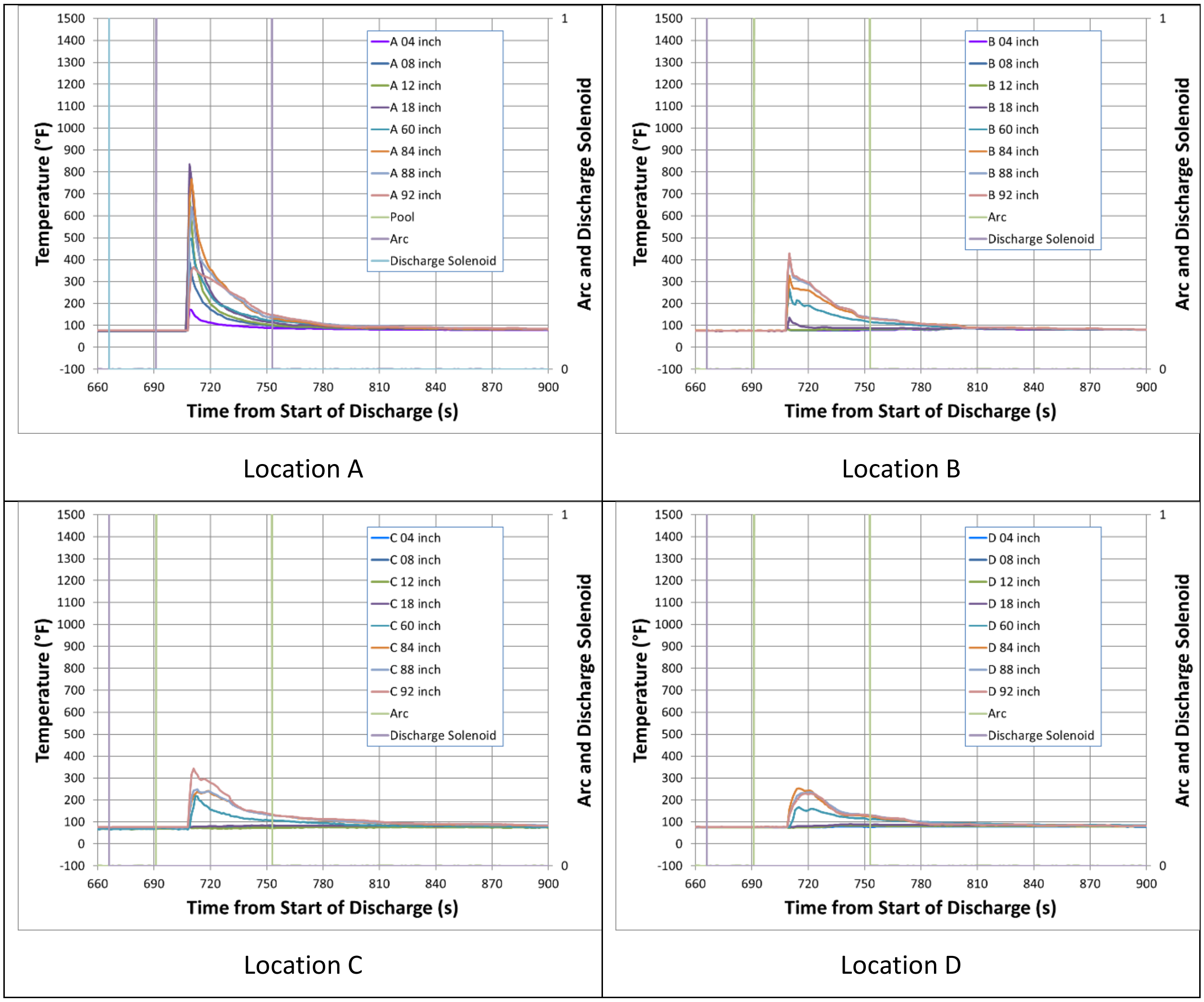


Figure 441 – RI_12 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 2 seconds. The deflagration pressure was sufficient to cause 5 of 6 deflagration vents to open. The deflagration also forced open the other two doors of the cooler as shown in Figure 442.

Figure 442 – RI_12 Deflagration showing doors forced open due to developed pressure.

Test RI_13 (3-Door Cooler; 355 gram; Internal Release)

Test RI_13 was performed without ignition sources. The interior leak was at an evaporator return bend. The interior fans were not operating during this test. The purpose was to search for signs of door gasket leakage by comparing interior concentrations with RI_02 which used similar parameters. The key parameters and results of this test are summarized in the following table.

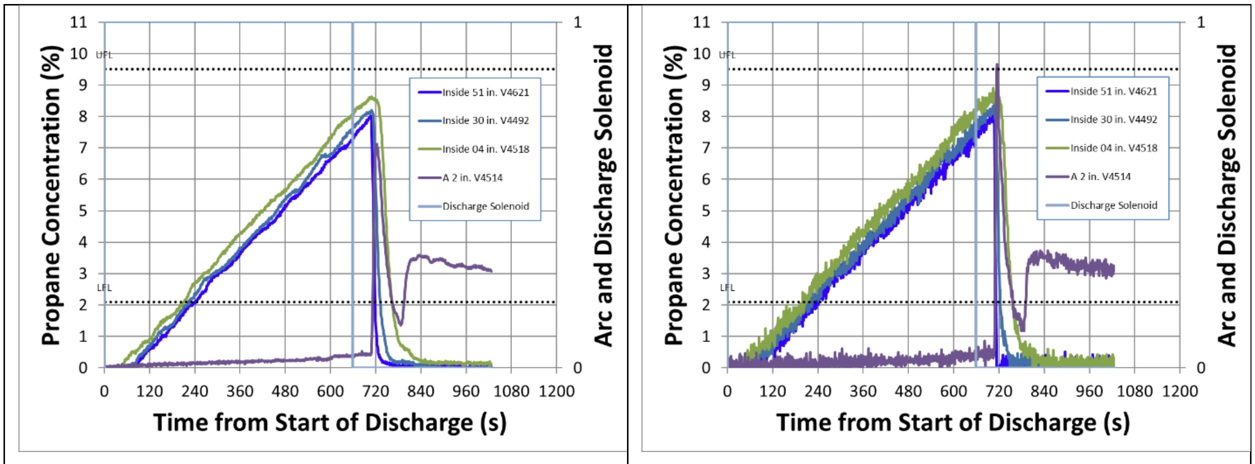
Table 94 – RI_13 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	355	11:10	0.530	Evaporator Return Bend	10.8 0.4	Well Mixed (Internal) Test Room
Measured	347	10:59	0.528		8.6 8.7 9.7	Internal Internal Deconvoluted Electric Arc Location

Per procedure, the discharge was stopped after 11 minutes and 10 seconds. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 443 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 51 inches. As the door opens the sensor at 51 inches decreases the fastest, followed by the 30 inch level, while the 4 inch sensor decreased at the slowest rate.

The concentration at the electric arc location (A 2 in.) shows a slight increase prior to the door opening, most likely due to door gasket leakage onto the floor near the cooler. This leakage accounts for the peak concentrations being less than the calculated well-mixed value. After the door is opened, the arc location increases to a value above the LFL of 2.1% and peaks at 8.6% (9.7% deconvoluted).

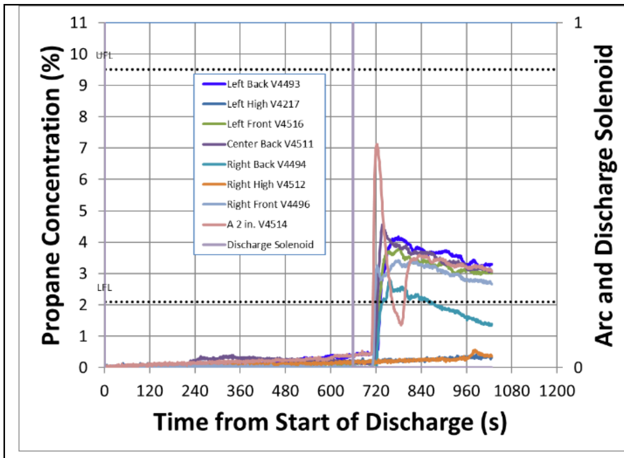


Concentrations	Deconvoluted Concentrations

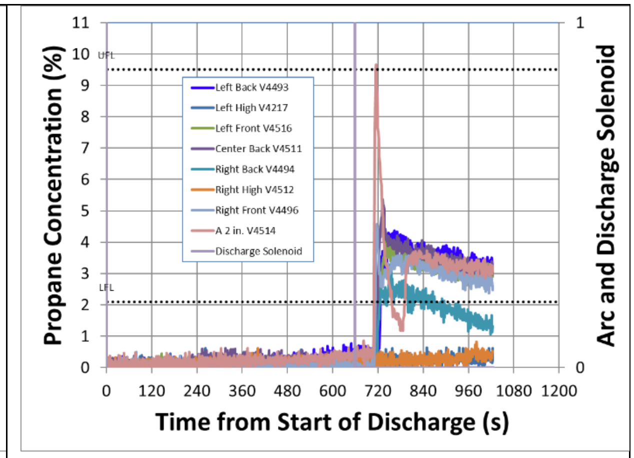
Figure 443 – RI_13 Internal Concentrations

Figure 444 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording at the 8 locations specified in by 2-89 CDV. Observations of this test include the following:

- The data show the concentration at location A 2-inches peaked at 9.7% (deconvoluted) immediately after the door was opened
- Several sensors at the 2-inch height showed larger concentrations than in the RI_02 test. This increase was due to leakage from the door gaskets.
- The Right-side High sensor (externally attached to the unit) showed a steady increase from the start of the discharge to the end of data recording. This sensor did not show evidence of drift in tests before or after this test. Both High sensors were near incandescent lights at the ceiling level and showed steadily increasing sensor temperatures. It appears that uneven heating of the electro-chemical media contributed to this effect. All other sensors showed relatively constant temperatures.
- All external concentrations settled at a level above LFL at the end of data recording. The one exception was the Right-side Back which was located close to the test room exterior door. This same effect was observed test RI_02. The suspect cause is leakage through the exterior door weather seal.



Concentrations



Deconvoluted Concentrations

Figure 444 – RI_13 Concentrations

Figure 445 compares the concentrations at the interior sensor (4 inch level) for tests RI_02 and RI_13. The data shows higher concentrations were achieved in this later test. The assumption of significant door gasket leakage was negated by this data.

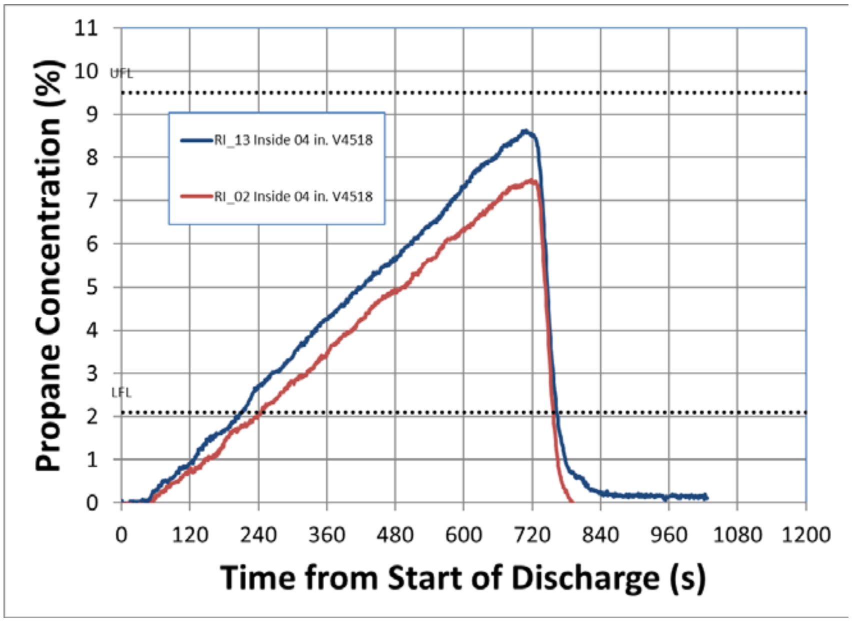


Figure 445 – RI_13 to RI_02 Concentration Comparison

Figure 447 shows the change in temperature at location A after the door opening. Temperatures at the 4, 8, 12, and 18 inch heights showed a drop from the air leaving the cooler (cooled by evaporation of liquid propane). There was no effect at the 60-inch height and above.

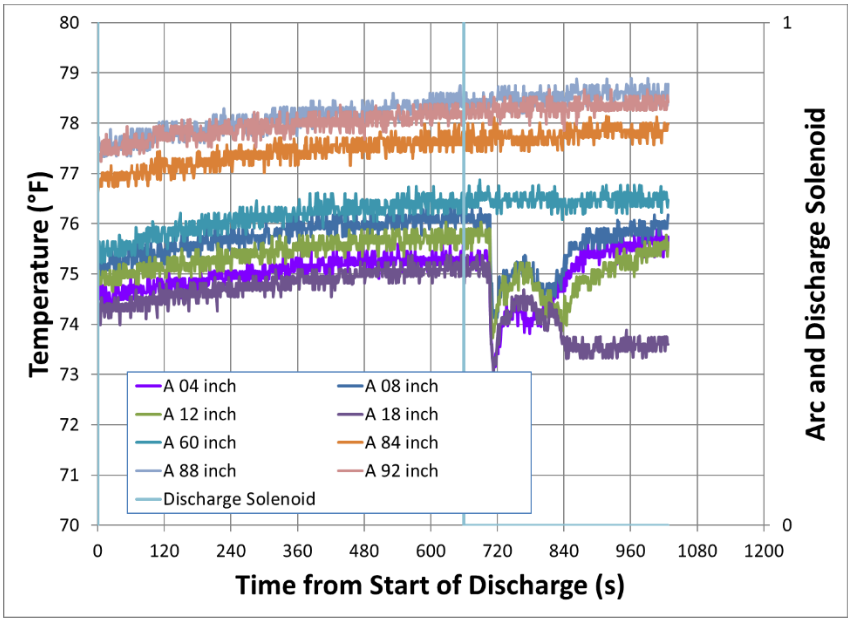


Figure 446 – RI_13 Temperature effect after door opening

Figure 447 shows similar but less intense drops in temperature as the cooled propane/air mixture migrated throughout the test room at floor level.

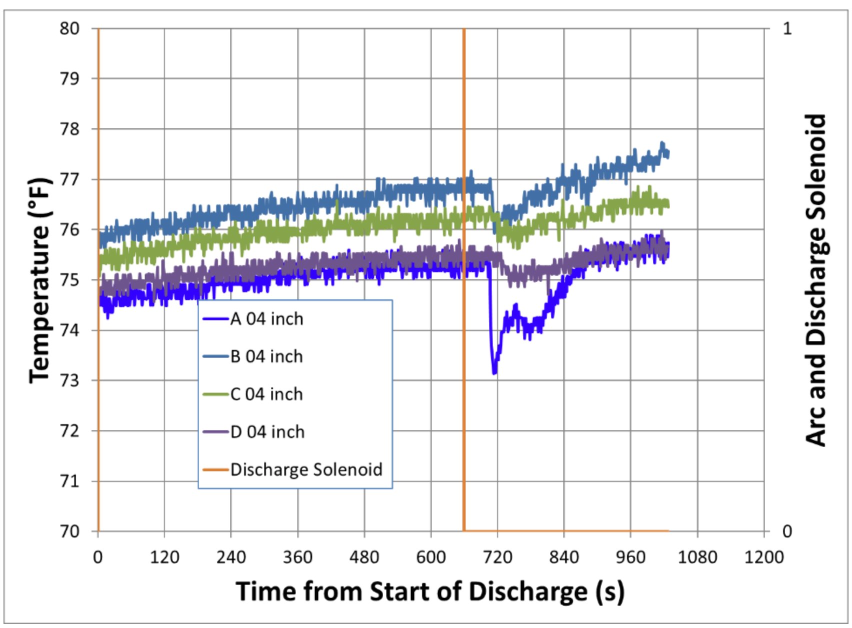


Figure 447 – RI_13: Temperatures at the 4-inch level

The profiles of the above two figures are similar to those found in test RI_02 (Figure 378 and Figure 379).

Figure 448 shows the mass flow rate and total mass flow. The spike at 180 seconds was due to an electrical interference. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

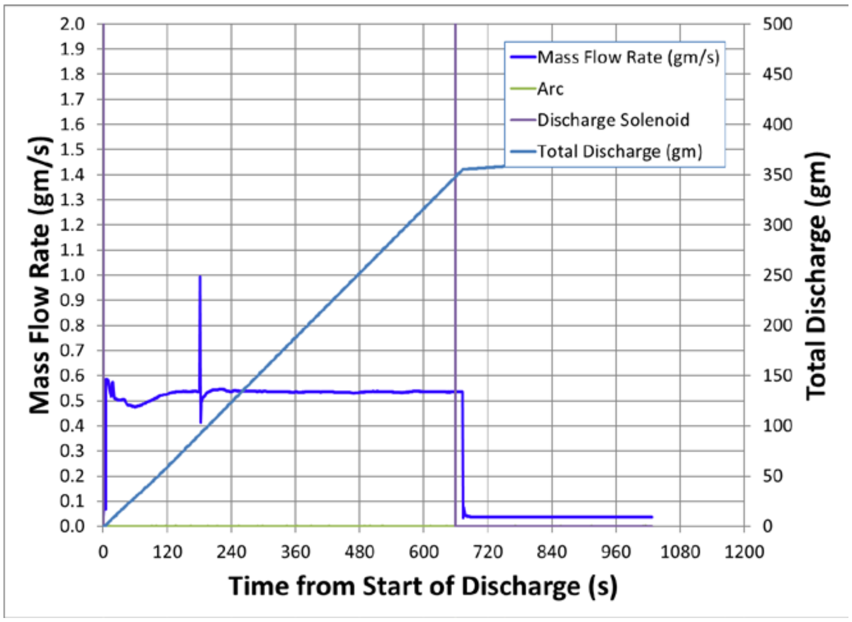


Figure 448 – RI_13 Mass Flow

Figure 449 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. The release tank pressure transmitter had failed prior to this test and was replaced prior to test RI_17. Release pressure is approximately equal to pressurizer pressure during the discharge when the two tanks are cross-connected.

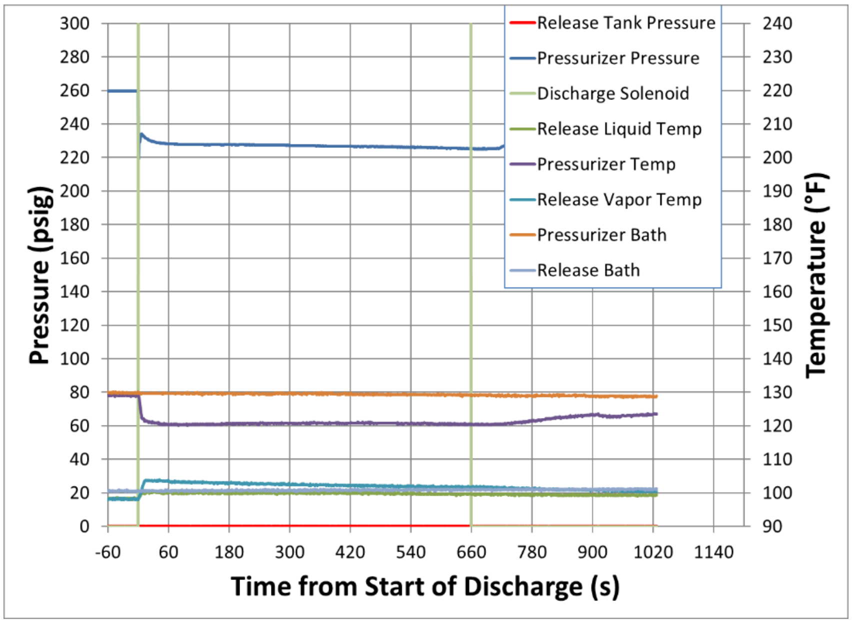


Figure 449 – RI_13 Pressurizer and Release Tank Pressure and Temperatures

Test RI_14 (3-Door Cooler; 150 gram; Internal Release)

Test RI_14 was performed without ignition sources in order to measure propane concentrations prior to the conduct of test RI_15. The key parameters and results of this test are summarized in the following table.

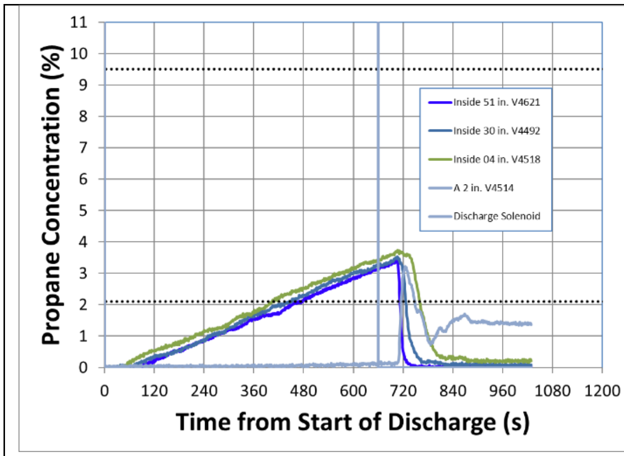
Table 95 – RI_14 Summary

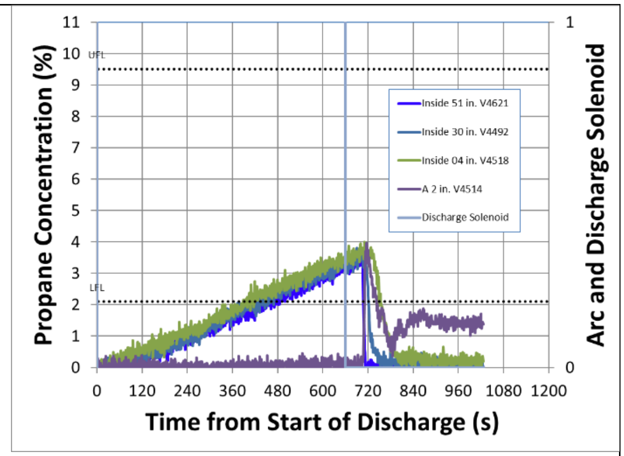
	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	150	11:10	0.224	Evaporator Return Bend	4.4	Well Mixed (Internal)
Measured	154	11:00	0.234		3.7	Internal
					4.0	Internal Deconvoluted
					3.1	Electric Arc Location

Per procedure, all doors of the cooler remained closed for 30 seconds after completion of the release. The center door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2 minutes following the door opening.

Figure 450 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 51 inches. As the door opens the sensor at 51 inches decreases the fastest, followed by the 30 inch level, while the 4 inch sensor decreased at the slowest rate.

The sensor at the electric arc location (A 2 in.) shows a slight increase prior to the door opening, most likely due to door gasket leakage onto the floor near the cooler. This leakage accounts for the peak concentrations being less than the calculated well-mixed value. After the door is opened, the arc location increases to a value above the LFL of 2.1% and peaks at 3.1% (4.0% deconvoluted).

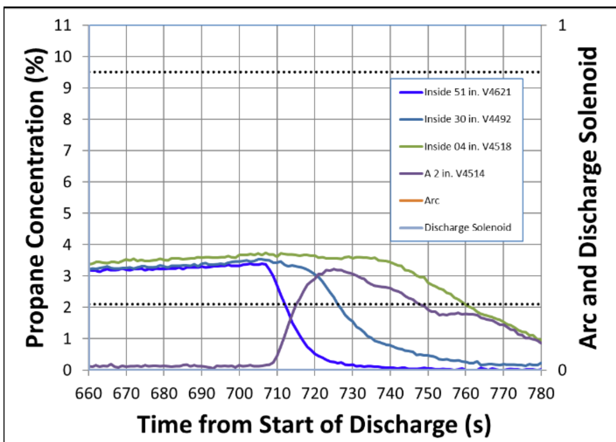


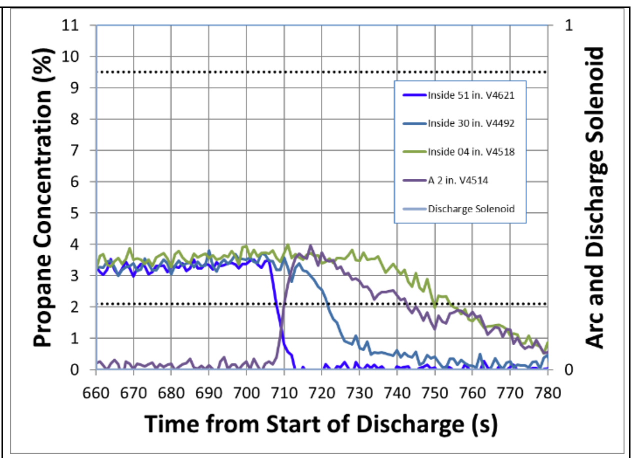


Concentrations	Deconvoluted Concentrations

Figure 450 – RI_14 Concentrations

Figure 451 focuses on the concentrations after completion of the discharge. The graphs show that the concentration at the arc location remains above the LFL for approximately 30 seconds. For reference, the door opening began at 690 seconds on these timelines.





Concentrations	Deconvoluted Concentrations

Figure 451 – RI_14 Concentrations after Discharge Completion

Figure 452 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

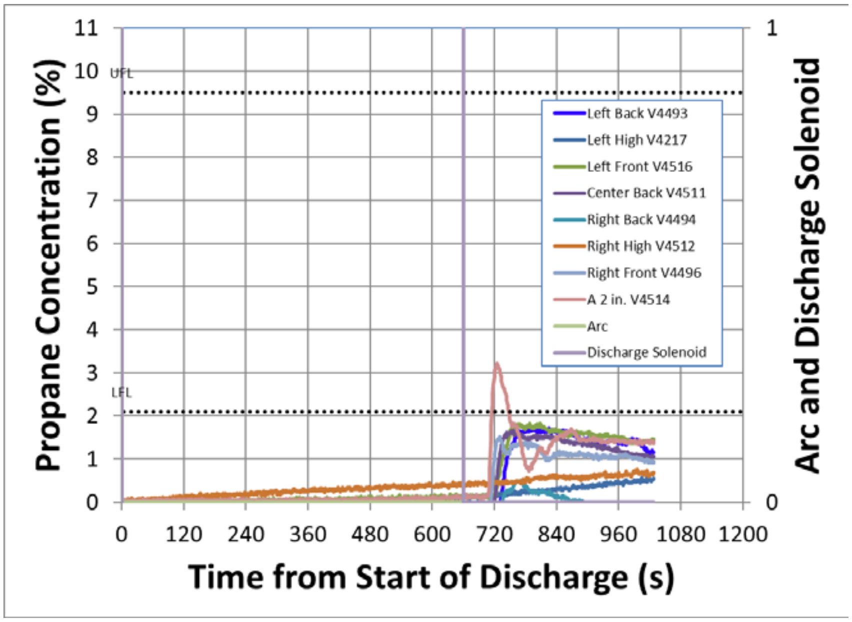


Figure 452 – RI_14 Concentrations at 8 locations surrounding cooler

Figure 453 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to integrate the total mass release.

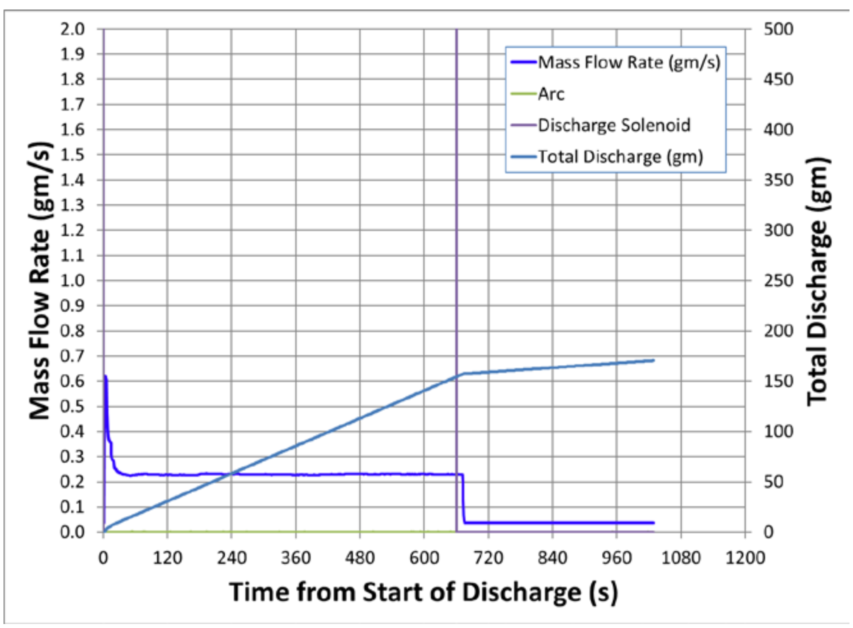


Figure 453 – RI_14 Mass Flow

Figure 454 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests. The drop in pressurizer pressure after completion of the discharge was due to disconnection of the tank in preparation for its replacement with a fresh tank for the next test.

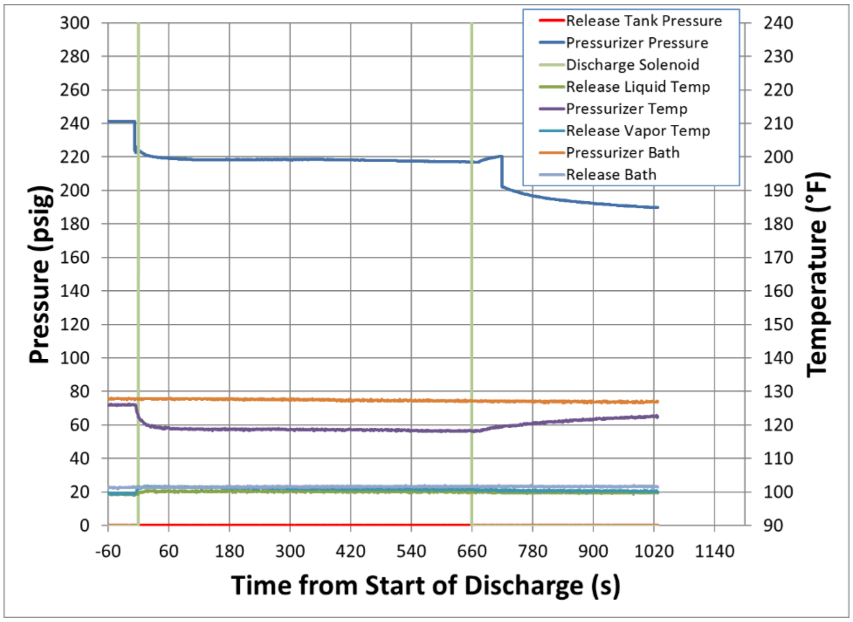


Figure 454 – RI_14 Pressurizer and Release Tank Pressure and Temperatures

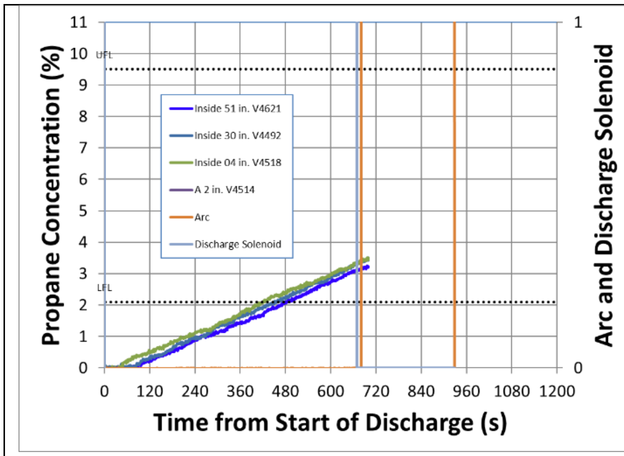
Test RI_15 (3-Door Cooler; 150 gram; Internal Release, with Arc Igniters)

Test RI_15 was performed with ignition sources and resulted in ignition at the arc location. The key parameters and results of this test are summarized in the following table.

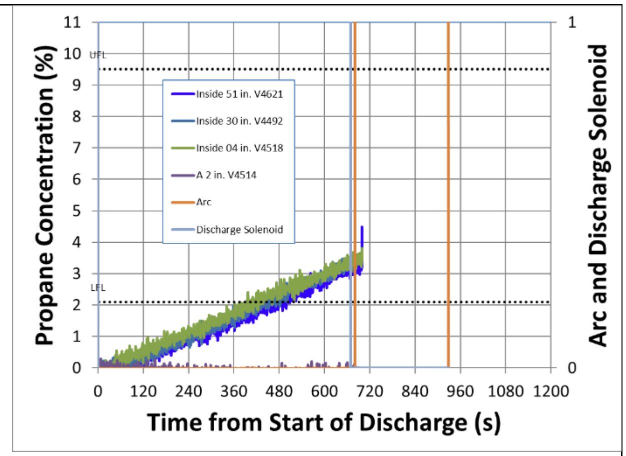
Table 96 – RI_15 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	150	11:10	0.224	Evaporator Return Bend
Measured	154	11:09	0.231	

Figure 455 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations



Deconvoluted Concentrations

Figure 455 – RI_15 Concentrations

Figure 456 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets. This data is similar to that obtained in test RI_14 (see Figure 452).

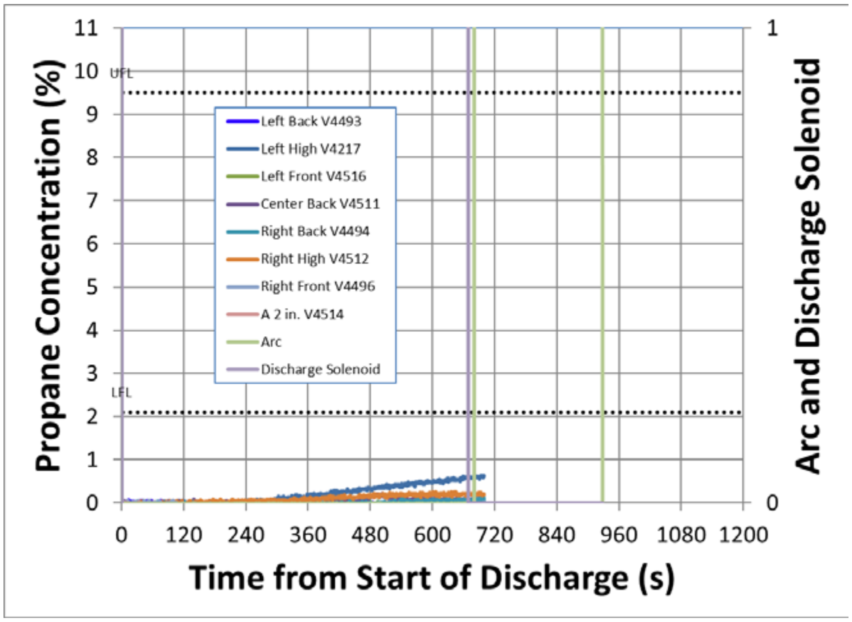


Figure 456 – RI_15 Concentrations at 8 locations surrounding cooler

Figure 457 compares the concentrations at the interior sensor (4 inch level) in tests RI_14 and RI_15 to show that concentrations were similar to within a few tenths of a percent.

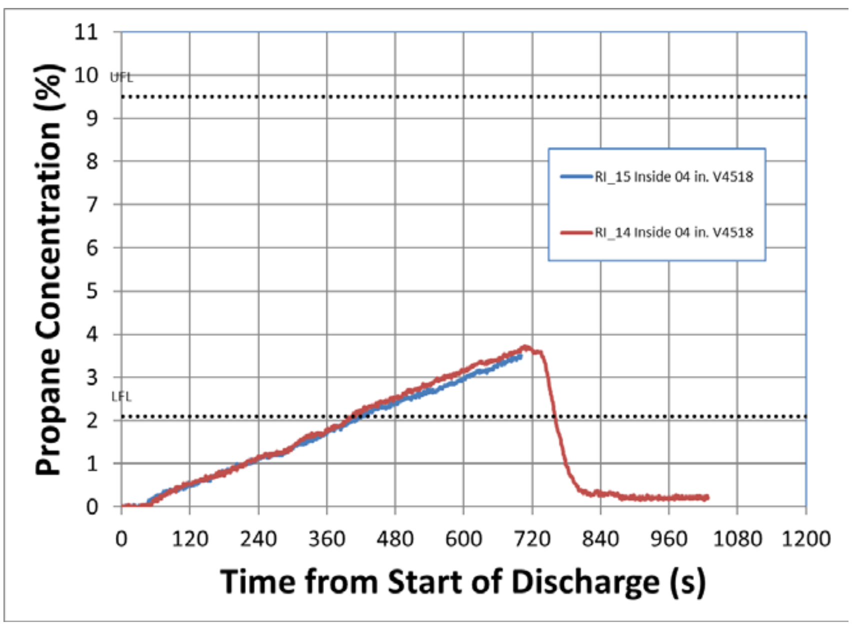


Figure 457 – RI_15 to RI_14 Concentration Comparison

Figure 458 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

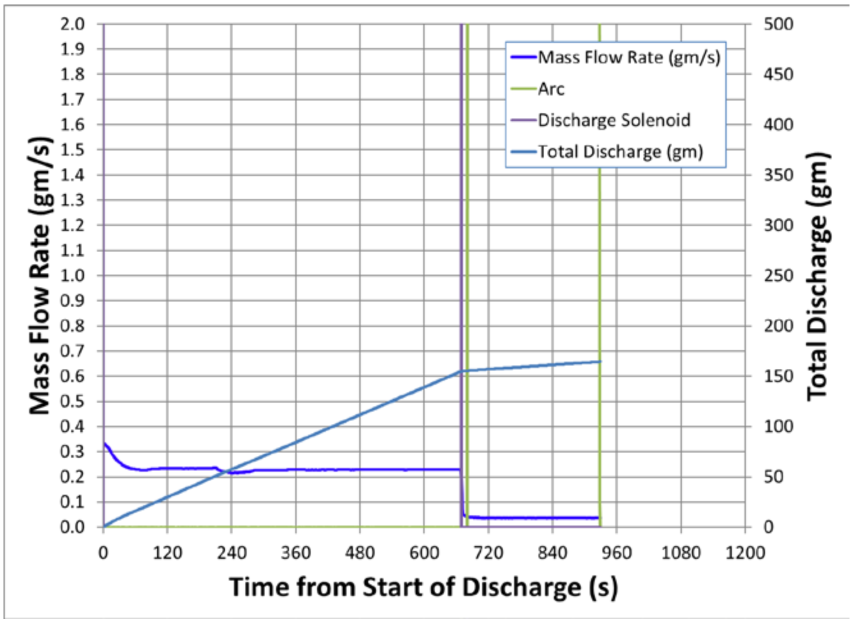


Figure 458 – RI_15 Mass Flow

Figure 459 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced in later tests.

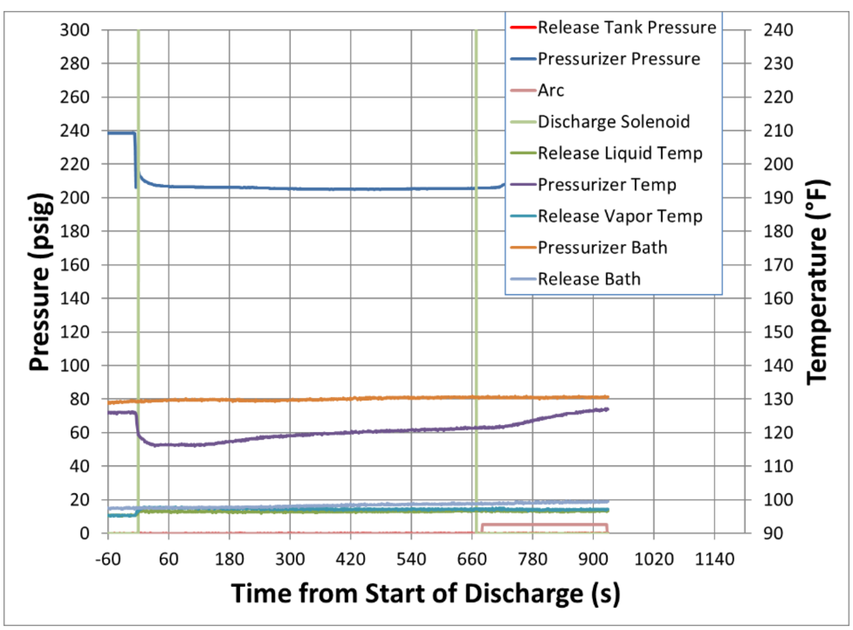


Figure 459 – RI_15 Pressurizer and Release Tank Pressure and Temperatures

Figure 460 shows the temperatures developed at the various locations following ignition. The data shows the highest temperature at location A at the 18 inch level close to the ignition source. Within a few seconds the highest temperatures were recorded at 4 inches below the ceiling (92 inches) due to buoyancy of the heated air.

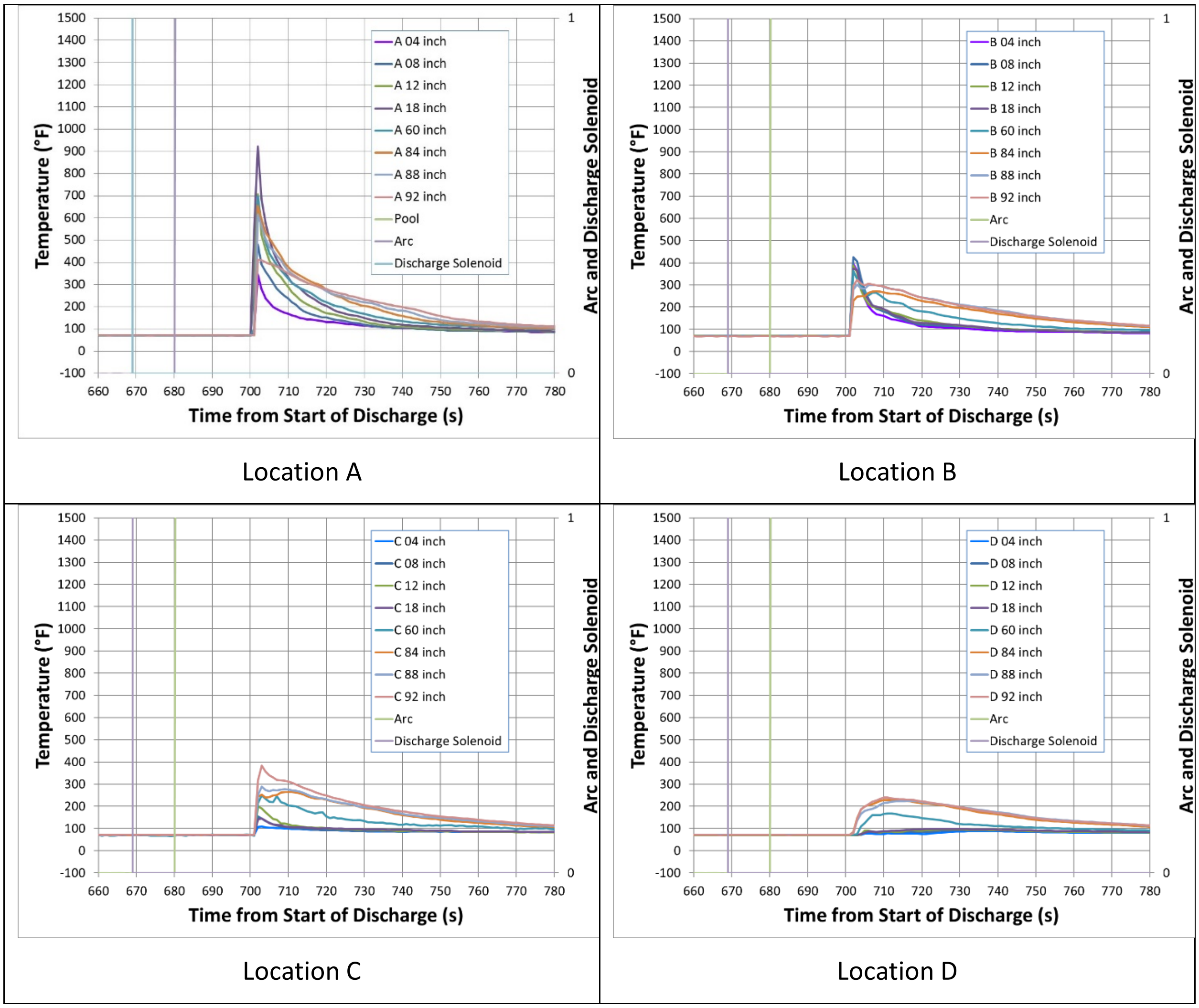


Figure 460 – RI_15 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 2 seconds. The deflagration pressure was sufficient to cause 5 of 6 deflagration vents to open. The deflagration also forced open the other two doors of the cooler as shown in Figure 461. The doors were thrown completely open and then bounced shut.

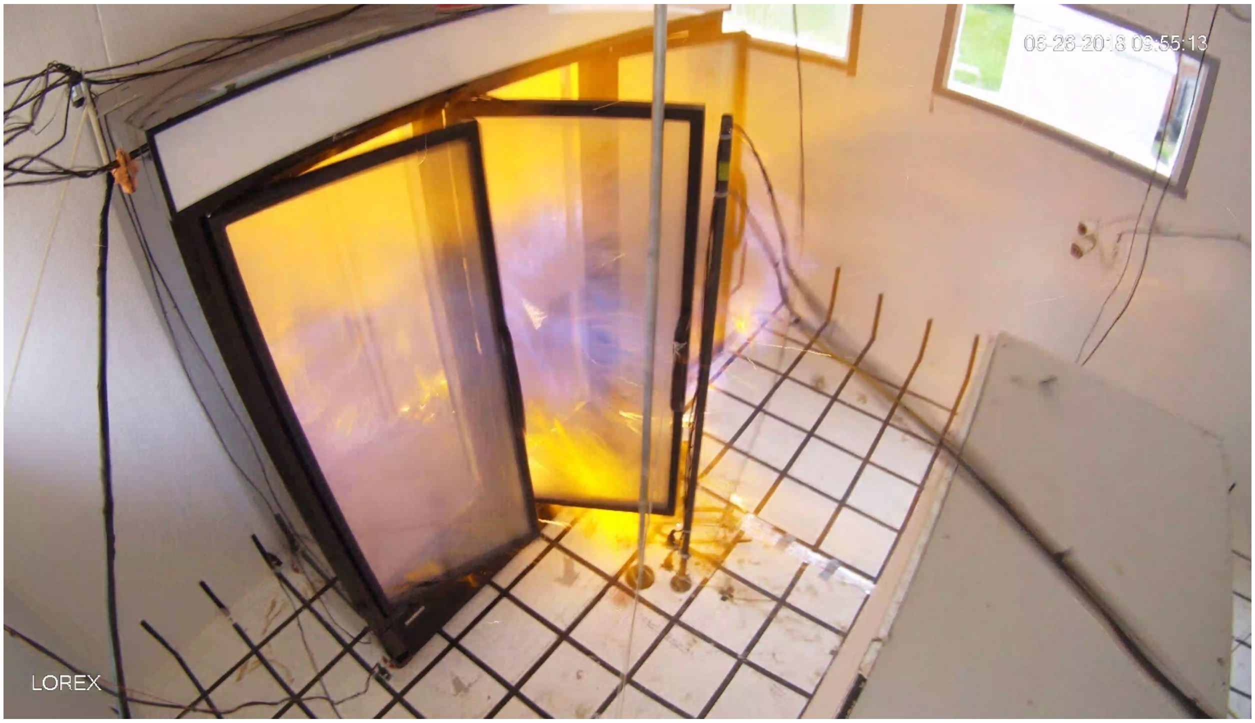


Figure 461 – RI_15 Deflagration showing doors forced open due to developed pressure.

Test RI_16 (3-Door Cooler; 150 gram; Internal Release)

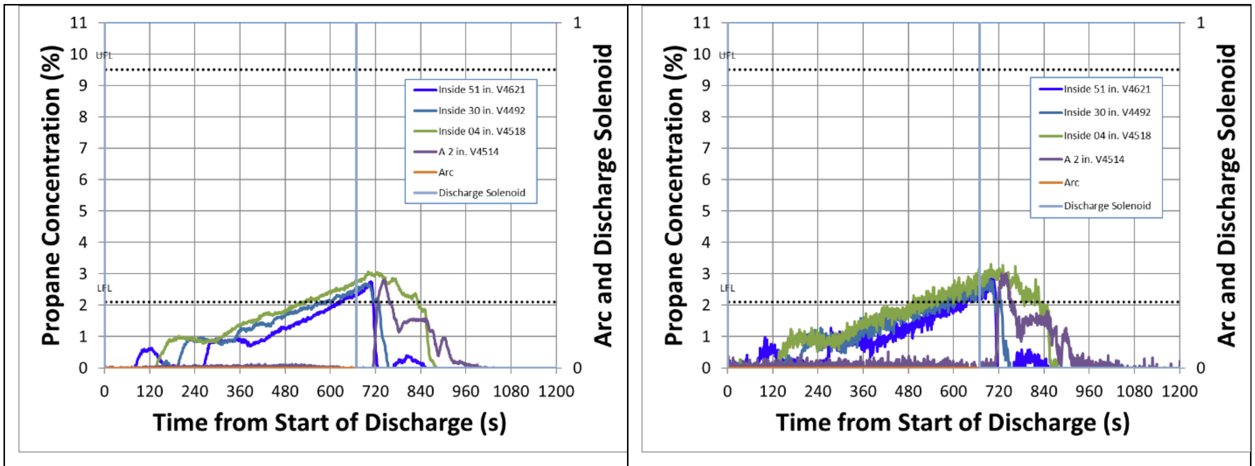
Test RI_16 was performed without ignition sources in order to measure propane concentrations and verify the sealing of the door gaskets. The door gaskets were found to be leaking excessively due to damage from previous fires. All three door gaskets were replace following this test. The key parameters and results of this test are summarized in the following table.

Table 97 – RI_16 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	150	11:10	0.224	Evaporator Return Bend	4.4	Well Mixed (Internal)
Measured	150	11:09	0.225		3.1 3.3 3.0	Internal Internal Deconvoluted Electric Arc Location

Per procedure, all doors of the cooler remained closed for 30 seconds after completion of the release. The center door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2 minutes following the door opening.

Figure 462 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. From the start of the discharge it appears that the door gaskets are leaking. Instead of the normal, almost linear buildup of concentration, there is a delayed increase in concentration.



Concentrations	Deconvoluted Concentrations

Figure 462 – RI_16 Concentrations

Figure 463 compares the concentrations at the interior sensor (4 inch level) for tests RI_01 and RI_16. The graphs show that the RI_16 concentrations are inconsistent with the RI_01 data. The decision was made to replace all three door gaskets before the next test.

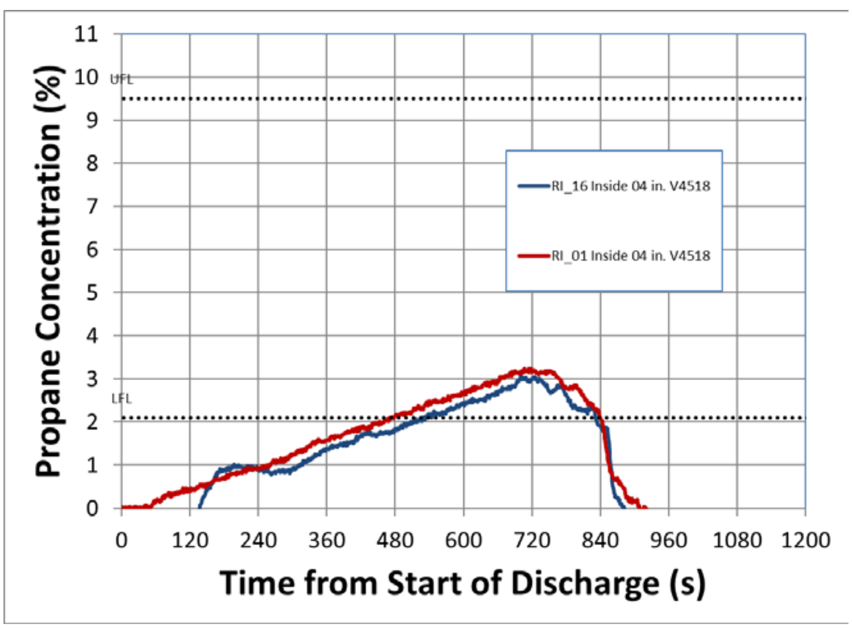


Figure 463 – RI_16 to RI_01 Concentration Comparison

Figure 464 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

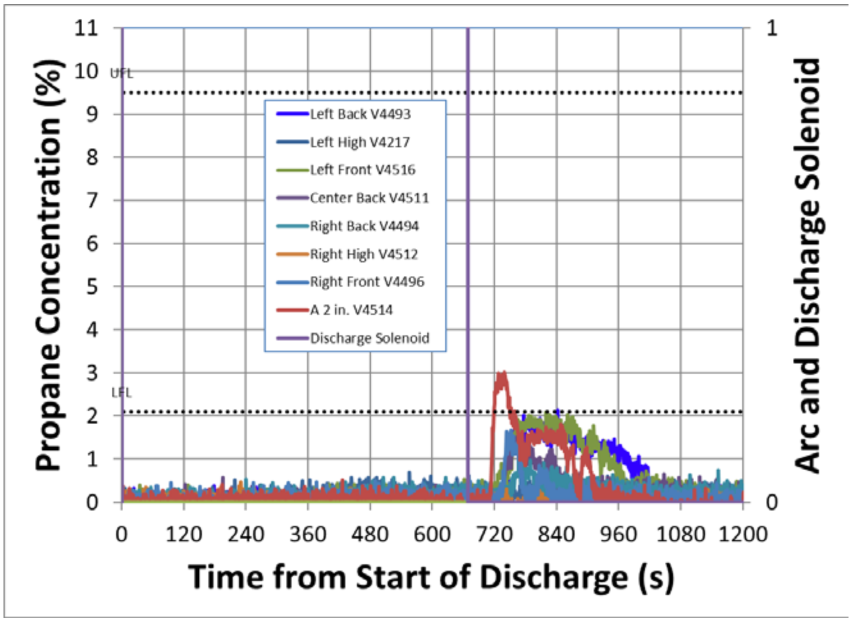


Figure 464 – RI_16 Concentrations at 8 locations surrounding cooler

Figure 465 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to integrate the total mass release.

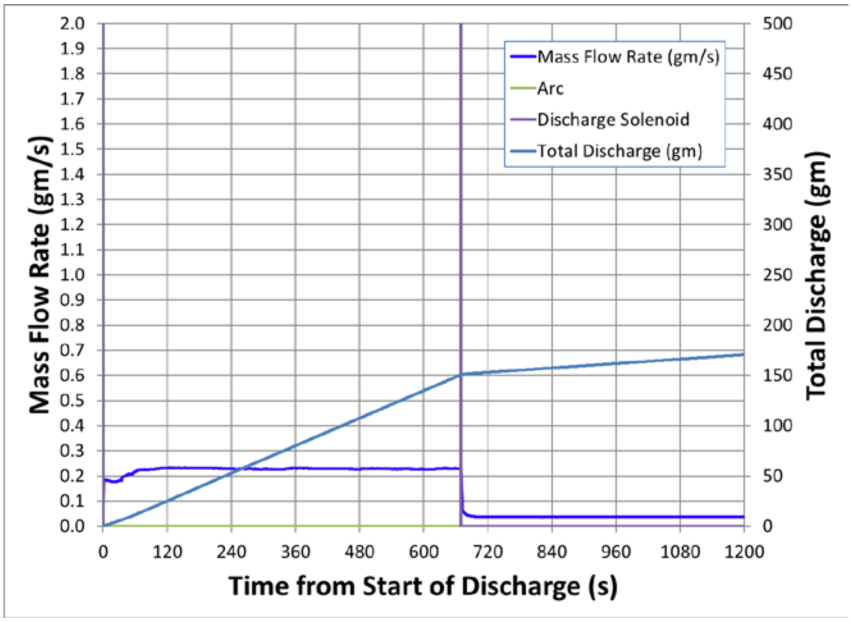


Figure 465 – RI_16 Mass Flow

Figure 466 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The release tank pressure transmitter had failed prior to this test and was replaced prior to test RI_17. The drop in pressurizer pressure after completion of the discharge was due to disconnection of the tank in preparation for its replacement with a fresh tank for the next test.

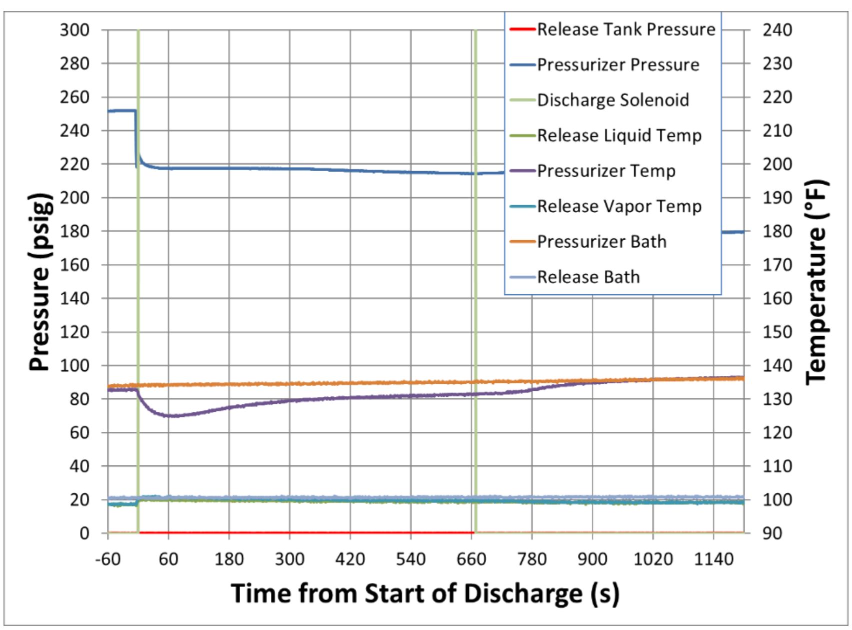


Figure 466 – RI_16 Pressurizer and Release Tank Pressure and Temperatures

Test RI_17 (3-Door Cooler; 200 gram; Internal Release)

Test RI_17 was performed without ignition sources in order to measure propane concentrations prior to the conduct of test RI_18. The key parameters and results of this test are summarized in the following table.

Table 98 – RI_17 Summary

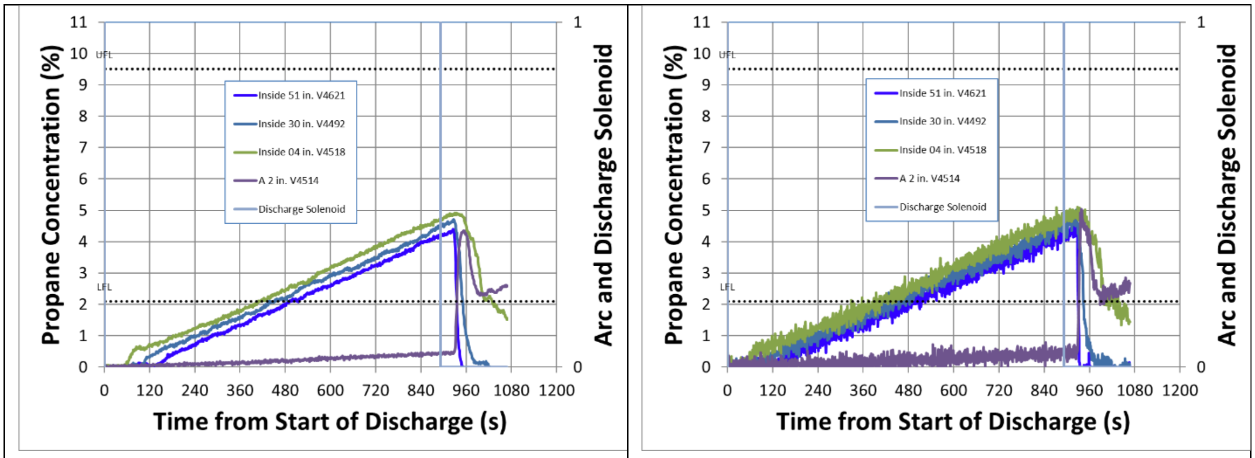
	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	200	11:10	0.299	Evaporator Return Bend	5.9	Well Mixed (Internal)
Measured	204	14:52	0.229		4.9	Internal
					5.1	Internal Deconvoluted
					4.4	Electric Arc Location

A longer discharge duration was used in this test in order to verify the repair of the door gaskets following earlier tests. The rate of discharge was selected to match the rate of the 150 gram discharges (150 grams in 670 seconds).

Per procedure, all doors of the cooler remained closed for 30 seconds after completion of the release. The center door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following the discharge was completed.

Figure 568 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 51 inches. As the door opens the sensor at 51 inches decreases the fastest, followed by the 30 inch level, while the 4 inch sensor decreased at the slowest rate.

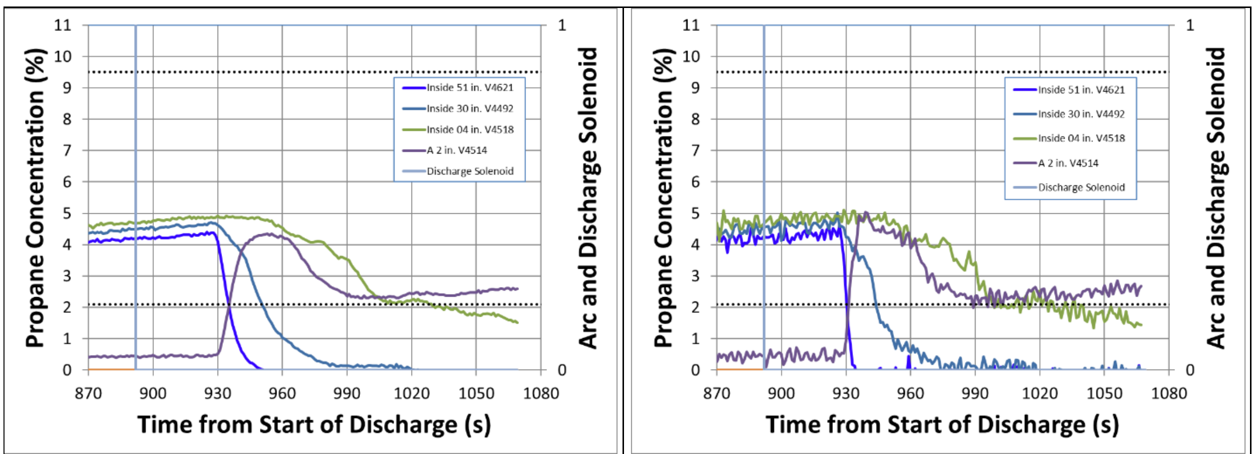
The sensor at the electric arc location (A 2 in.) shows a slight increase prior to the door opening, most likely due to door gasket leakage onto the floor near the cooler. This leakage accounts for the peak concentrations being less than the calculated well-mixed value. After the door was opened, the arc location sensor increased to a value above the LFL of 2.1% and peaks at 4.4% (5.0% deconvoluted).



Concentrations	Deconvoluted Concentrations

Figure 467 – RI_17 Concentrations

Figure 569 focuses on the concentrations after completion of the discharge. The graphs show that the concentration at the arc location remained above the LFL for the remainder of the data recording. For reference, the door opening began at 922 seconds on these timelines.



Concentrations	Deconvoluted Concentrations

Figure 468 – RI_17 Concentrations after Discharge Completion

Figure 570 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets. At 2.5 minutes after the door opening, many of these sensors show concentrations about the LFL (2.1%).

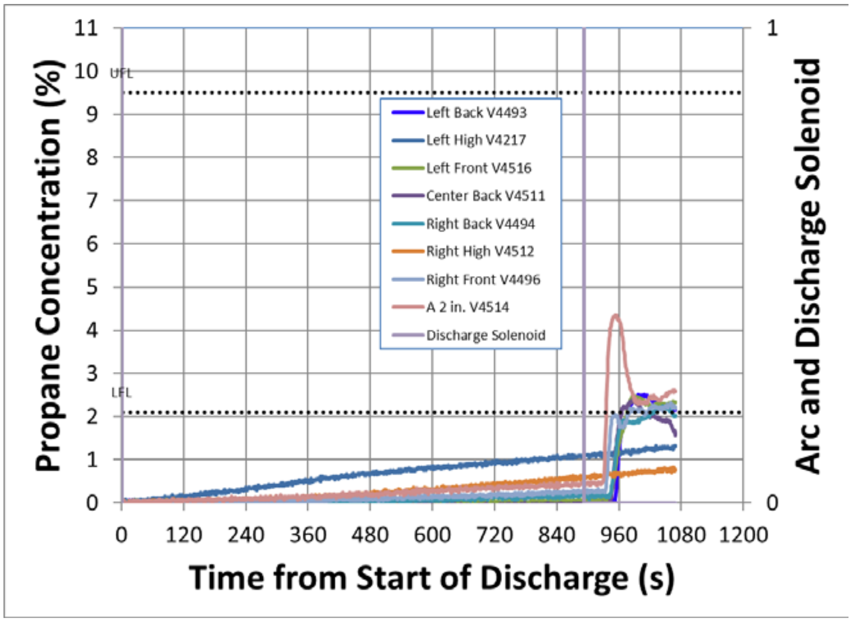


Figure 469 – RI_17 Concentrations at 8 locations surrounding cooler

Figure 571 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

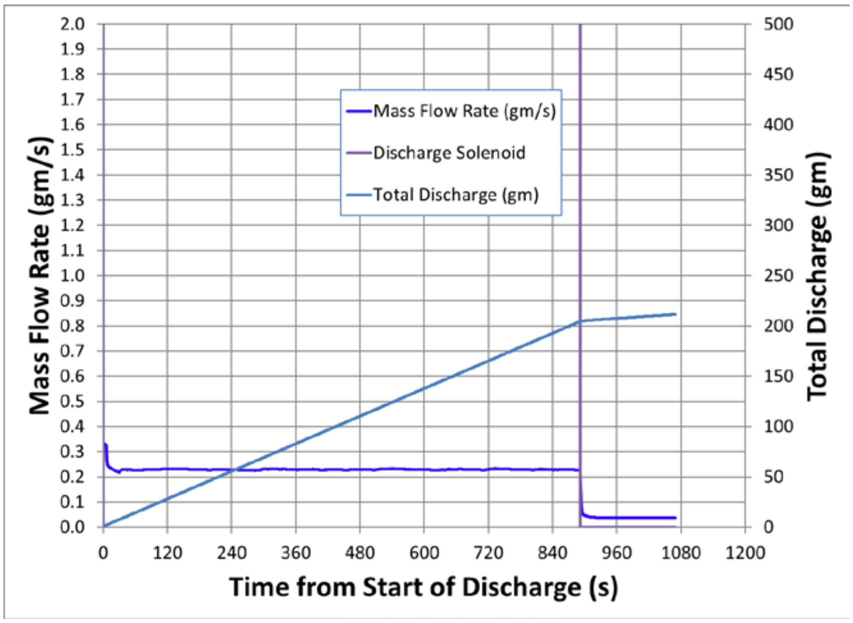


Figure 470 – RI_17 Mass Flow

Figure 572 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The drop in pressurizer pressure after completion of the discharge was due to disconnection of the tank in preparation for its replacement with a fresh tank for the next test.

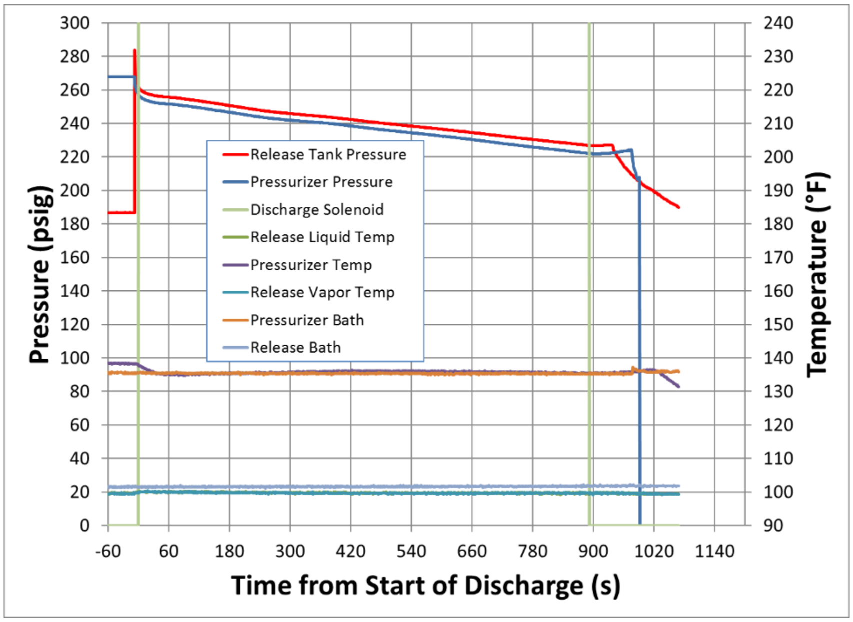


Figure 471 – RI_17 Pressurizer and Release Tank Pressure and Temperatures

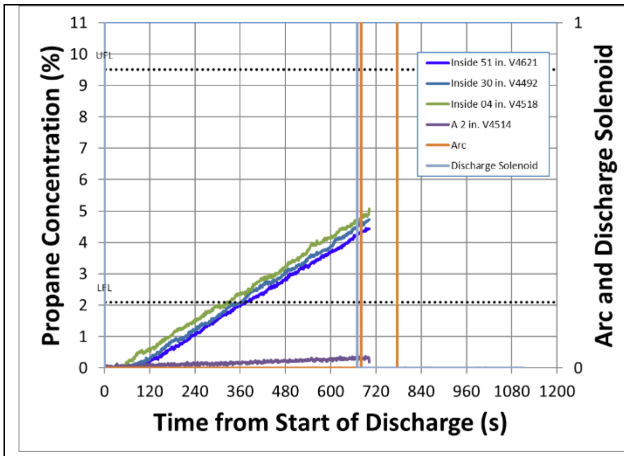
Test RI_18 (3-Door Cooler; 200 gram; Internal Release, with Arc Igniters)

Test RI_18 was performed with ignition sources and resulted in ignition at the arc location. The ignition event was in the transition between a deflagration and detonation because the apparent flame front speed was a significant fraction of the speed of sound. The key parameters and results of this test are summarized in the following table.

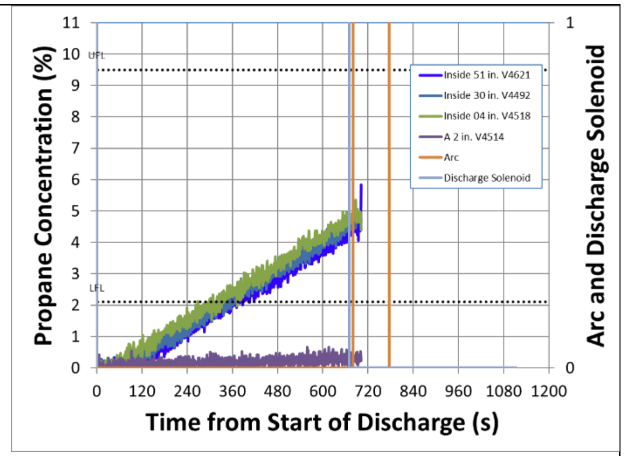
Table 99 – RI_17 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	200	11:10	0.299	Evaporator Return Bend
Measured	198	11:10	0.297	

Figure 573 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations



Deconvoluted Concentrations

Figure 472 – RI_18 Concentrations

Figure 574 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets. After accounting for the different discharge time in RI_17, this data is similar to that obtained in test RI_17 (see Figure 570).

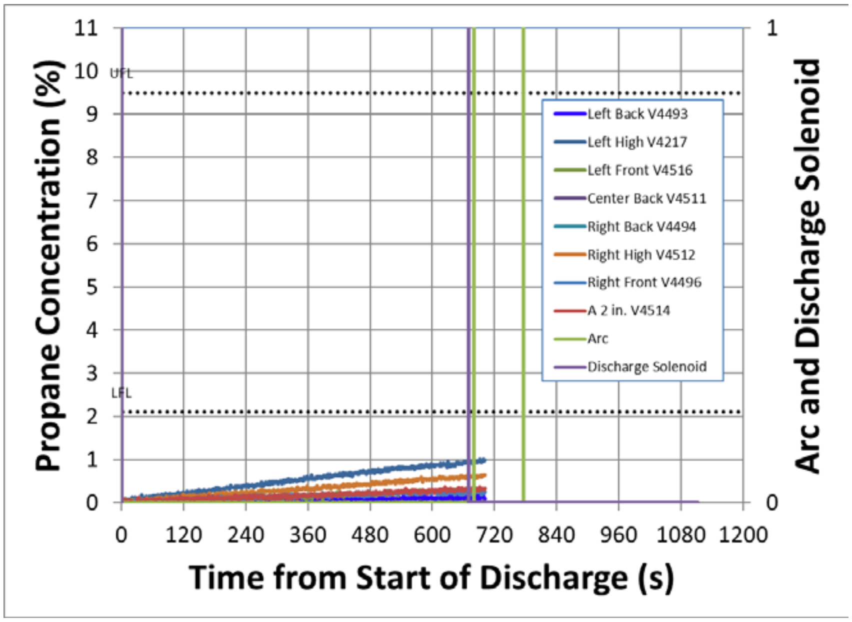


Figure 473 – RI_18 Concentrations at 8 locations surrounding cooler

Figure 575 compares the concentrations at the interior sensor (4 inch level) from tests RI_17 and RI_18 to show that concentrations were similar to within a few tenths of a percent relative to the discharge time. The range pf the upper x-axis scale for RI_17 is based the discharge time plus the 30 seconds soak time (922 seconds). The range of the lower x-axis scale for RI_18 has the same basis, but the range is 700 seconds. This data show that leakage from the door gaskets had little effect on the build-up of propane concentration in spite of the small difference in discharge rates.

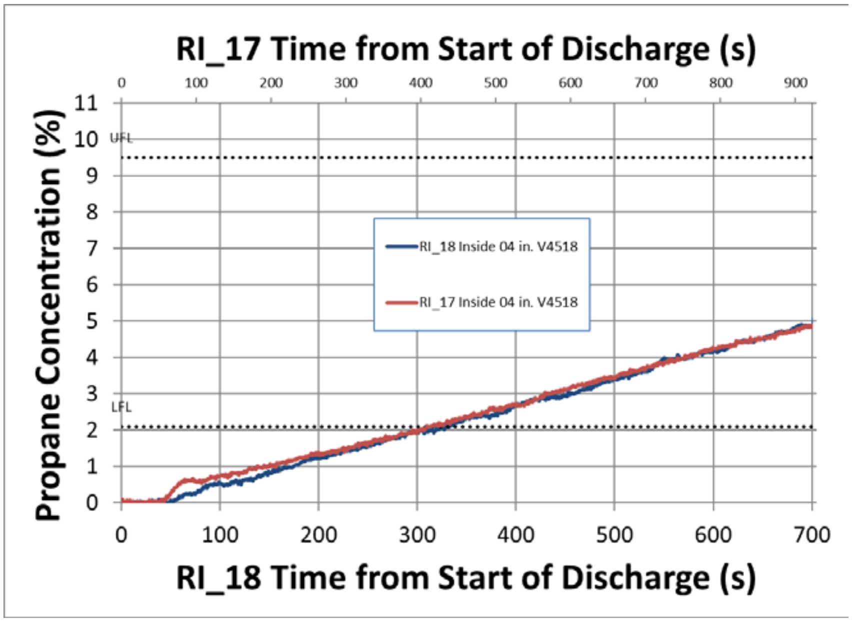


Figure 474 – RI_18 to RI_17 Concentration Comparison

Figure 576 shows the mass flow rate and total mass flow. Flow was initially low followed by the operator throttling up the flow rate to a constant level for the remainder of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

At time 703 seconds there is a spike caused by the quasi-detonation shaking the table holding the mass flow sensor. This spike does not represent an actual flow signal because the discharge solenoid was closed before the quasi-detonation.

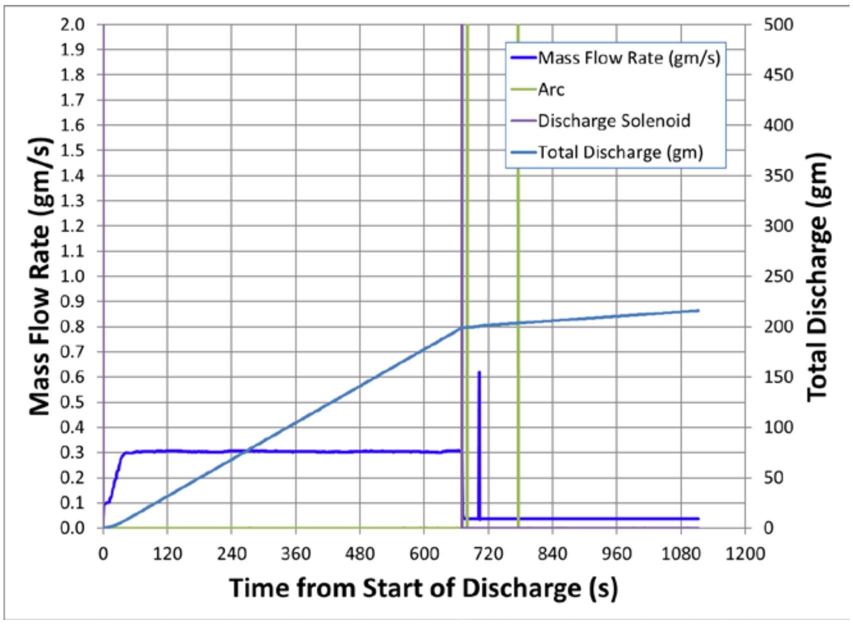


Figure 475 – RI_18 Mass Flow

Figure 577 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

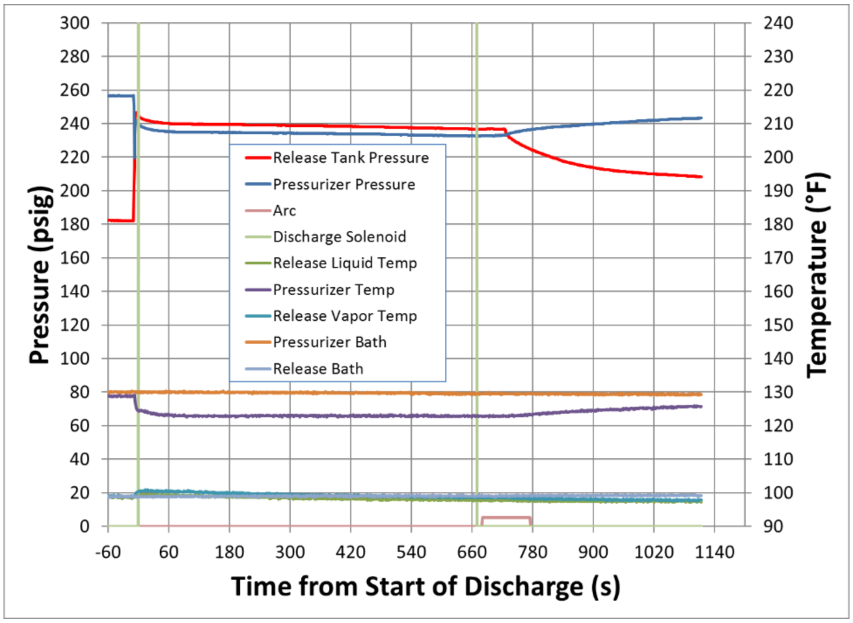


Figure 476 – RI_18 Pressurizer and Release Tank Pressure and Temperatures

Figure 578 shows the temperatures developed at the various locations following ignition. The data shows the highest temperature at location A at the 12 inch level close to the ignition source. Within a few seconds the highest temperatures were recorded at 4 inches below the ceiling (92 inches) due to buoyancy of the heated air.

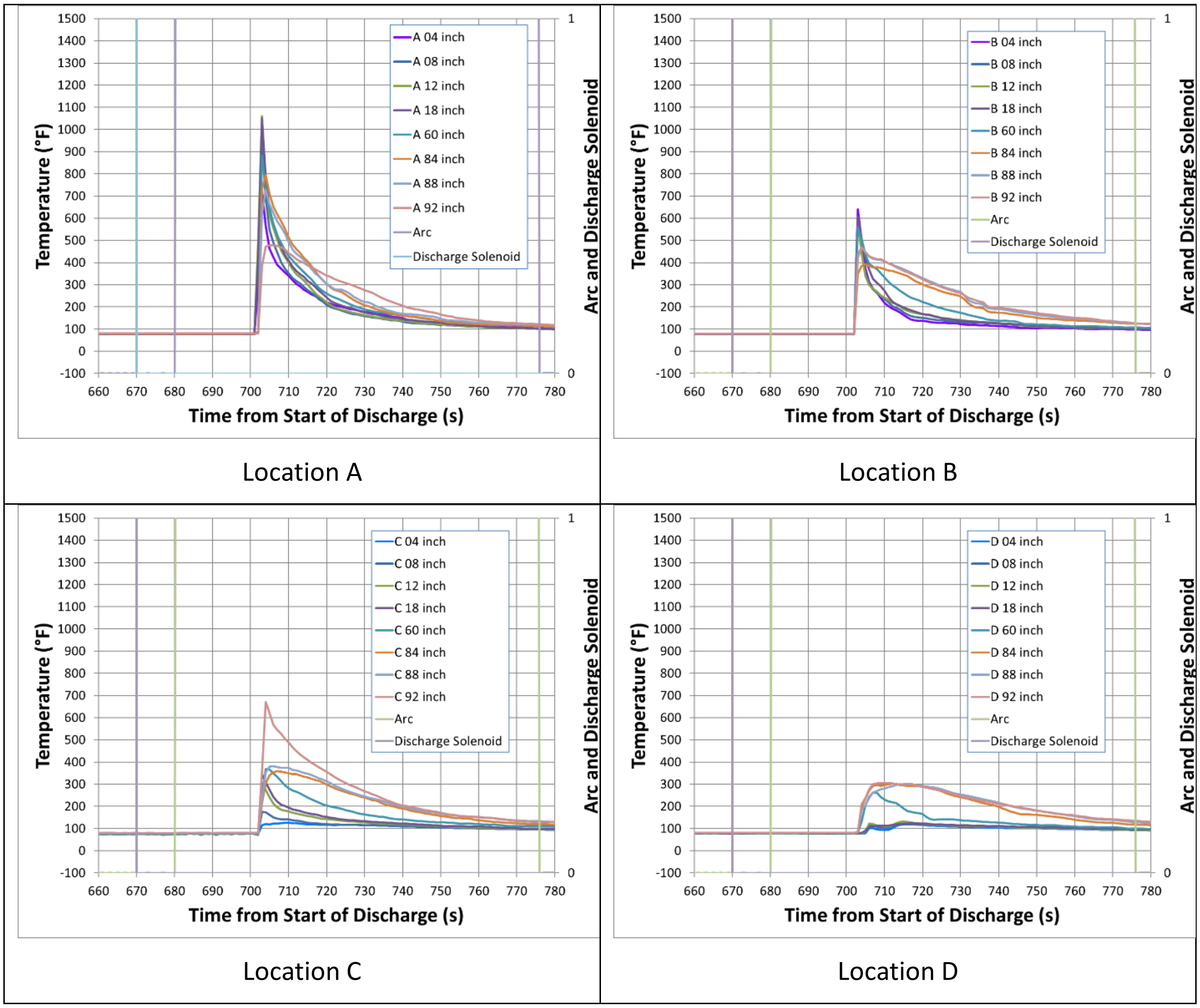


Figure 477 – RI_18 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 2 seconds. The deflagration pressure was sufficient to cause all 6 deflagration vents to open. The room pressure transmitter was inoperable during this test. Analysis of the videos shows a relatively slower speed flame progressing from the arc to the interior of the cooler. When this flame reached to top inside section of the cooler a quasi-detonation occurred with an estimated flame speed of approximately 130 m/s. The speed of sound is approximately 345 m/s which denotes the transition from deflagrations to detonations. This high fraction, 40%, of the speed of sound classifies this event as a quasi-detonation. [3]

Inspection of the exterior door and frame after this test showed that the door frame had been split and the latch mechanism broken due to the overpressure.

Figure 76 documents the estimate of the flame speed from the high speed camera.

	
Start of high speed flame	27 milliseconds after start of high speed flame
The high speed flame has extended 3.5 m from the cooler in 27 milliseconds or 130 m/s. The camera view changed due to the pressure wave impacting the camera's wall.	

Figure 478 – RI_18 Deflagration Overpressure Effects

Test RI_19 (3-Door Cooler; 397 gram; External Release; Fan Off)

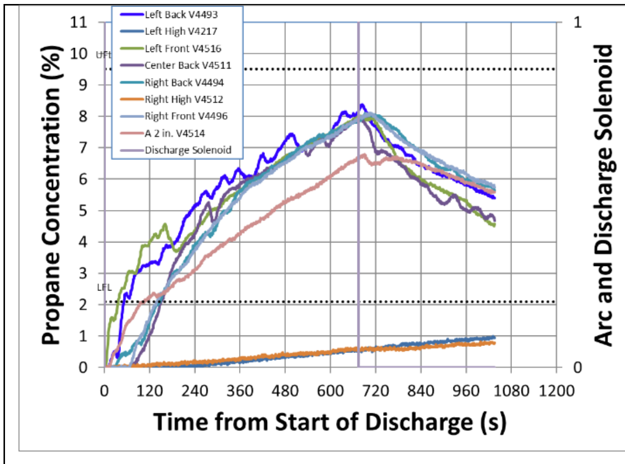
Test RI_19 was performed without ignition sources in order to measure propane concentrations prior to the conduct of test RI_20. This test involved an exterior release at the return bend of the condenser coil. The key parameters and results of this test are summarized in the following table.

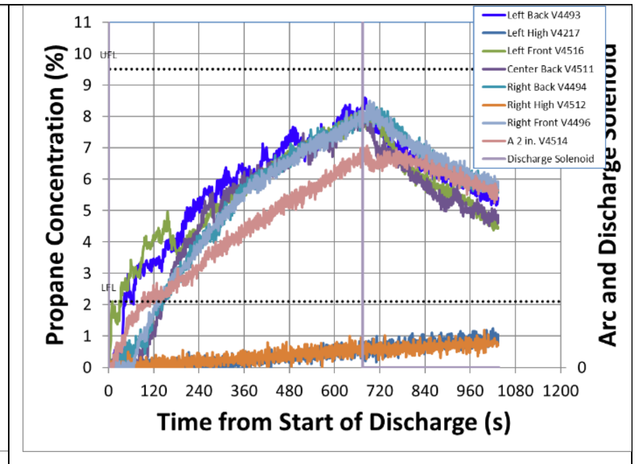
Table 100 – RI_19 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	397	11:10	0.593	Condenser Return Bend	0.5	Whole Room and Well Mixed
Measured	403	11:10	0.598		8.4 8.6 6.8	External External Deconvoluted Electric Arc Location

Per procedure, the discharge was initiated and stopped after 11 minutes and 10 seconds. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 524 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording at the 8 locations specified in by 2-89 CDV. The data show that the left-front sensor (closest to the condenser coil) recorded a value above the LFL within 30-35 seconds after the start of the discharge. All sensors at the 2 inch level were above LFL after 140 seconds and remained above the LFL until the end of data recording. The two sensors located high on the sides of the cooler reached a maximum value of 1.0% concentration.





Concentrations	Deconvoluted Concentrations

Figure 479 – RI_19 Concentrations

Figure 525 shows concentration measurements at other locations in the test room. The "Pan" sensor was located in the condensate pan just behind the condenser coil. The three sensors inside the cooler showed very little increase because the doors were closed. Additionally, the bottom of the cooler compartment was above floor level. The sensor at location A and 8 inches above the floor showed a maximum concentration of 4.0% . This shows that the entire volume of flammable mixture was located near the floor. The sensor at location B and 2 inches above the floor was nearly uniform with the A-2 inch location. This observation and the video of the fire in test RI_20 shows that this flammable layer was distributed throughout the room at floor level.

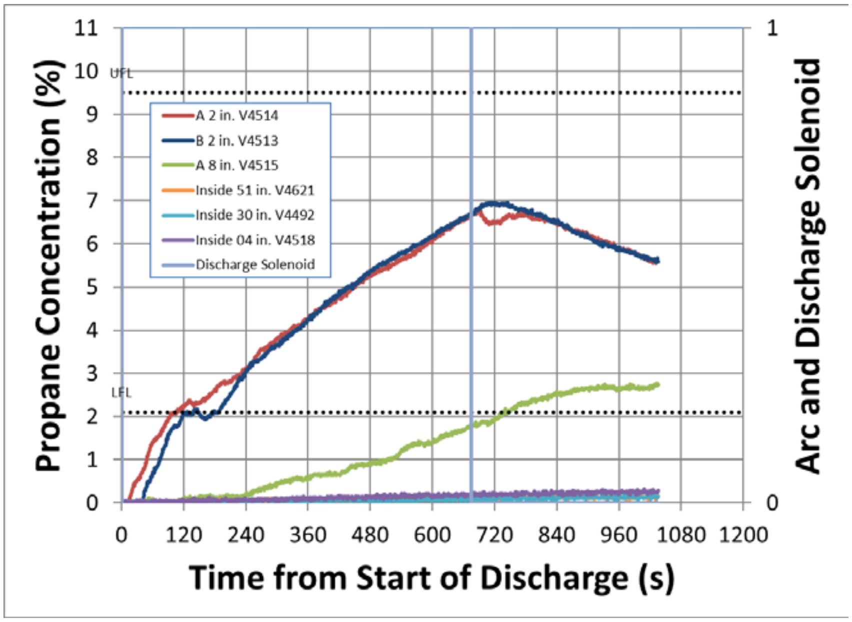


Figure 480 – RI_19 Other Concentrations

Figure 526 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

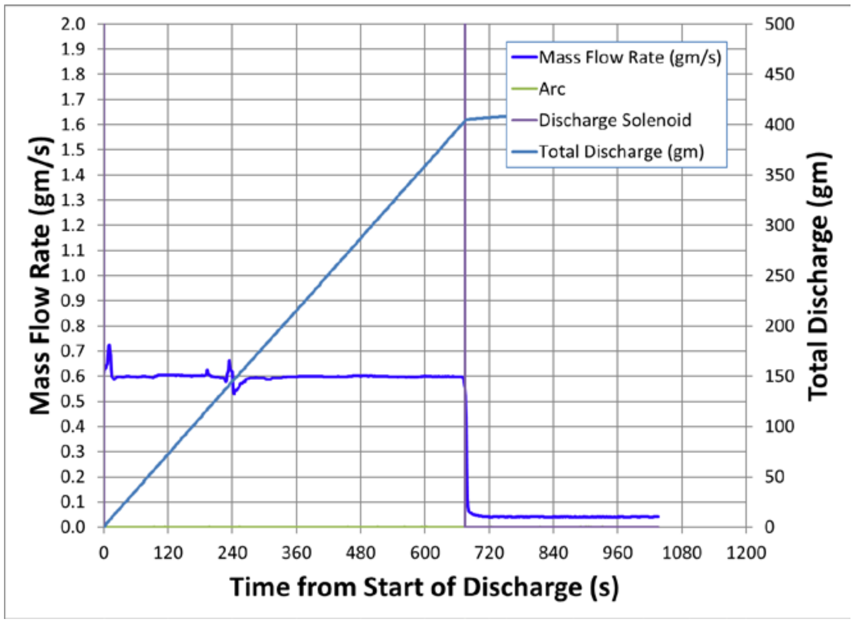


Figure 481 – RI_19 Mass Flow

Figure 527 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

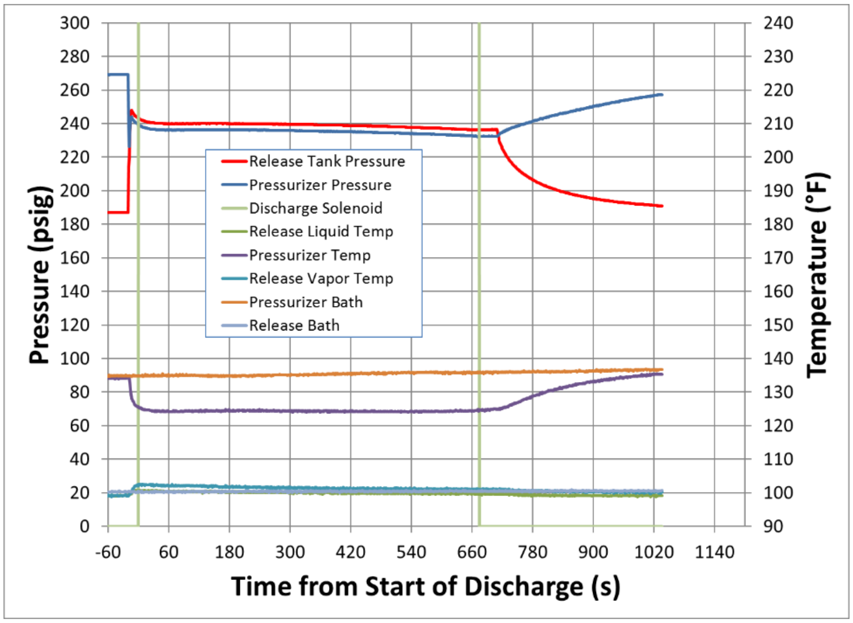


Figure 482 – RI_19 Pressurizer and Release Tank Pressure and Temperatures

Test RI_20 (3-Door Cooler; 397 gram; External Release, Fan off, with Arc Igniters)

Test RI_20 was performed with ignition sources and resulted in ignition at the arc locations. The key parameters and results of this test are summarized in the following table.

Table 101 – RI_20 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	397	11:10	0.593	Condenser Return Bend
Measured	400	11:10	0.597	

Figure 528 shows the concentrations measured up to the point that combustion products caused a false measure of propane concentration. The figure shows the concentrations at the eight locations specified by 2-89 CDV.

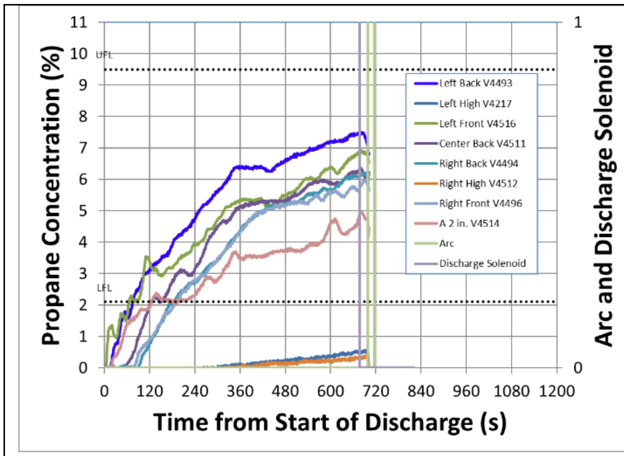
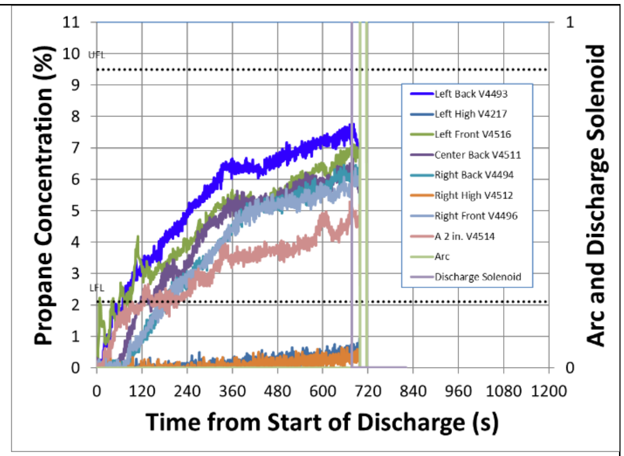
	
Concentrations	Deconvoluted Concentrations

Figure 483 – RI_20 Concentrations

Figure 529 compares the concentrations at Left-Back exterior sensor in tests RI_19 and RI_20 to show that concentrations were similar to within a few tenths of a percent.

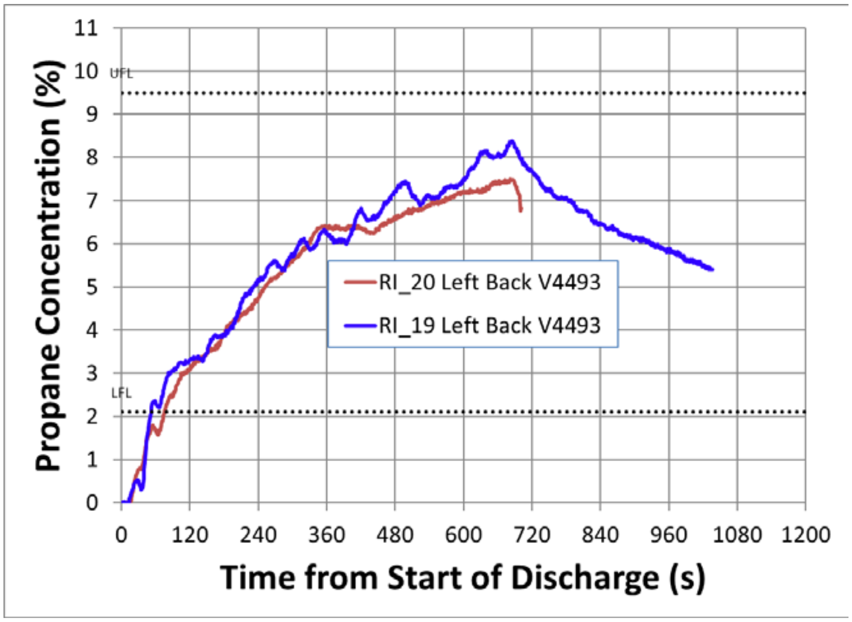


Figure 484 – RI_20 to RI_19 Concentration Comparison

Figure 530 shows the mass flow rate and total mass flow. While the initial flow rate was low, the operator was then able to throttle up to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

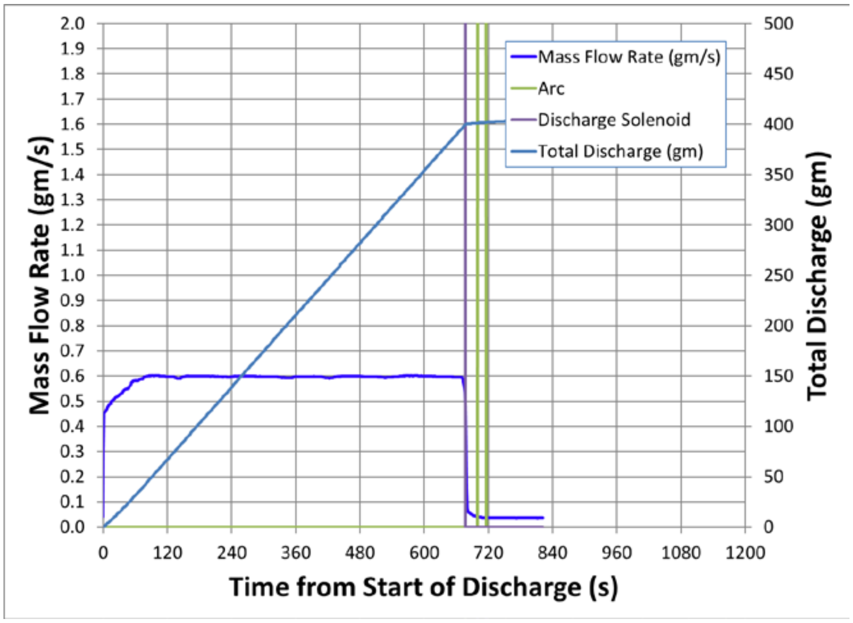


Figure 485 – RI_20 Mass Flow

Figure 531 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

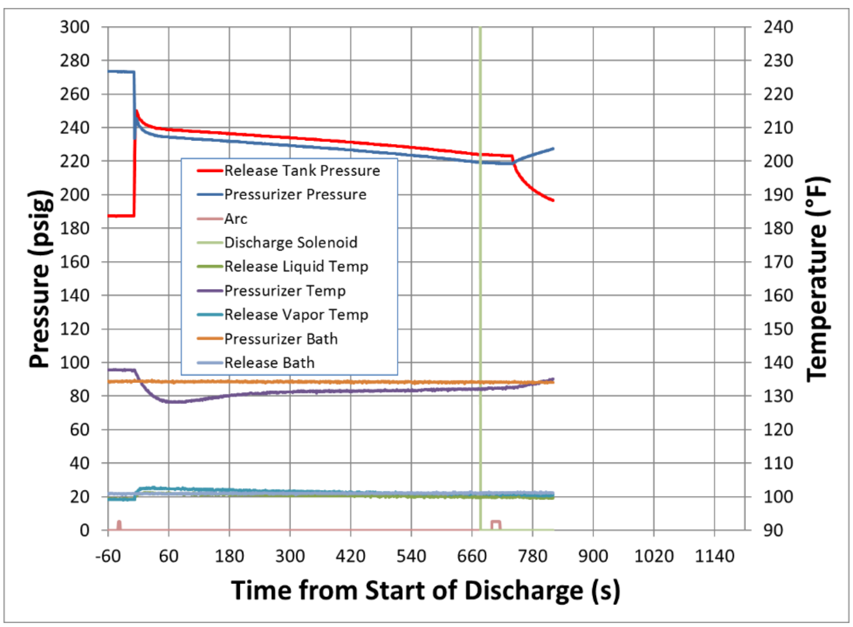


Figure 486 – RI_20 Pressurizer and Release Tank Pressure and Temperatures

Figure 532 shows the temperatures developed at the various locations following ignition. The data shows the highest peak temperatures at location B and D (4 inch and 12 inch, respectively). Location D is the most remote location from the electric arc demonstrating that the floor level flammable mixture pool had spread throughout the test room. Within a few seconds the highest temperatures were recorded at 4 inches below the ceiling (92 inches) due to buoyancy of the heated air.

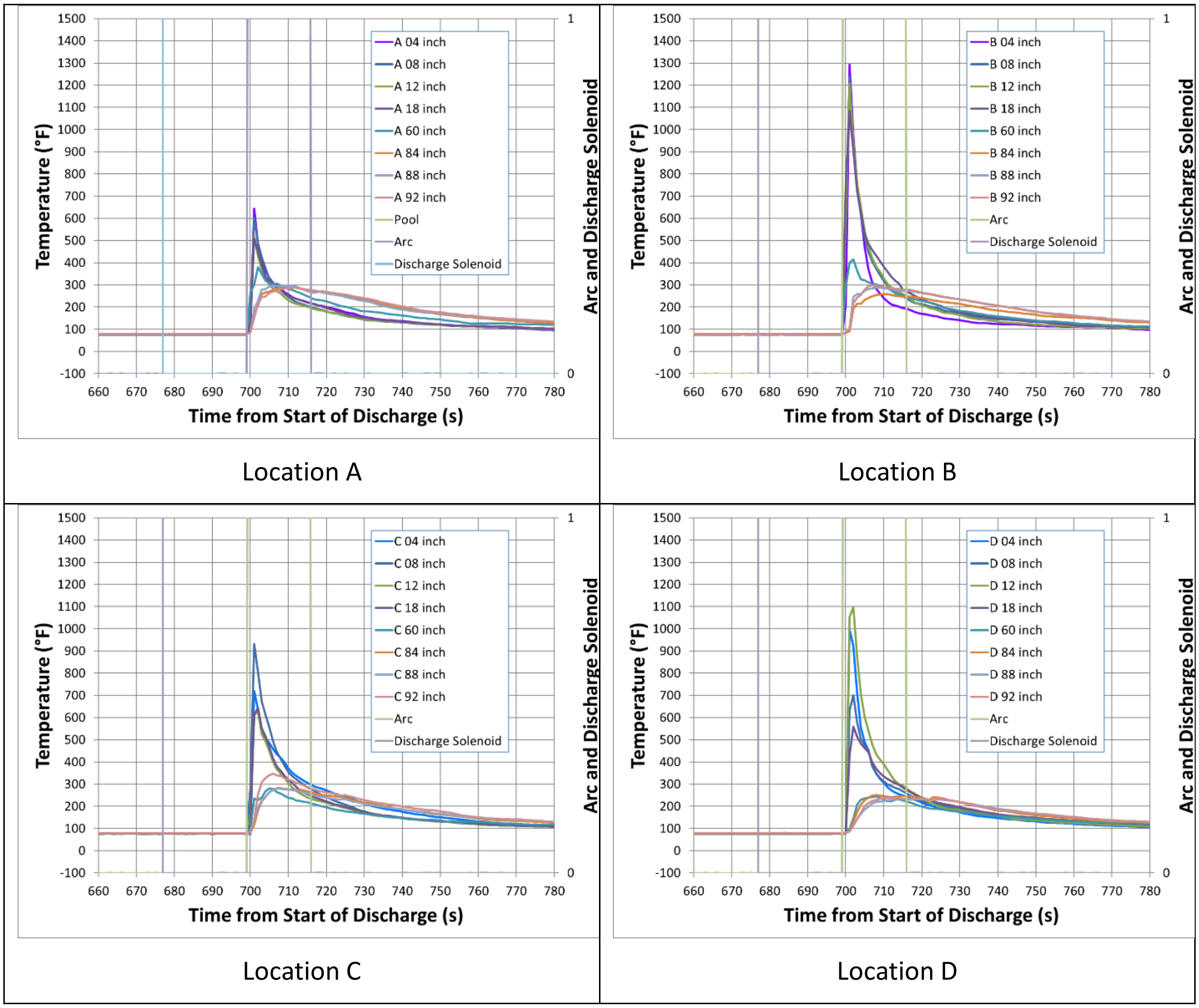


Figure 487 – RI_20 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for three seconds with the exception of the cheesecloth strips which had all ignited. Figure 488 shows the faint blue rings of a pre-mixed flame propagating from arc locations A and B. The Location B propagating ring is visible in the reflection on the cooler doors.

Figure 488 – RI_20 Simultaneous Ignition at Locations A and B

Figure 489 shows additional evidence of a pool at floor level as the flame front is captured just prior to washing over location D, the most remote location from the leak at the condenser and the electric arcs.

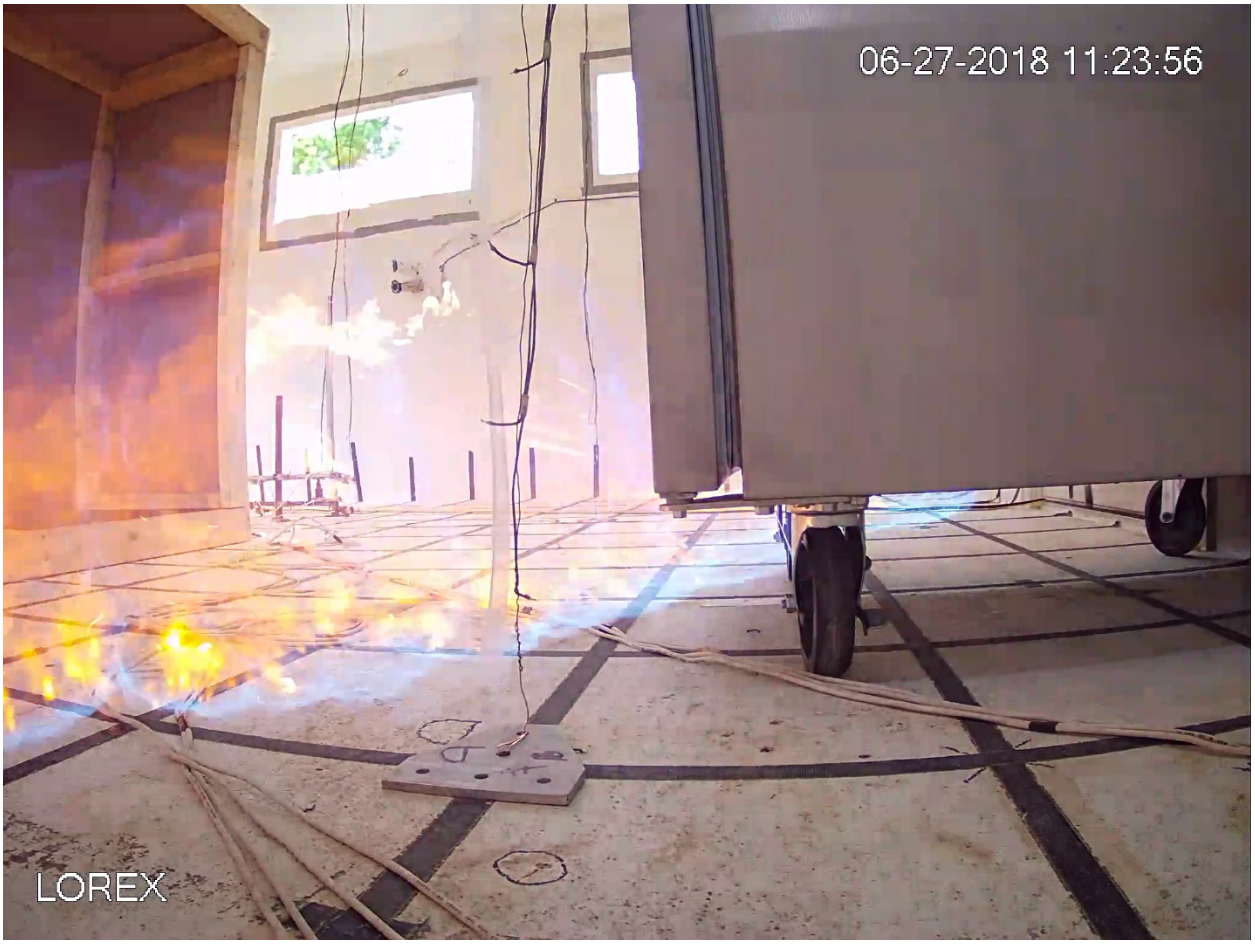


Figure 489 – RI_20 Floor level flame front propagating to location D

Figure 490 shows that the rear door of the test room was blown open by the overpressure as well as four of the deflagration vents. The latch of the test room door had been damaged by overpressure in test RI_18. For test RI_20 the door had been sealed with duct tape, but did not have sufficient holding force to keep the door closed during this event.

Figure 490 – RI_20 Overpressure causing damaged door latch to release

Test RI_37 (3-Door Cooler; 397 gram; External Release; Fan On; with Arc Igniters)

Test RI_37 was performed with ignition sources, but there was no resulting ignition. The exterior leak was at a condenser return bend with the condenser fan operating throughout this test. The purpose was to demonstrate the effect of the fan on propane concentration. The key parameters and results of this test are summarized in the following table.

Table 102 – RI_37 Summary

<table>
<tr><th></th><th>Discharge Amount (g)</th><th>Duration of Discharge MM:SS</th><th>Discharge Rate (g/s)</th><th>Leak Location</th><th colspan="2">Maximum Concentration (%)</th></tr>
<tr><td>Planned</td><td>397</td><td>11:10</td><td>0.593</td><td rowspan="4">Condenser Return Bend</td><td>0.5</td><td>Whole Room and Well Mixed</td></tr>
<tr><td rowspan="3">Measured</td><td rowspan="3">392</td><td rowspan="3">11:10</td><td rowspan="3">0.586</td><td>1.2</td><td>External</td></tr>
<tr><td>1.4</td><td>External Deconvoluted</td></tr>
<tr><td>1.1</td><td>Electric Arc Location</td></tr>
</table>

Per procedure, the discharge was stopped after 11 minutes and 10 seconds. The electric arcs were energized 27 seconds after completion of the discharge. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 491 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording at the 8 locations specified in by 2-89 CDV. The data show that the right-back sensor recorded a peak of 1.2%. The deconvoluted data show peak values of 1.4% at several sensors. The two sensors located high on the cooler reach a maximum value of 1.2% and 1.1% concentration (left and right, respectively).

This data show that the fan was effective at mixing high and low sensor locations to nearly uniform values. These values are above the expected uniformly mixed value of 0.5%. Sensors were not located further away from the cooler than location B and concentrations at more remote parts of the test room are unknown.

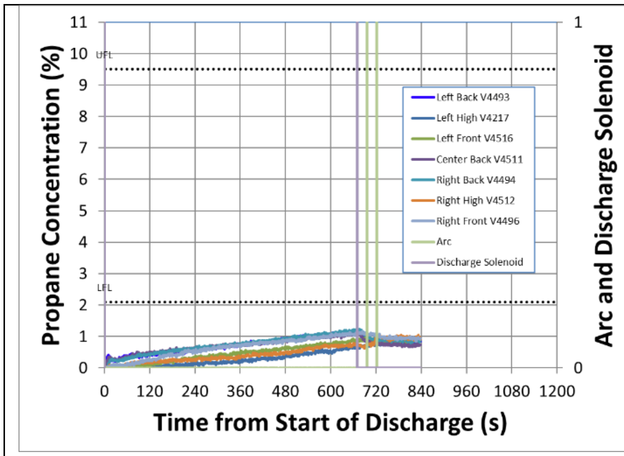
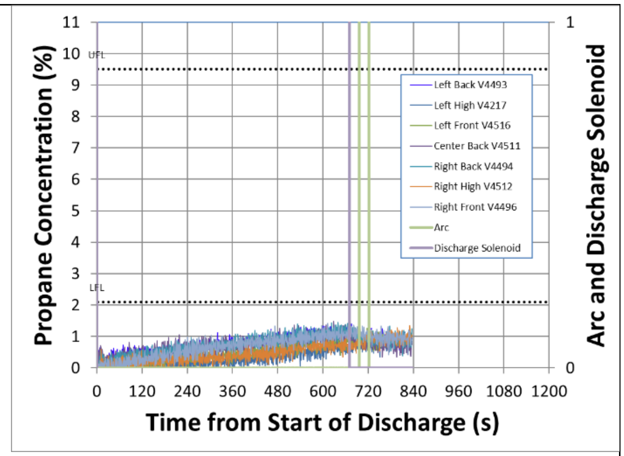
	
Concentrations	Deconvoluted Concentrations

Figure 491 – RI_37 Concentrations

Figure 492 shows concentration measurements at other locations in the test room. The “Pan” sensor was located in the condensate pan just behind the condenser coil and closest to the discharge location. This sensor showed the highest concentrations during the discharge, but quickly dropped to the level of other sensors immediately after the discharge was complete.

The three sensors inside the cooler showed very little increase because the doors were closed.

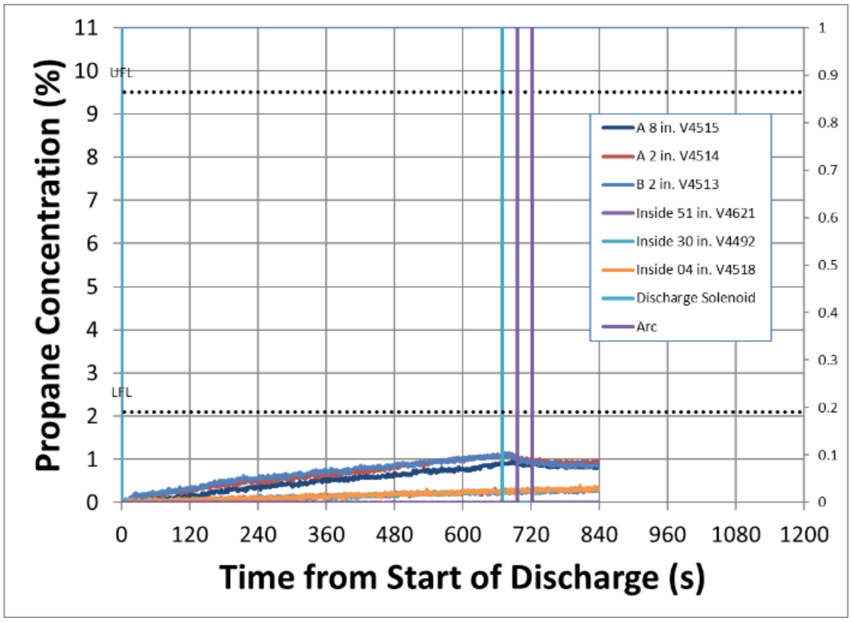


Figure 492 – RI_37 Other Concentrations

Figure 493 shows the mass flow rate and total mass flow. The initial flow was low and operator was then able to throttle up the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used calculate the total mass release.

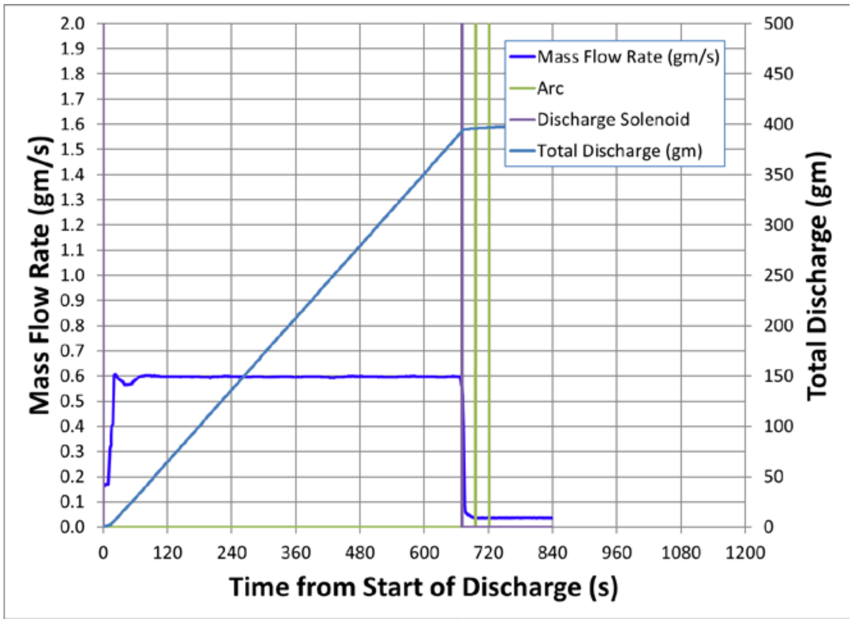


Figure 493 – RI_37 Mass Flow

Figure 494 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began a return to pre-test pressures based on their respective bath temperatures.

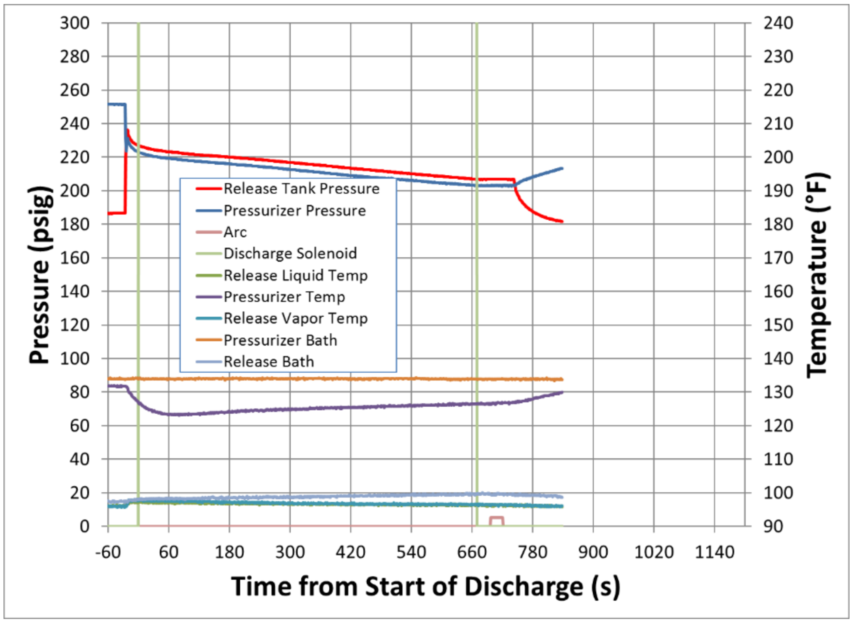


Figure 494 – RI_37 Pressurizer and Release Tank Pressure and Temperatures

Appendix E Task 2 Single Door Reach-In Cooler Test Data and Summary

This appendix summarizes the tests with the single-door reach in cooler.

The following table summarizes all tests with the single-door reach-in cooler. The sections that follow describe each test in detail.

Temperatures are color coded according to the following legend:

Range
< 0°F
0 – 105 °F
105 – 400 °F
400°F and higher

Table 103 – Single-Door Reach-in Cooler Tests

												Raw Video Times HH:MM:SS									Maximum Concentrations, Location, and Time Relative to Start of Discharge			Deconvoluted Concentrations, Location, and Time Relative to Start of Discharge			
Test Code	Date	Purpose	Condenser Fan State	Planned Discharge (g)	Planned Discharge Rate (g/s)	Planned Duration (MM:SS)	Measured Mass (g)	Measured Rate (g/s)	Measured Duration (MM:SS)	Discharge Location	Discharge Opening Capillary Tube I.D. (in.)	Door Start	Door Open	Ignition	Max Pressure (mmHg)	Max Temp (°F)	Max Temp Location	Max Ceiling Temp (°F)	Number of Vents Burst/Melted	Result	Location	Max Conc. (%)	Max Conc. Time (s)	Location	Max Decon. (%)	Max Decon. Time (s)	Analysis File
RI_21	03-Jul-2018	Concentration	NA	25	0.224	01:52	24	0.214	01:52	Evap.	0.026	13:03:17	13:03:23	NA	NA: Concentration Measurements						Inside 54 in.	0.4	168	Inside 54 in.	0.6	160	RI_21_2018-07-03-1257 Analysis.xlsx
RI_22	03-Jul-2018	Concentration	NA	50	0.224	03:43	47	0.211	03:42	Evap.	0.026	13:37:19	13:37:22	NA							Inside 54 in.	2.3	267	Inside 54 in.	2.7	263	RI_22_2018-07-03-1328 Analysis.xlsx
RI_23	03-Jul-2018	Concentration	NA	75	0.224	05:35	76	0.228	05:34	Evap.	0.026	14:09:32	14:09:35	NA							Inside 30 in.	5.2	367	Inside 54 in.	5.5	369	RI_23_2018-07-03-1357 Analysis.xlsx
RI_24	03-Jul-2018	Concentration	NA	100	0.224	07:27	103	0.233	07:25	Evap.	0.026	14:42:06	14:42:09	NA							Inside 30 in.	7.1	478	Inside 30 in.	7.3	476	RI_24_2018-07-03-1430 Analysis.xlsx
RI_25	05-Jul-2018	Concentration	NA	125	0.224	09:18	124	0.224	09:12	Evap.	0.026	10:49:23	10:49:26	NA							Inside 30 in.	8.4	586	Inside 30 in.	8.6	585	RI_25_2018-07-05-1034 Analysis.xlsx
RI_26	05-Jul-2018	Concentration	NA	150	0.224	11:10	154	0.229	11:09	Evap.	0.026	11:26:24	11:26:27	NA							Inside 30 in.	10.6	704	Inside 30 in.	10.8	703	RI_26_2018-07-05-1110 Analysis.xlsx
RI_27	05-Jul-2018	Concentration	Off	397	0.593	11:10	390	0.583	10:50	Cond.	0.026	NA: External Release									Vent	1.8	606	Vent	2.0	476	RI_27_2018-07-05-1354 Analysis.xlsx
RI_28	05-Jul-2018	Concentration	On	397	0.593	11:10	394	0.590	11:09	Cond.	0.026										Vent	0.9	652	Vent	1.1	731	RI_28_2018-07-05-1427 Analysis.xlsx
RI_29	06-Jul-2018	Ignition Test	Off	397	0.593	11:10	406	0.606	11:10	Cond.	0.026	Igniter energized at 09:41:34			0.0	89	B-18	76	0/0	None	Vent	2.0	630	Vent	2.2	626	RI_29_2018-07-06-0925 Analysis.xlsx
RI_30	09-Jul-2018	Ignition Test	NA	75	0.224	05:35	81	0.242	05:35	Evap.	0.026	10:33:06	10:33:08	10:33:09	2.9	957	B-18	236	4/1	Ignition	NA: Ignition occurred						RI_30_2018-07-09-1022 Analysis 50 Hz.xlsx
RI_31	09-Jul-2018	Concentration	NA	100	0.224	07:27	103	0.231	07:25	Evap.	0.026	No Video Recorded			NA: Concentration Measurements						Inside 04 in.	7.3	461	Inside 04 in.	7.6	460	RI_31_2018-07-09-1117 Analysis.xlsx
RI_32	09-Jul-2018	Ignition Test	NA	100	0.224	07:27	102	0.229	07:26	Evap.	0.026	13:29:54	13:29:57	13:29:57	3.4	788	A-08	316	2/2	Ignition	NA: Ignition occurred						RI_32_2018-07-09-1317 Analysis 50 Hz.xlsx
RI_33	09-Jul-2018	Concentration	NA	125	0.224	09:18	130	0.233	09:17	Evap.	0.026	14:33:16	14:33:19	NA	NA: Concentration Measurements						Inside 04 in.	8.9	590	Inside 04 in.	9.1	568	RI_33_2018-07-09-1419 Analysis.xlsx
RI_34	09-Jul-2018	Ignition Test	NA	125	0.224	09:18	128	0.229	09:18	Evap.	0.026	15:16:12	15:16:15	15:16:15	5.3	914	A-12	473	1/4	Ignition	NA: Ignition occurred						RI_34_2018-07-09-1502 Analysis 50 Hz.xlsx
RI_35	10-Jul-2018	Concentration	NA	150	0.224	11:10	153	0.229	11:09	Evap.	0.026	09:34:06	09:34:09	NA	NA: Concentration Measurements						Inside 30 in.	10.5	703	Inside 30 in.	10.7	702	RI_35_2018-07-10-0916 Analysis.xlsx
RI_36	10-Jul-2018	Ignition Test	NA	150	0.224	11:10	149	0.225	11:01	Evap.	0.026	13:24:19	13:24:22	13:24:22	3.6	774	A-18	440	1/3	Ignition	NA: Ignition occurred						RI_36_2018-07-10-1307 Analysis 50 Hz.xlsx

Notes:

- The times recorded for the raw video are from the date/time stamp (time portion only) in the video.
- Temperatures are recorded in the cases where ignition occurred.
- Propane concentrations are recorded in cases where the igniters were not used except for RI_29.
- Test RI_29 (ignition tests) does record concentrations because there was no sign of ignition at the electric arc.
- Refer to the main body of the report for the description of sensor locations.

Videos for each test are stored separately. The correspondence of channel number to camera view is as follows:

Video Channel	Camera Location
2	East Wall Upper
3	Northeast Floor Corner
4	South Wall Center
6	East Side Vents
7	West Side Vents
9	Test Marquee and Clock
10	IR Camera West Wall
11	West Wall Upper

High speed camera videos are stored in the same folder for each test. High speed cameras were used where ignition was expected. The following table matches the test number with the high-speed camera video:

High Speed Cameras		
Test	**Floor Level**	**High Level**
RI_30	CIMG3372.MOV	CIMG3373.MOV
RI_32	CIMG3373.MOV	CIMG3374.MOV
RI_34	CIMG3374.MOV	CIMG3375.MOV
RI_36	CIMG3375.MOV	CIMG3376.MOV

Note: The cameras assigned file names automatically. Some filenames are identical and are stored separately. For example CIMG3474.MOV appears twice on the list above, but they contain different video.

Test RI_21 (25 g; Internal Release)

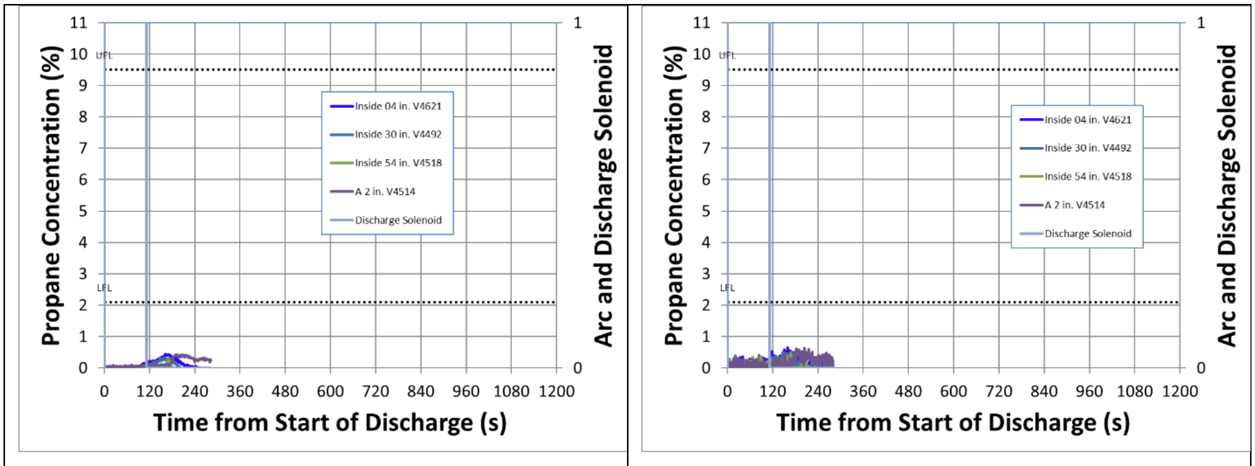
Test RI_21 was performed without ignition sources to measure propane concentrations. Because this test was part of the risk assessment for ignition (step-wise approach to 150 g), there was no associated igniter test. The key parameters and results of this test are summarized in the following table.

Table 104 – RI_21 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	25	01:52	0.224	Evaporator Return Bend	2.3	Calculated with no leakage and well mixed
					0.03	Well mixed in test room
Measured	24	01:52	0.214		0.4	Internal
					0.7	Internal Deconvoluted
					0.5	Electric Arc Location

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 495 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording. Concentrations did not exceed 0.5%.



Concentrations	Deconvoluted Concentrations

Figure 495 – RI_21 Concentrations

Figure 496 shows the measured concentrations at the eight locations specified by 2-89 CDV. There was a slight increase in concentration after the cooler door was opened. The maximum concentration observed was 0.5%.

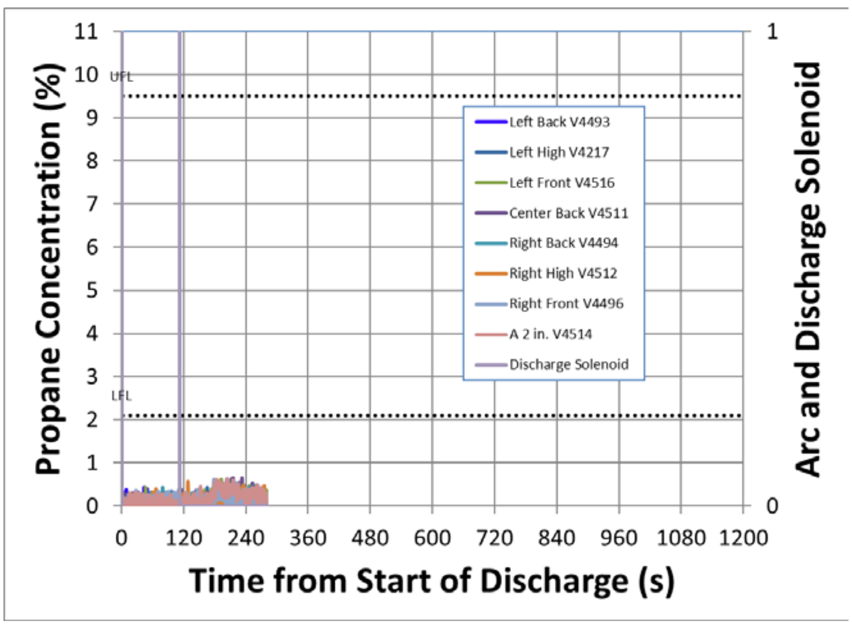


Figure 496 – RI_21 Concentrations at 8 locations surrounding cooler

Figure 497 shows the mass flow rate and total mass flow. The operator had some difficulty establishing a constant flow. This was corrected in later tests. In any case, the discharge solenoid was closed when a 25 g discharge was observed. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

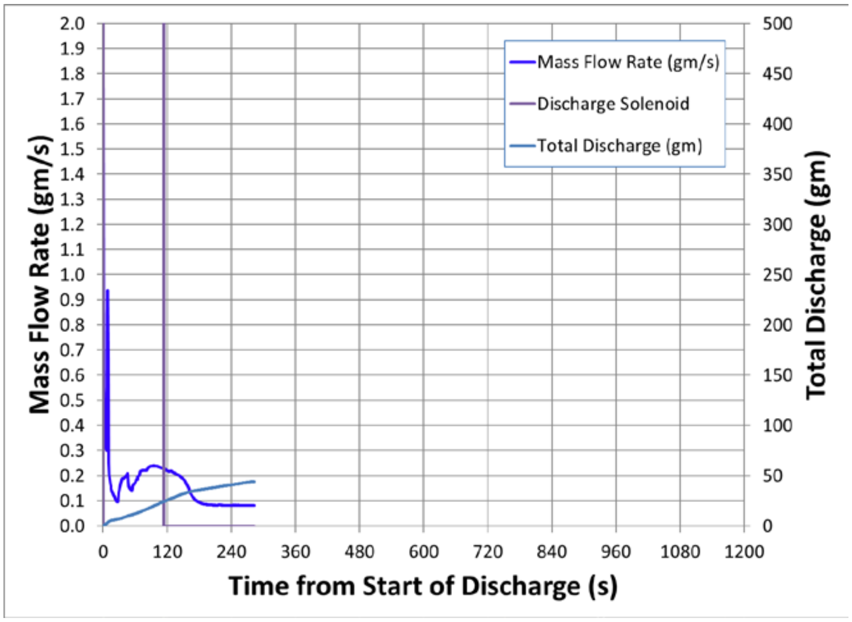


Figure 497 – RI_21 Mass Flow

Figure 572 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

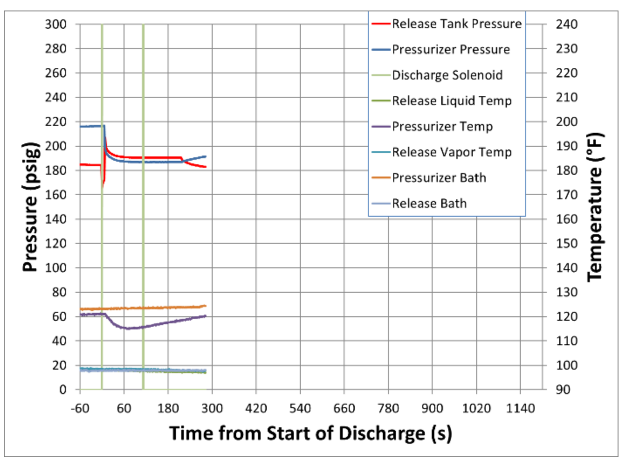


Figure 498 – RI_21 Pressurizer and Release Tank Pressure and Temperatures

Test RI_22 (50 g; Internal Release)

Test RI_22 was performed without ignition sources to measure propane concentrations. Because this test was part of the risk assessment for ignition (step-wise approach to 150 g), there was no associated igniter test. The key parameters and results of this test are summarized in the following table.

Table 105 – RI_22 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	50	03:43	0.224	Evaporator Return Bend	4.6	Calculated with no leakage and well mixed
					0.06	Well mixed in test room
Measured	47	03:42	0.211		2.3	Internal
					2.8	Internal Deconvoluted
					1.7	Electric Arc Location

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 499 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording. The data show concentrations above the LFL inside the cooler, but the peak at the electric arc location is less than LFL at 1.7%.

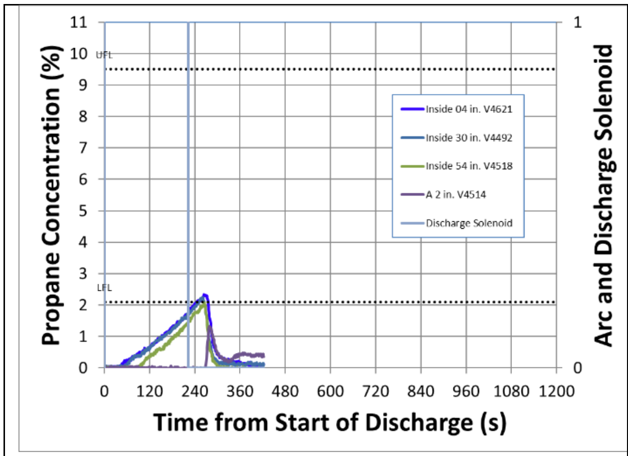
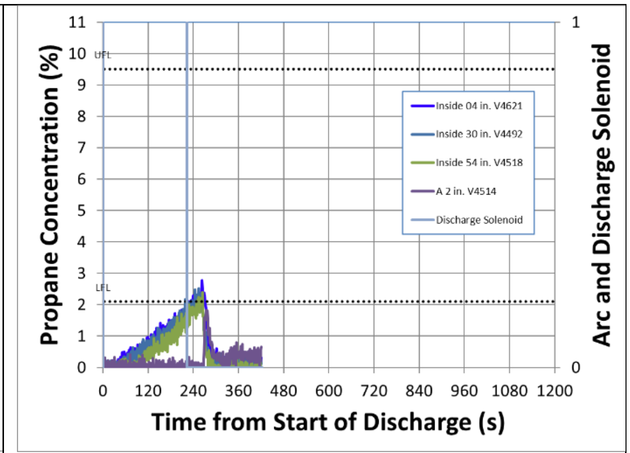
	
Concentrations	Deconvoluted Concentrations

Figure 499 – RI_22 Concentrations

Figure 496 shows the measured concentrations at the eight locations specified by 2-89 CDV. All concentrations were less than the LFL of propane.

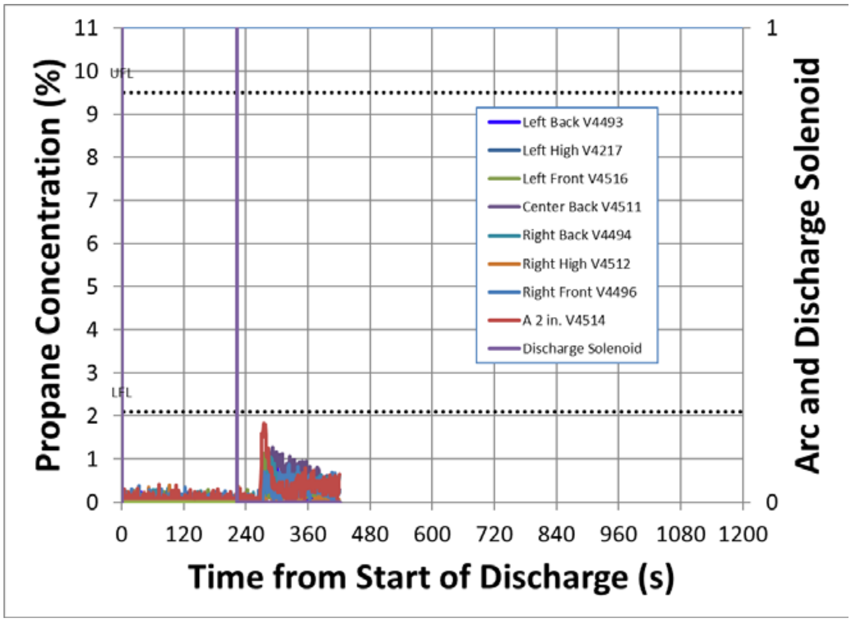


Figure 500 – RI_22 Concentrations at 8 locations surrounding cooler

Figure 501 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

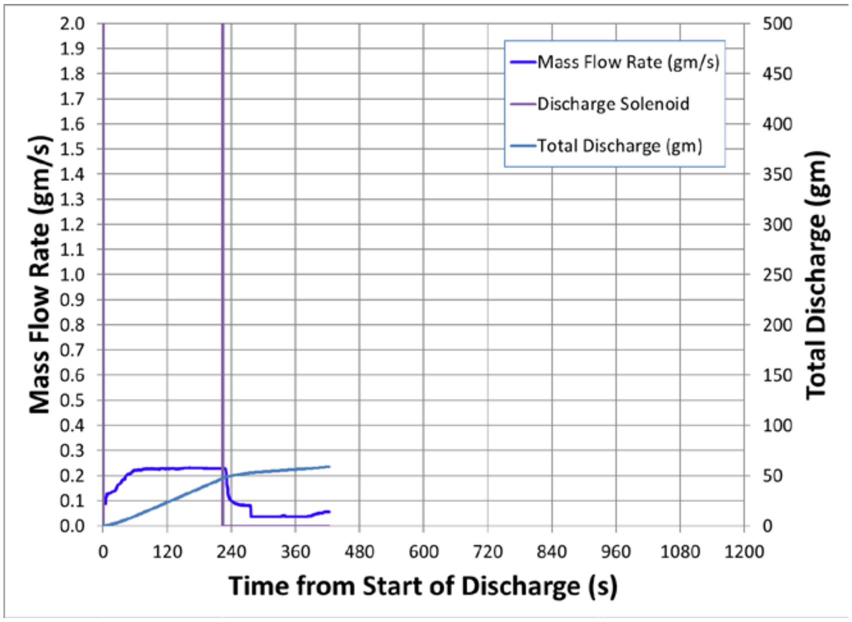


Figure 501 – RI_22 Mass Flow

Figure 502 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

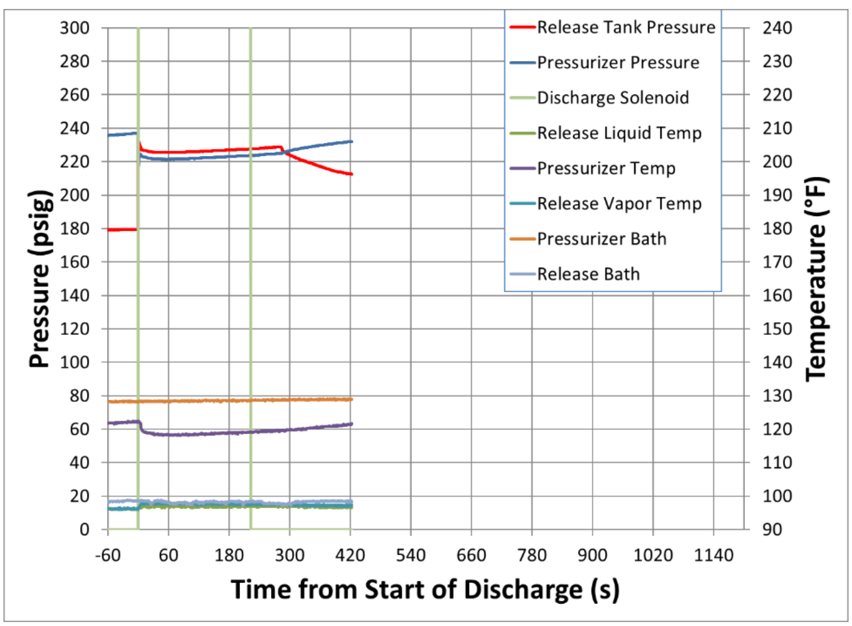


Figure 502 – RI_22 Pressurizer and Release Tank Pressure and Temperatures

Test RI_23 (75 g; Internal Release)

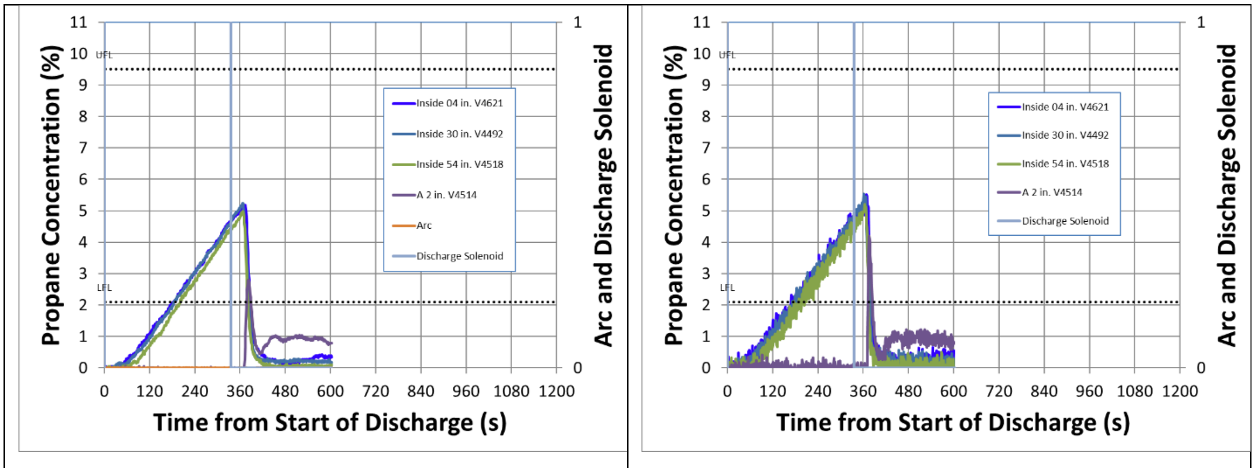
Test RI_23 was performed without ignition sources to measure propane concentrations. This concentration test showed a concentration above LFL at the electric arc location and was followed by an igniter test later in the program (RI_30).

Table 106 – RI_23 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	75	05:35	0.224	Evaporator Return Bend	6.9	Calculated with no leakage and well mixed
					0.09	Well mixed in test room
Measured	76	05:34	0.228		5.2	Internal
					5.5	Internal Deconvoluted
					4.2	Electric Arc Location

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 503 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording. The data show concentrations above the LFL inside the cooler, but the peak at the electric arc location is less than LFL at 1.7%.



Concentrations	Deconvoluted Concentrations

Figure 503 – RI_23 Concentrations

Figure 504 shows the measured concentrations at the eight locations specified by 2-89 CDV. There was a period of 20 seconds when some concentrations were above the LFL of propane. Final propane concentrations at the floor level were between 0.5% and 1.2%. Concentrations at the high level were negligible.

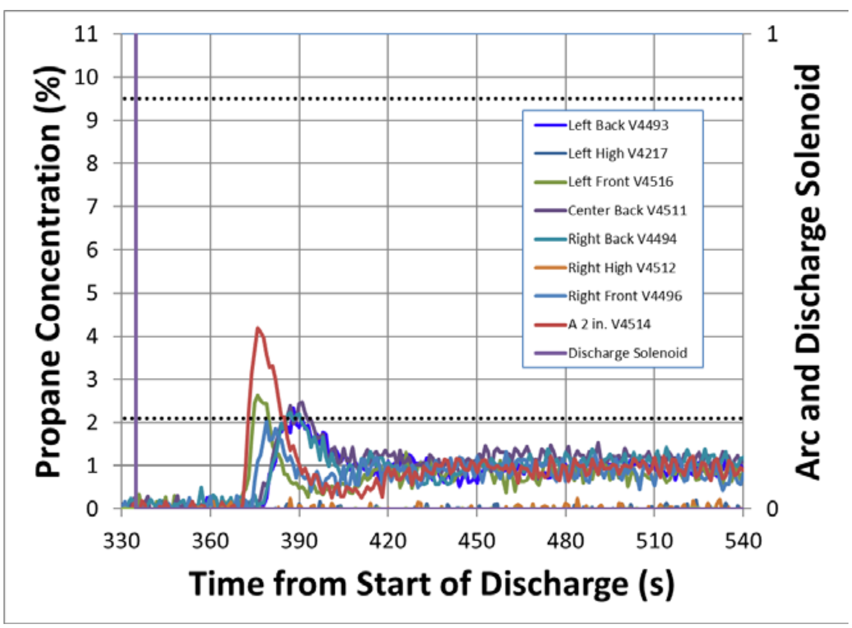


Figure 504 – RI_23 Concentrations at 8 locations surrounding cooler

Figure 505 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

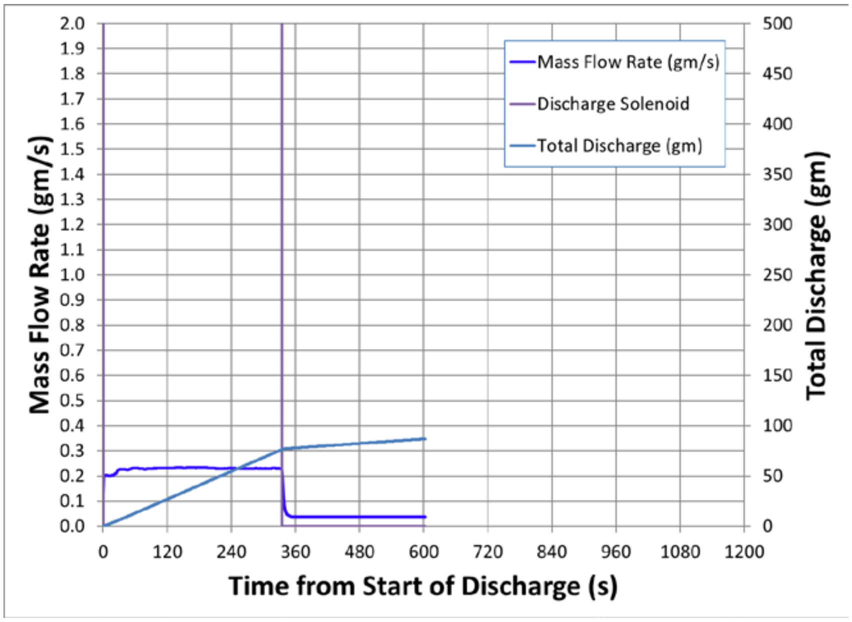


Figure 505 – RI_23 Mass Flow

Figure 506 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

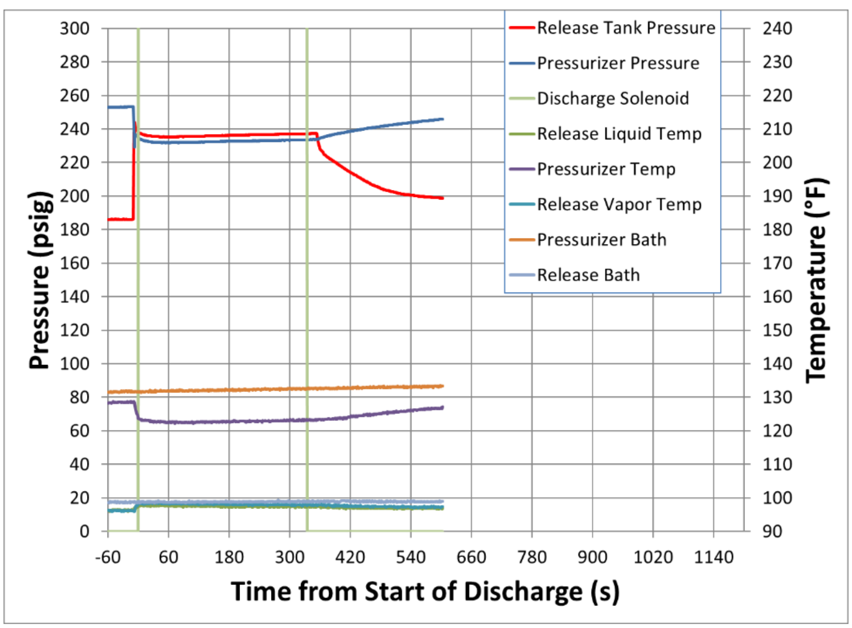


Figure 506 – RI_23 Pressurizer and Release Tank Pressure and Temperatures

Test RI_24 (100 g; Internal Release)

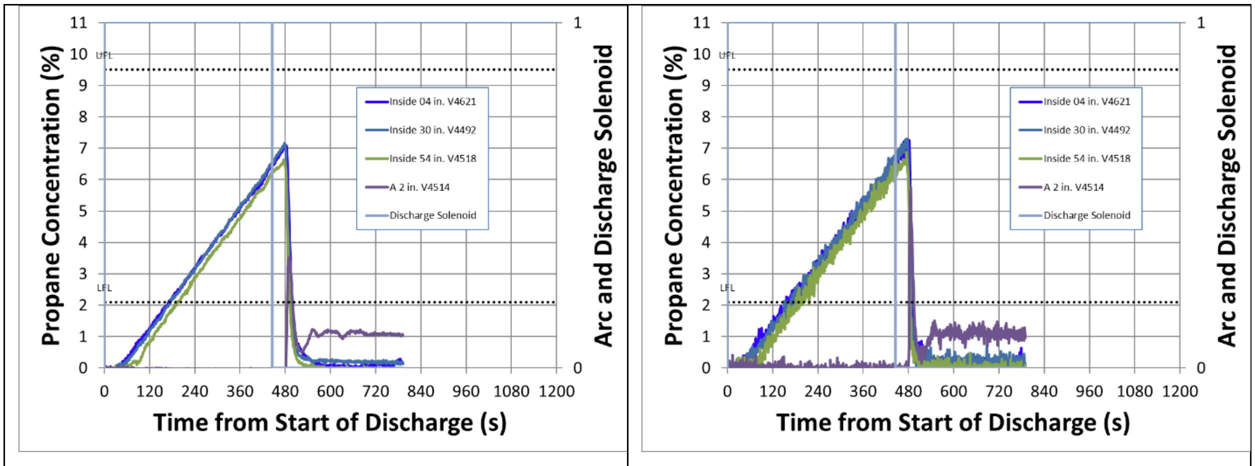
Test RI_24 was performed without ignition sources to measure propane concentrations. This concentration test showed a concentration above LFL at the electric arc location and was followed by an igniter test later in the program (RI_31).

Table 107 – RI_24 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	100	07:27	0.224	Evaporator Return Bend	9.2	Calculated with no leakage and well mixed
					0.12	Well mixed in test room
Measured	103	07:25	0.233		7.1	Internal
					7.3	Internal Deconvoluted
					5.8	Electric Arc Location

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 507 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording.



Concentrations	Deconvoluted Concentrations

Figure 507 – RI_24 Concentrations

Figure 508 shows the measured concentrations at the eight locations specified by 2-89 CDV. There was a period of 22 seconds when some concentrations were above the LFL of propane. Final propane concentrations at the floor level were between 0.75% and 1.5%. Concentrations at the high level were negligible.

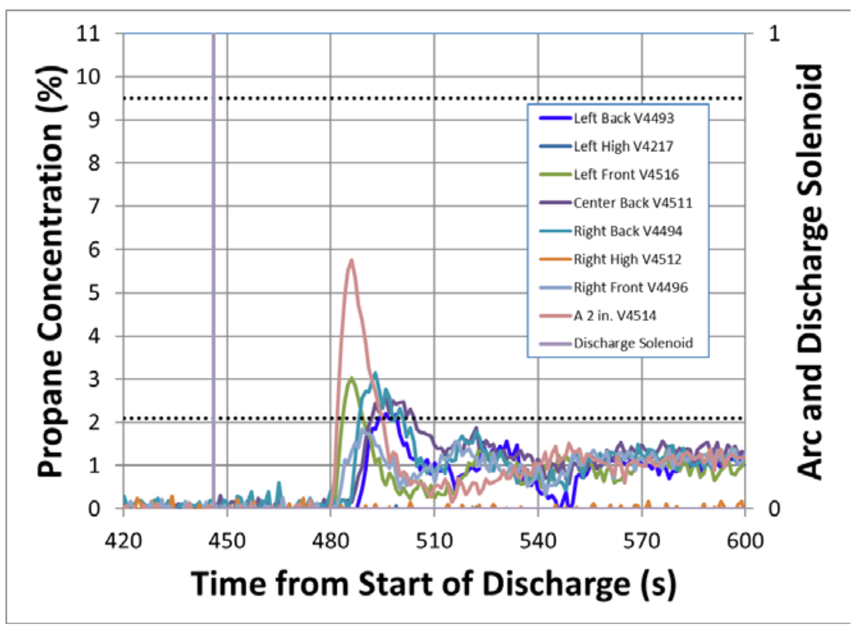


Figure 508 – RI_24 Concentrations at 8 locations surrounding cooler

Figure 509 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

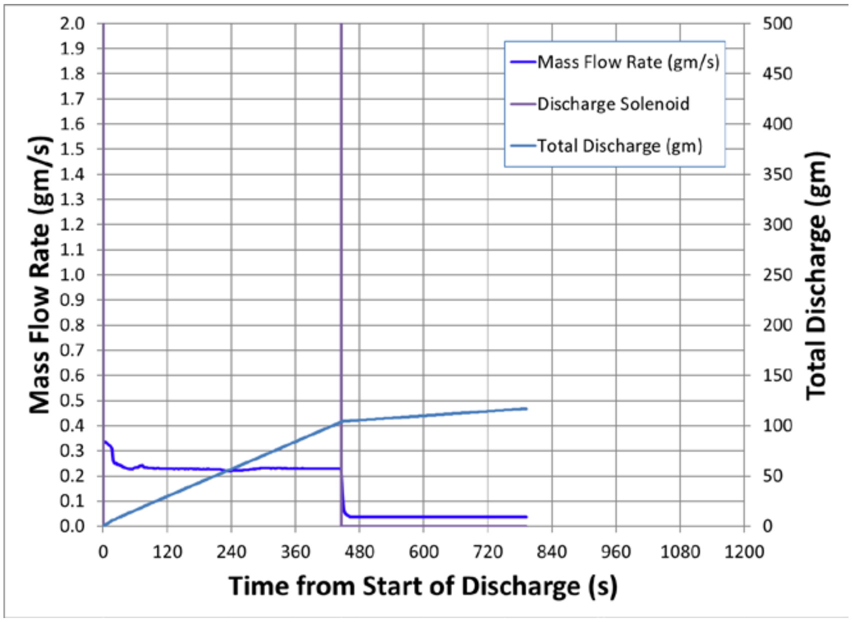


Figure 509 – RI_24 Mass Flow

Figure 510 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

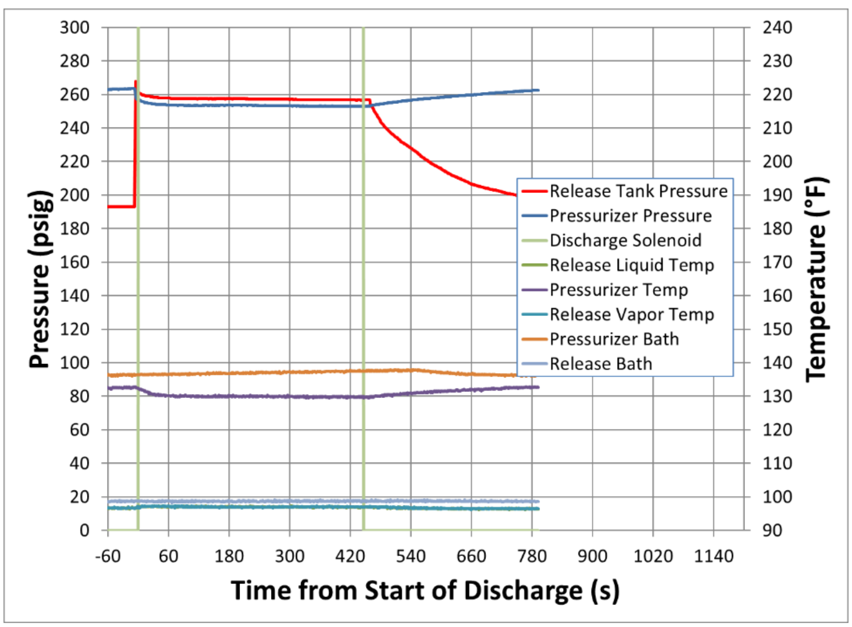


Figure 510 – RI_24 Pressurizer and Release Tank Pressure and Temperatures

Test RI_25 (125 g; Internal Release)

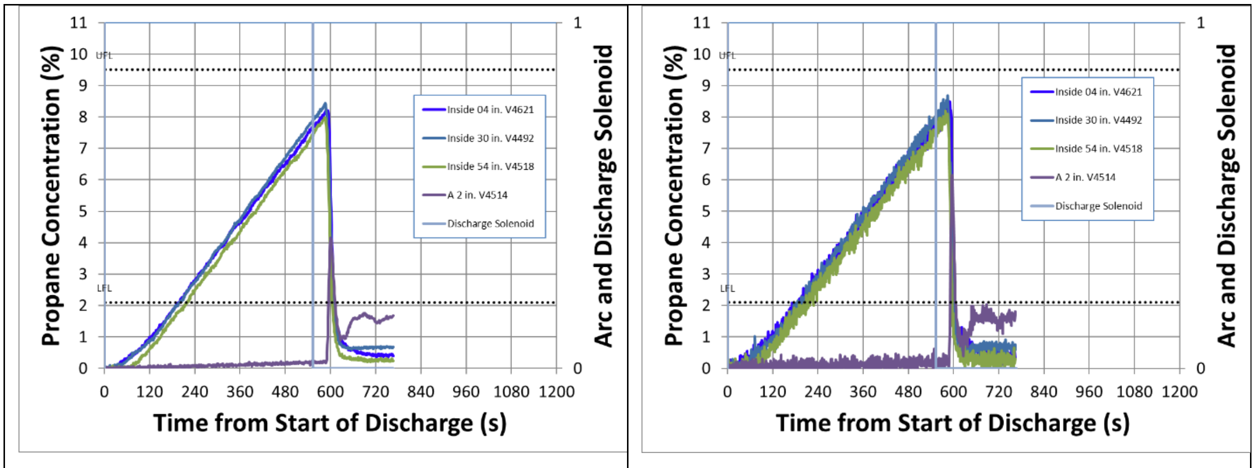
Test RI_25 was performed without ignition sources to measure propane concentrations. This concentration test showed a concentration above LFL at the electric arc location and was followed by an igniter test later in the program (RI_34). This test was also repeated in test RI_33 to check the door gaskets for leakage.

Table 108 – RI_25 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	125	09:18	0.224	Evaporator Return Bend	11.5 0.15	Calculated with no leakage and well mixed Well mixed in test room
Measured	124	09:12	0.224		8.4 8.7 6.3	Internal Internal Deconvoluted Electric Arc Location

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 511 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording.



Concentrations	Deconvoluted Concentrations

Figure 511 – RI_25 Concentrations

Figure 512 shows the measured concentrations at the eight locations specified by 2-89 CDV. There was a period of 43 seconds when some concentrations were above the LFL of propane. Final propane concentrations at the floor level were between 1.5% and 2.0%. Concentrations at the high level were averaging about 0.5%.

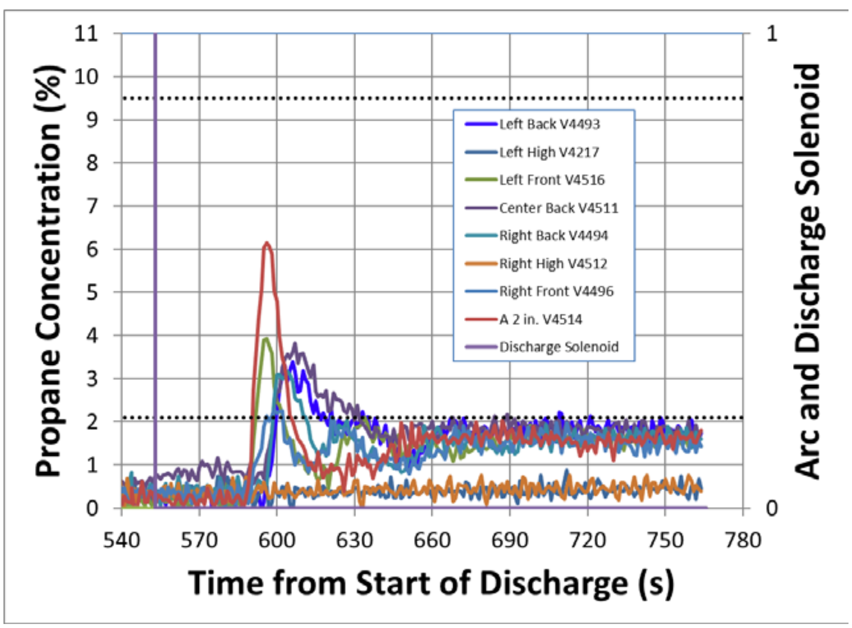


Figure 512 – RI_25 Concentrations at 8 locations surrounding cooler

Figure 513 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

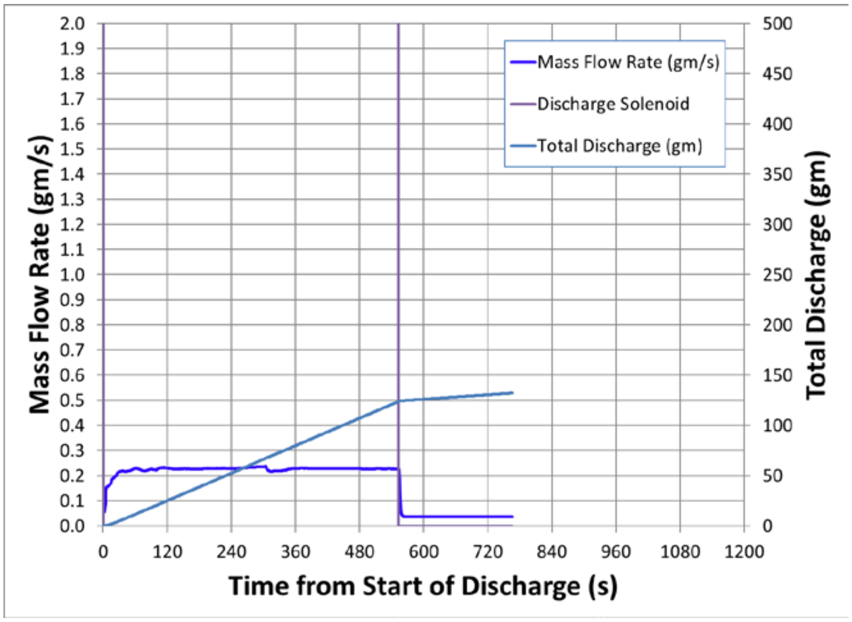


Figure 513 – RI_25 Mass Flow

Figure 514 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

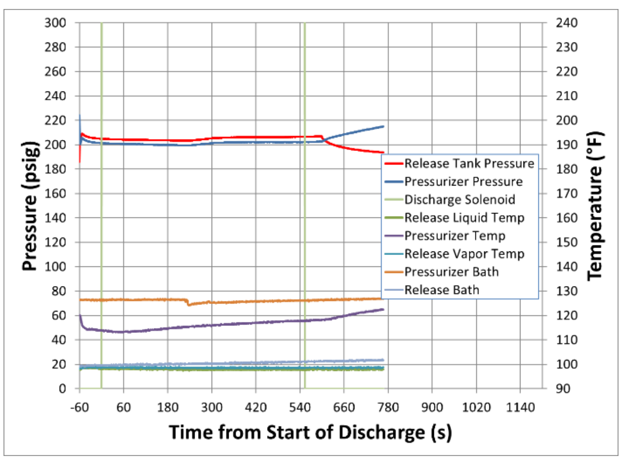


Figure 514 – RI_25 Pressurizer and Release Tank Pressure and Temperatures

Test RI_26 (150 g; Internal Release)

Test RI_26 was performed without ignition sources to measure propane concentrations. This concentration test showed a concentration above LFL at the electric arc location and was followed by an igniter test later in the program (RI_34). This test was also repeated in test RI_35 to check the door gaskets for leakage.

Table 109 – RI_26 Summary

<table>
<tr><th></th><th>Discharge Amount (g)</th><th>Duration of Discharge MM:SS</th><th>Discharge Rate (g/s)</th><th>Leak Location</th><th colspan="2">Maximum Concentration (%)</th></tr>
<tr><td>Planned</td><td>150</td><td>11:10</td><td>0.224</td><td rowspan="2">Evaporator Return Bend</td><td>13.8
0.18</td><td>Calculated with no leakage and well mixed
Well mixed in test room</td></tr>
<tr><td>Measured</td><td>154</td><td>11:09</td><td>0.229</td><td>10.6
10.9
8.8</td><td>Internal
Internal Deconvoluted
Electric Arc Location</td></tr>
</table>

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 515 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording.

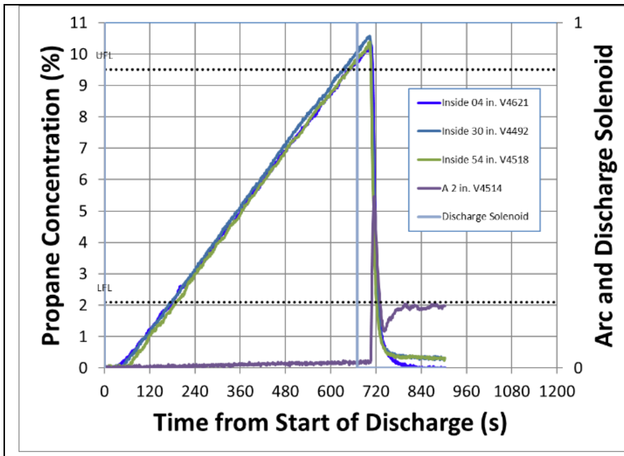
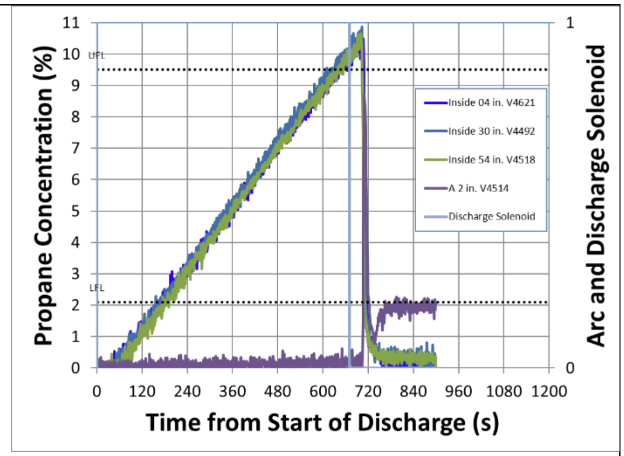
	
Concentrations	Deconvoluted Concentrations

Figure 515 – RI_26 Concentrations

Figure 516 shows the measured concentrations at the eight locations specified by 2-89 CDV. There was a period of 47 seconds when some concentrations were above the LFL of propane. Final propane concentrations at the floor level were between 1.6% and 2.0%. Concentrations at the high level negligible.

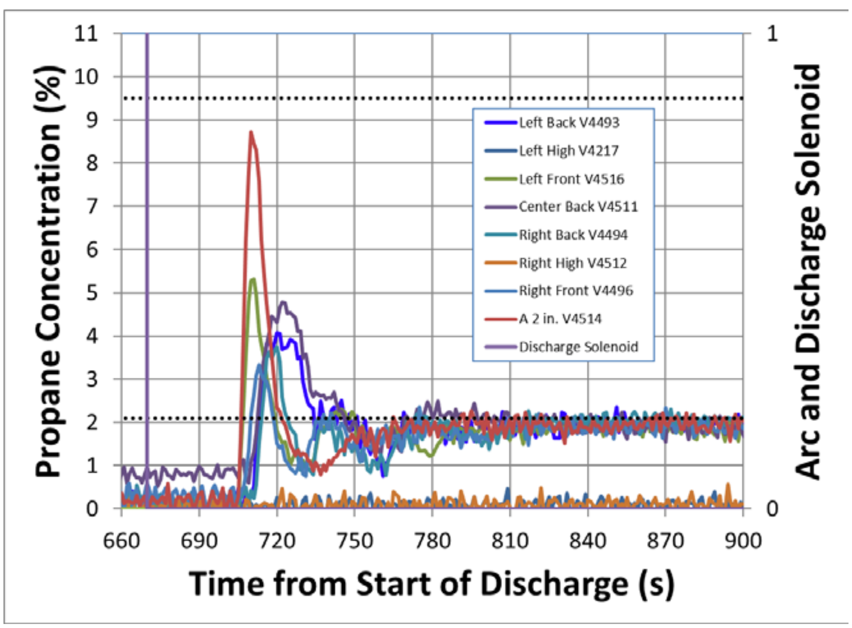


Figure 516 – RI_26 Concentrations at 8 locations surrounding cooler

Figure 517 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

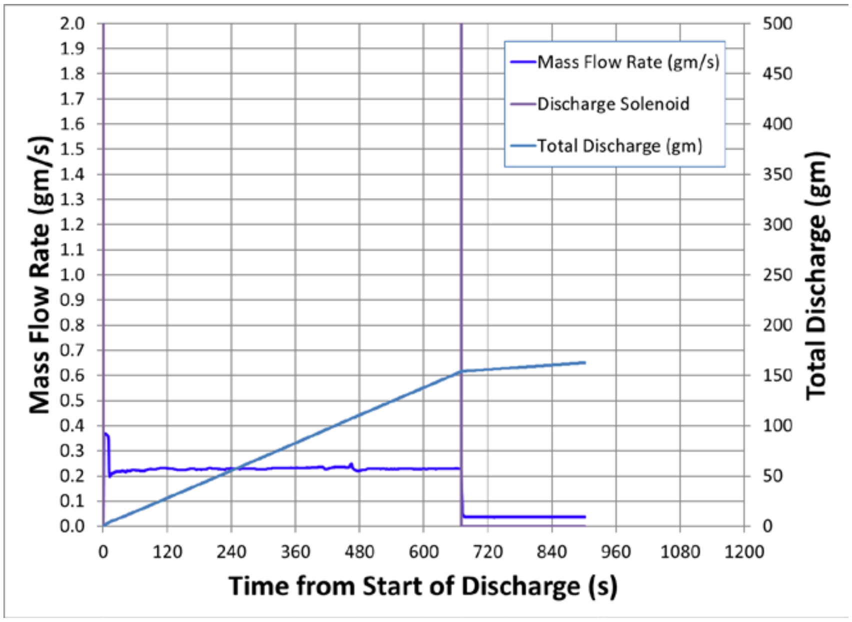


Figure 517 – RI_26 Mass Flow

Figure 518 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

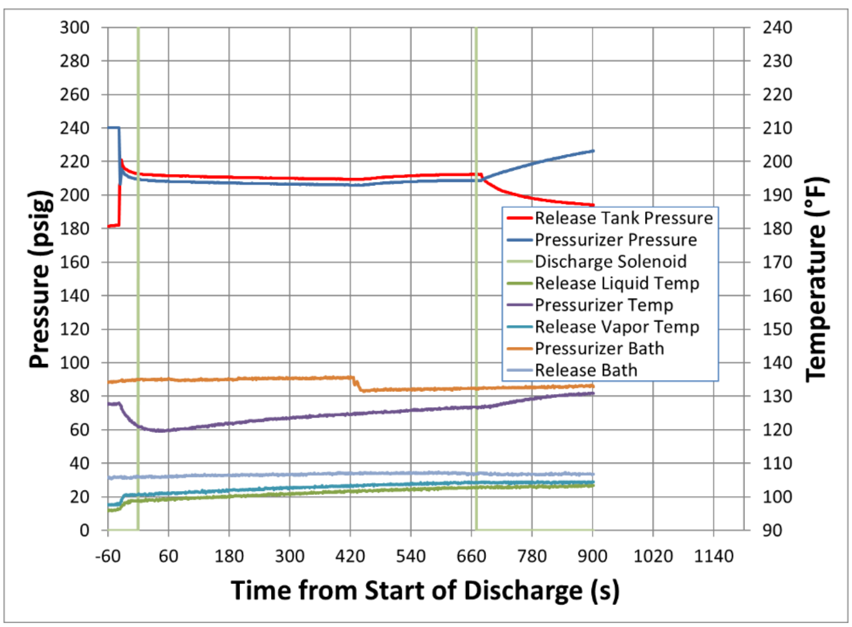


Figure 518 – RI_26 Pressurizer and Release Tank Pressure and Temperatures

Test RI_27 (397 g; External Release; Fan Off)

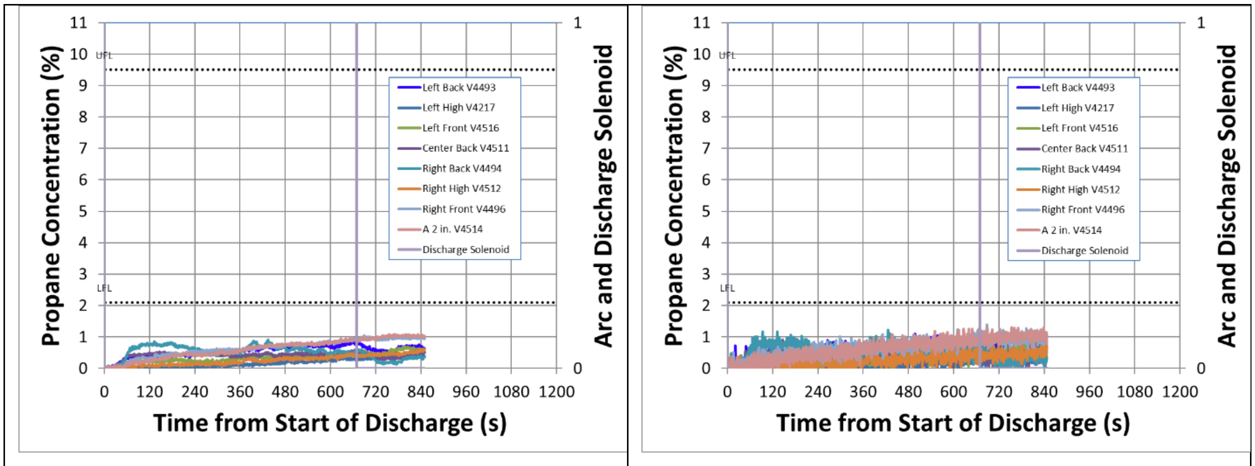
Test RI_27 was performed without ignition sources to measure propane concentrations prior to the conduct of test RI_29. This test involved an exterior release at the return bend of the condenser coil. The condenser fan was de-energized throughout this test. The key parameters and results of this test are summarized in the following table.

Table 110 – RI_27 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	397	11:10	0.593	Condenser Return Bend	0.5	Calculated if well Mixed in whole room
Measured	390	11:08	0.584		1.6 1.9 1.3	Cabinet Vent Cabinet Vent Deconvoluted Electric Arc Location

Per procedure, the discharge was initiated and stopped after 11 minutes and 10 seconds. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 519 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording at the 8 locations specified in by 2-89 CDV. The maximum recorded concentrations are all within a range of 0.2% to 1.3%. The highest of these concentrations show that mixing within the room volume was not complete (0.5%) but remained less than the LFL of propane.



Concentrations	Deconvoluted Concentrations

Figure 519 – RI_27 Concentrations

Figure 520 shows concentration measurements at other locations in the test room. The “Vent” sensor was located at the top of the cooler near the cabinet vent and near the leak location on the condenser return bend. The three sensors inside the cooler showed very little increase because the door was closed.

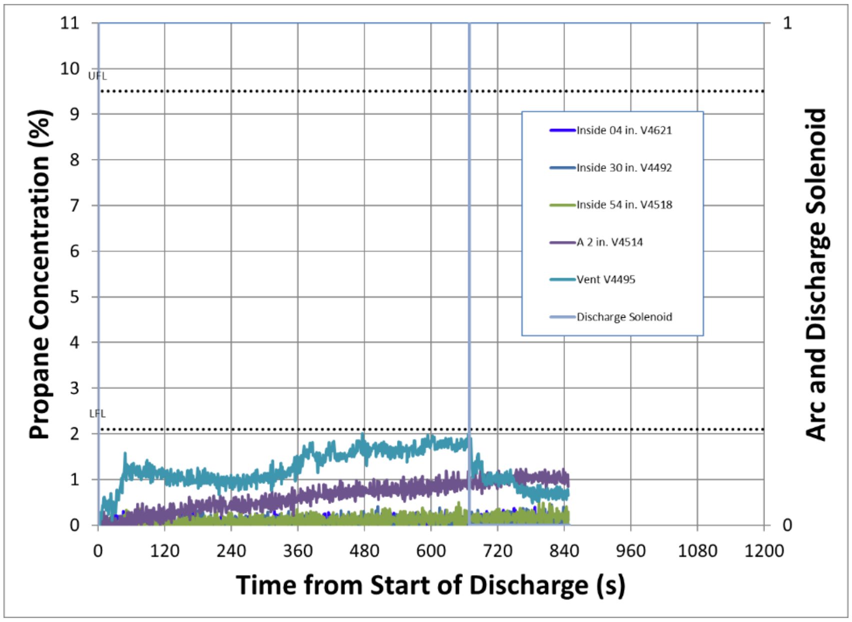


Figure 520 – RI_27 Other Concentrations

Figure 521 shows the location of the capillary tube at a return bend of the condenser coil. A thin stream of propane mist is shown leaving the end of the tube. The vent sensor is out of view at the far left of this frame.

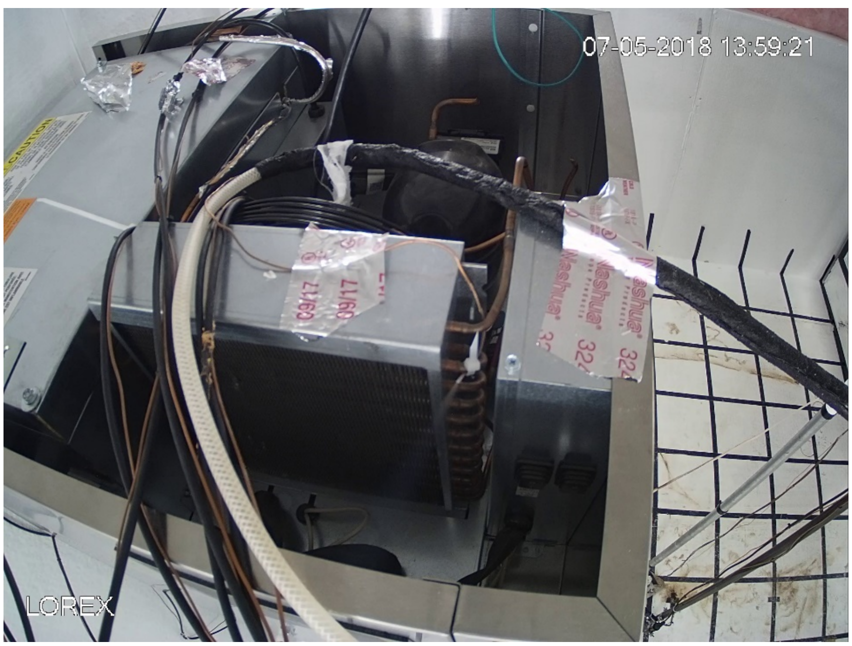


Figure 521 – RI_27 Single Door Cooler External Discharge Location

Figure 522 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

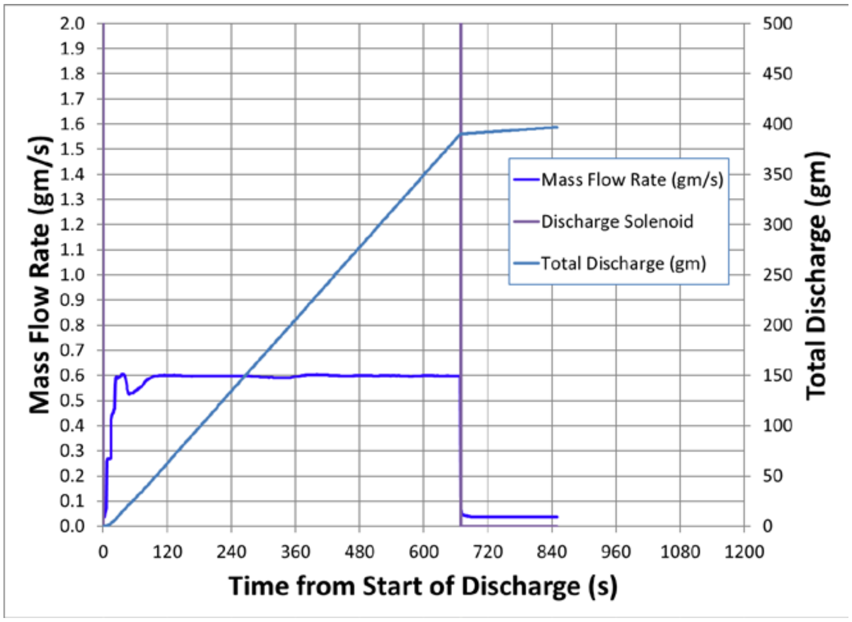


Figure 522 – RI_27 Mass Flow

Figure 523 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

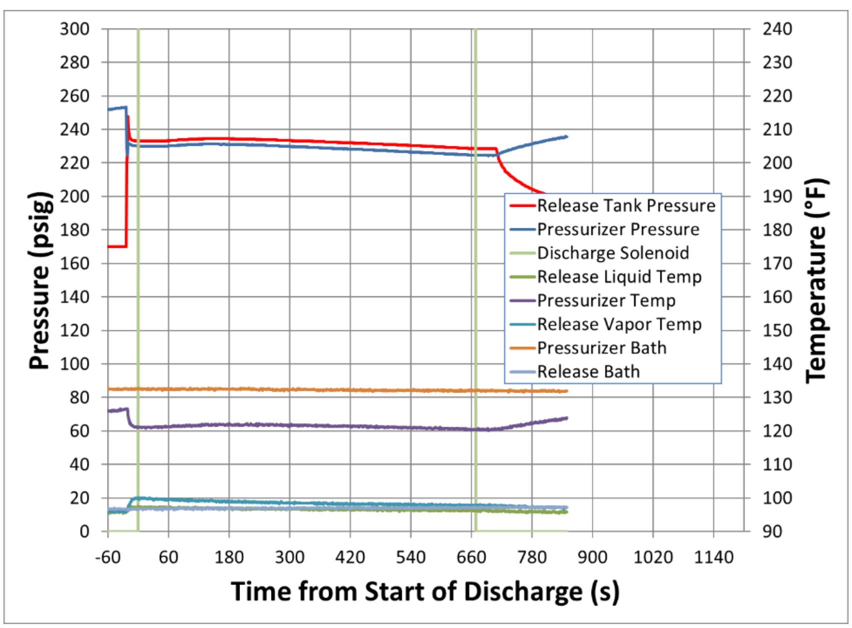


Figure 523 – RI_27 Pressurizer and Release Tank Pressure and Temperatures

Test RI_28 (397 grams; External Release; Fan On)

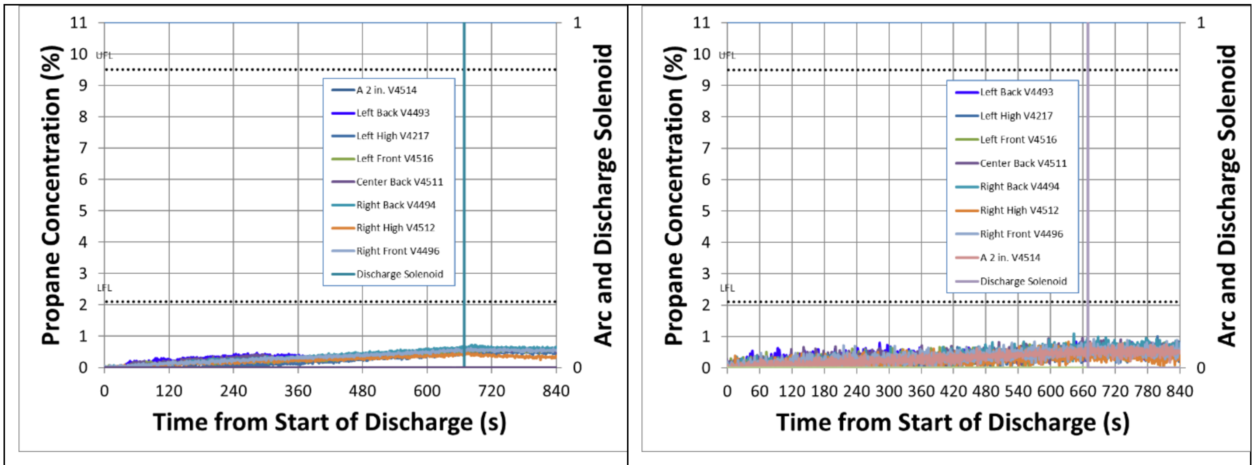
Test RI_28 was performed without ignition sources to measure propane concentrations prior to the conduct of test RI_29. This test involved an exterior release at the return bend of the condenser coil. The condenser fan was operating throughout this test. The key parameters and results of this test are summarized in the following table.

Table 111 – RI_28 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	397	11:10	0.593	Condenser Return Bend	0.5	Calculated if well Mixed in whole room
Measured	394	11:09	0.590		0.7 1.1 0.6	External External Deconvoluted Electric Arc Location

Per procedure, the discharge was initiated and stopped after 11 minutes and 10 seconds. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 524 shows propane concentrations and deconvoluted values from the start of the discharge to the end of data recording at the 8 locations specified in by 2-89 CDV. The maximum recorded concentrations are all within a range of 0.5 to 0.7% which agrees closely with the expected value of 0.5% for this release well mixed in the entire room volume.



Concentrations	Deconvoluted Concentrations

Figure 524 – RI_28 Concentrations

Figure 525 shows concentration measurements at other locations in the test room. The "Vent" sensor was located at the top of the cooler near the cabinet vent and near the leak location on the condenser return bend. The three sensors inside the cooler showed very little increase because the door was closed.

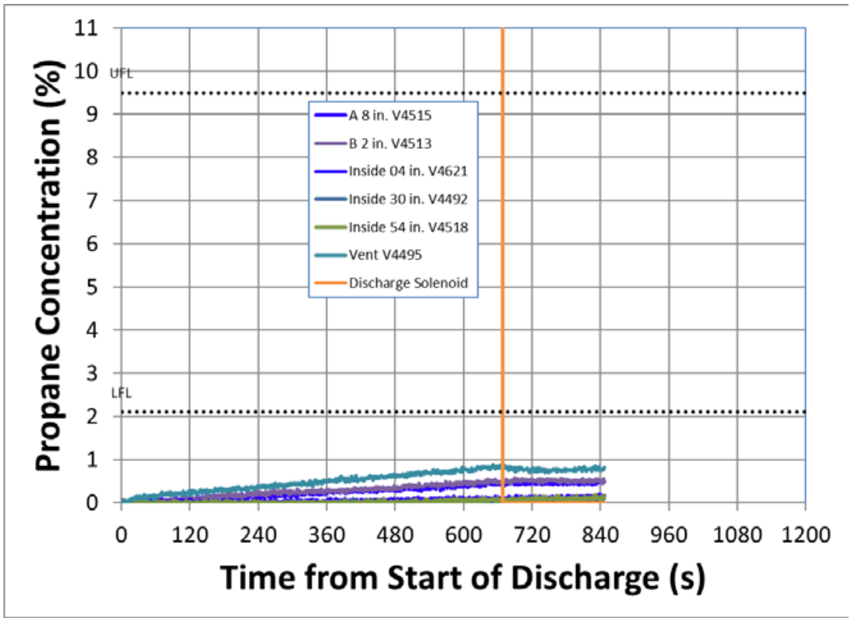


Figure 525 – RI_28 Other Concentrations

Figure 526 shows the mass flow rate and total mass flow. There was an initial surge in mass flow after the start of the discharge. The operator was then able to throttle back the flow rate to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

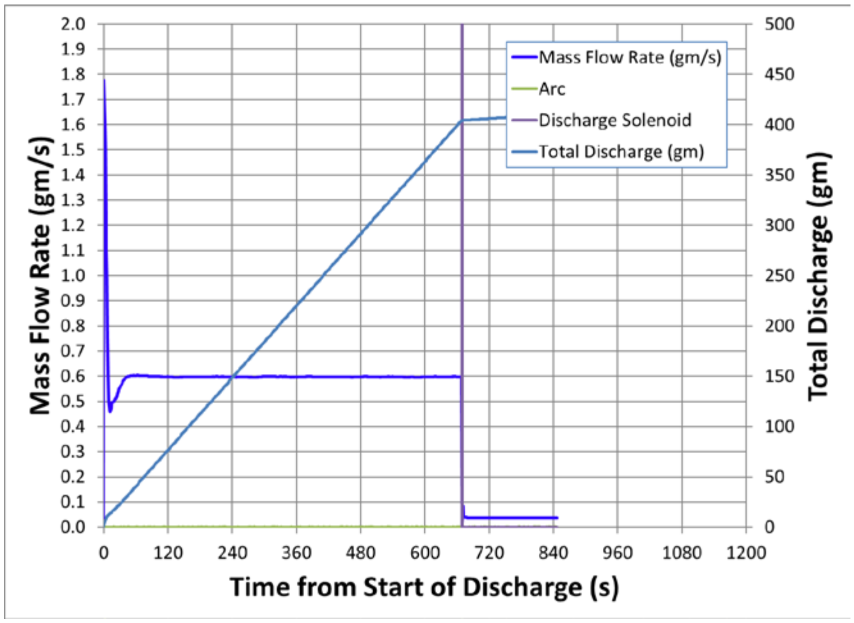


Figure 526 – RI_28 Mass Flow

Figure 527 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The data shows the equalization of pressure after the pressurizer was placed in series with the release tank. After completion of the discharge, pressures in both tanks began to return to pre-test pressures based on their respective bath temperatures.

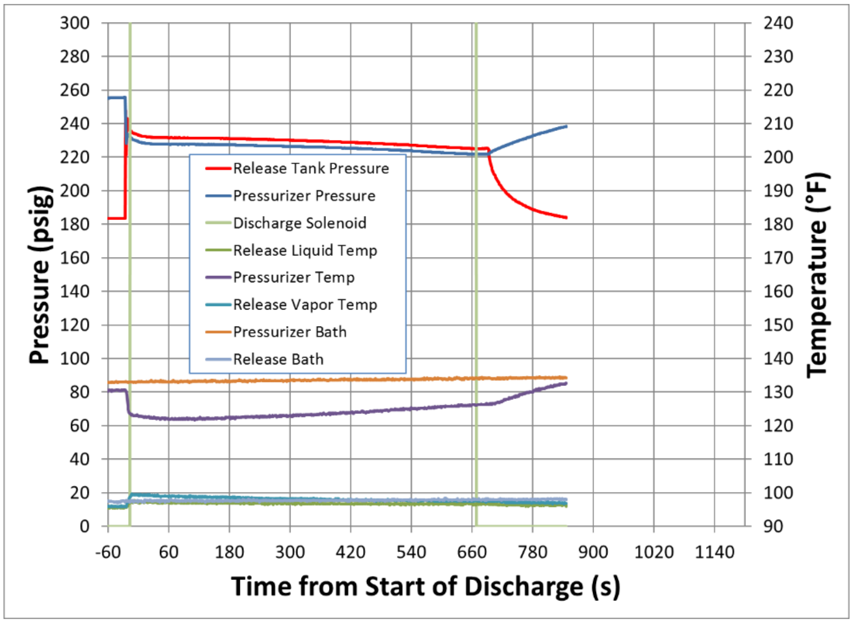


Figure 527 – RI_28 Pressurizer and Release Tank Pressure and Temperatures

Test RI_29 (397 grams; External Release, Fan off, with Arc Igniters)

Test RI_29 was performed with ignition sources and did not result in ignition at the arc locations. The key parameters and results of this test are summarized in the following table. The condenser fan was not running for this test.

Table 112 – RI_29 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	397	11:10	0.593	Condenser Return Bend
Measured	406	11:10	0.606	

Per procedure, the discharge was initiated and stopped after 11 minutes and 10 seconds. Data recording continued for a minimum of 2.5 minutes after the discharge was completed.

Figure 528 shows the concentrations measured throughout the test. The figure shows the concentrations at the eight locations specified by 2-89 CDV. The figure shows a wider range of concentrations than test RI_28. The increase in wind speed in Northbrook from July 5th to July 6th is suspected of causing additional air leakage into the test room during test RI_29 and diluting some concentrations. The three sensors at the back wall of the test room and 2 inches above the floor were most affected by leakage under the sill plate in the test room. The other sensors further from the rear wall showed a maximum concentration between 0.5% and 0.8%.

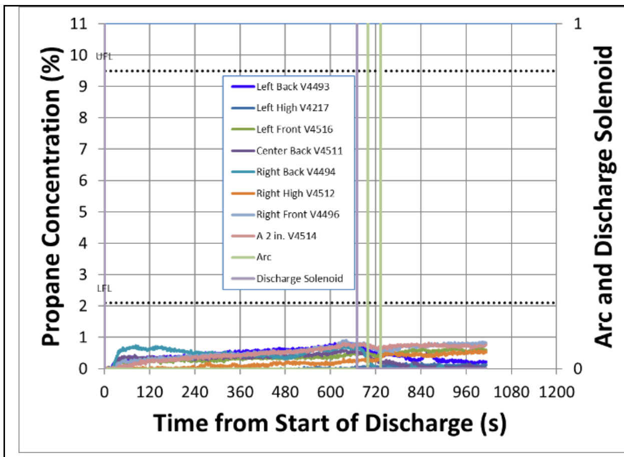
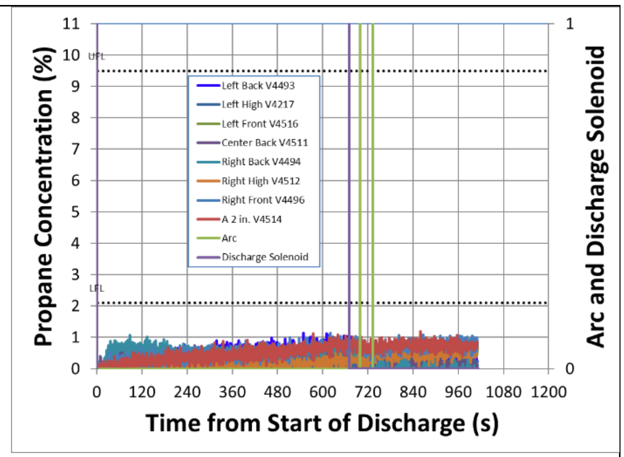
	
Concentrations	Deconvoluted Concentrations

Figure 528 – RI_29 Concentrations

Figure 529 compares the concentrations at Location A (2 inch) exterior sensor in tests RI_28 and RI_29 to show that concentrations were similar to within a few tenths of a percent.

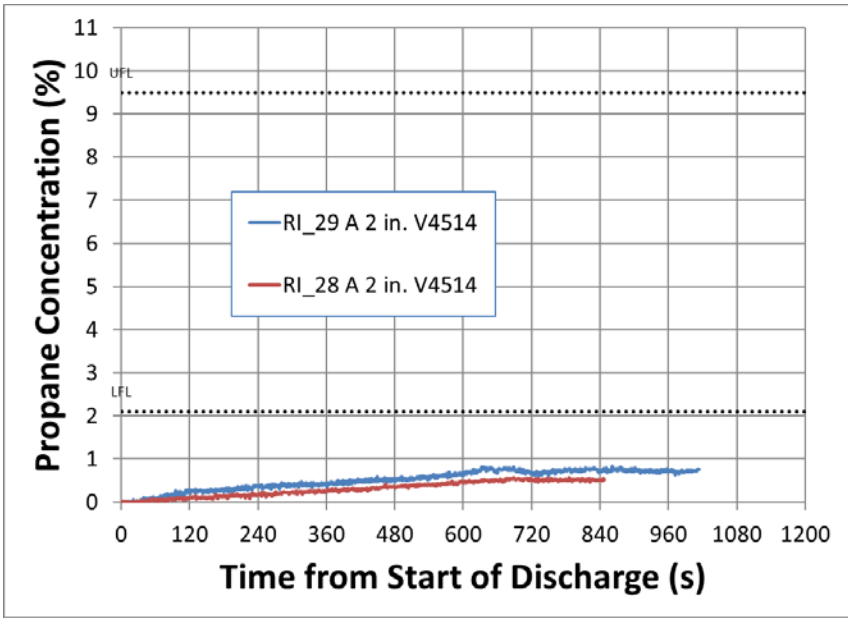


Figure 529 – RI_29 to RI_28 Concentration Comparison

Figure 530 shows the mass flow rate and total mass flow. The initial flow rate was high, but the operator was then able to throttle down to the desired flow and maintained control to the end of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

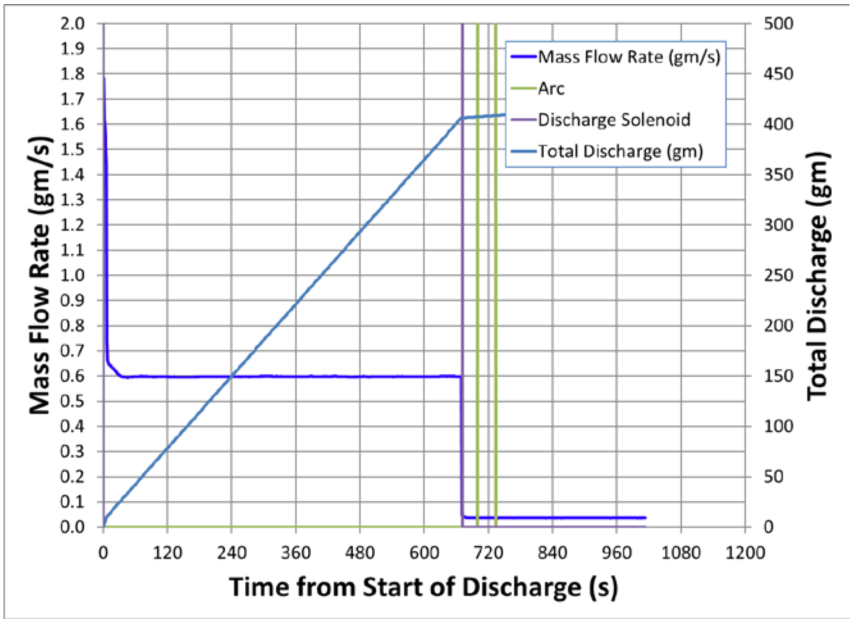


Figure 530 – RI_29 Mass Flow

Figure 531 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

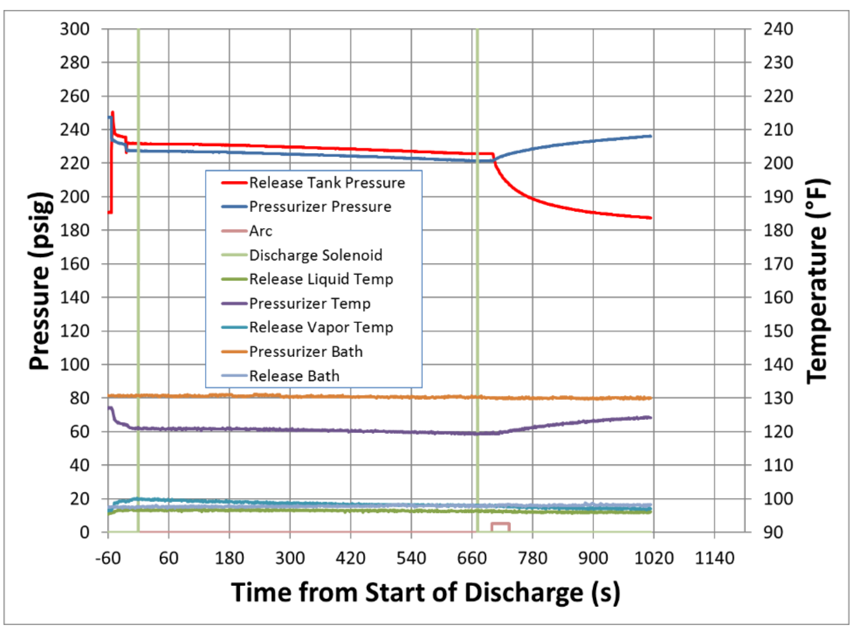


Figure 531 – RI_29 Pressurizer and Release Tank Pressure and Temperatures

There was no ignition in this test. Figure 532 shows the temperatures at location A demonstrating no increase above ambient conditions throughout the test.

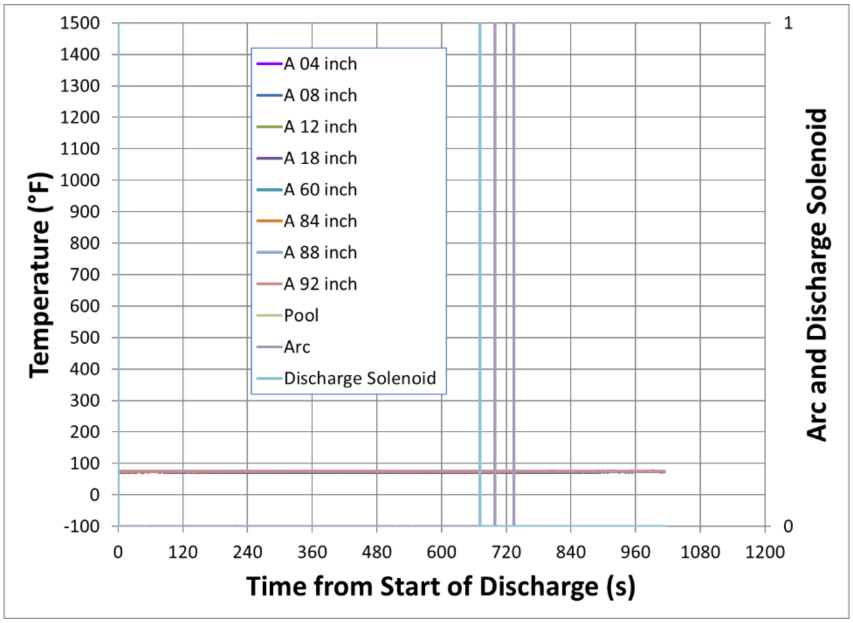


Figure 532 – RI_29 Temperatures at Locations A

Test RI_30 (75 grams; Internal Release, with Arc Igniters)

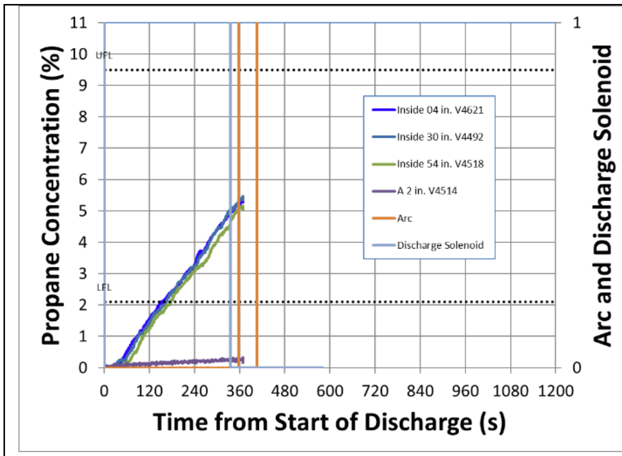
Test RI_30 was performed with ignition sources and resulted in ignition at the arc location. Just prior to the door opening, the internal concentrations were higher than stoichiometric conditions at 5.3%. Initial flaming at the electric arc was blue in color (pre-mixed) while later stages were yellow in color (diffusion flame). Four of the six deflagration vents were burst by the ignition.

Table 113 – RI_30 Summary

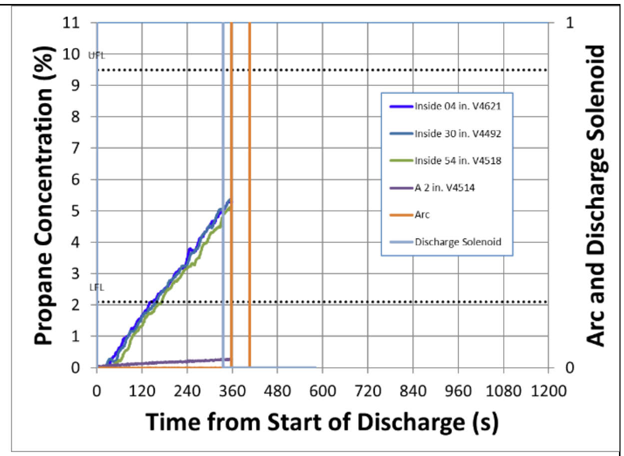
	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	75	05:35	0.224	Evaporator Return Bend
Measured	81	05:35	0.242	

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 533 shows the cooler interior concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations



Deconvoluted Concentrations

Figure 533 – RI_30 Concentrations

Figure 534 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

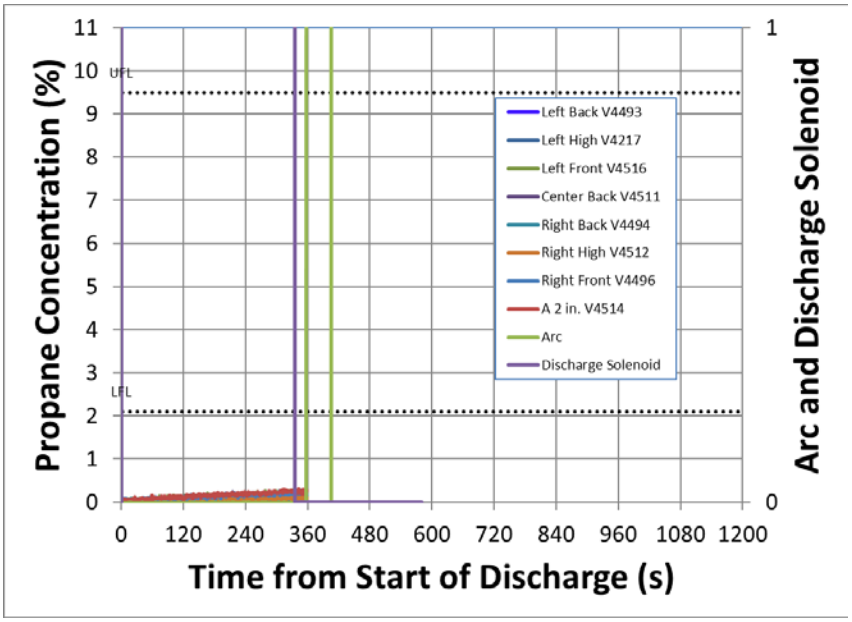


Figure 534 – RI_30 Concentrations at 8 locations surrounding cooler

Figure 535 compares the concentrations at the interior sensor (4-inch level) from tests RI_23 and RI_30 to show that concentrations were similar to within a few tenths of a percent relative to the discharge time. The data for test RI_30 looks choppy by comparison due to the difference in data acquisition rates (1 Hz vs. 50 hz).

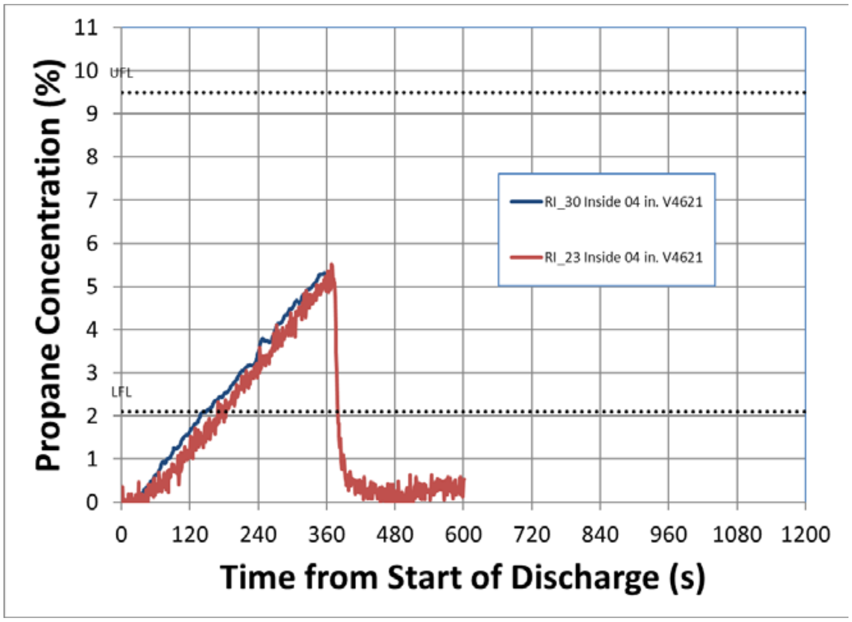


Figure 535 – RI_30 to RI_23 Concentration Comparison

Figure 536 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

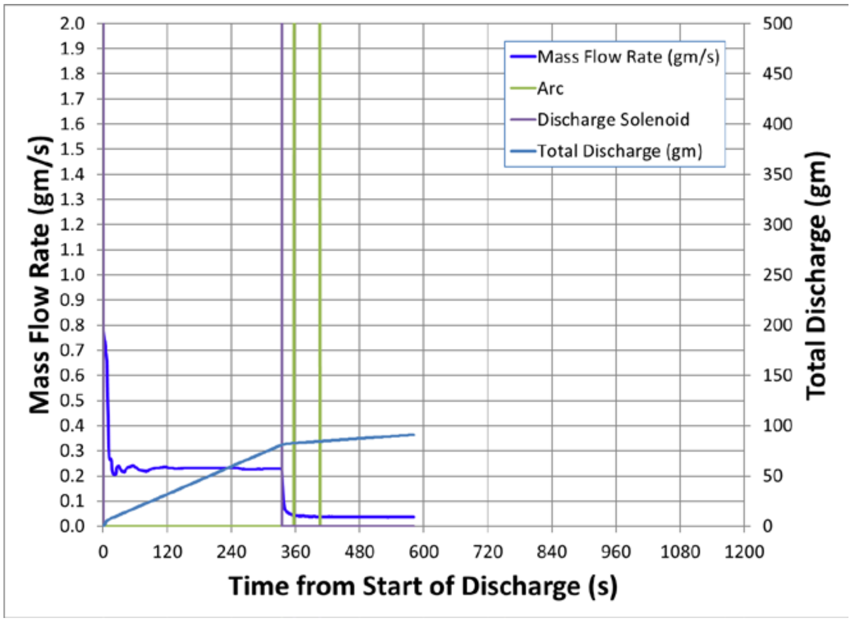


Figure 536 – RI_30 Mass Flow

Figure 537 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

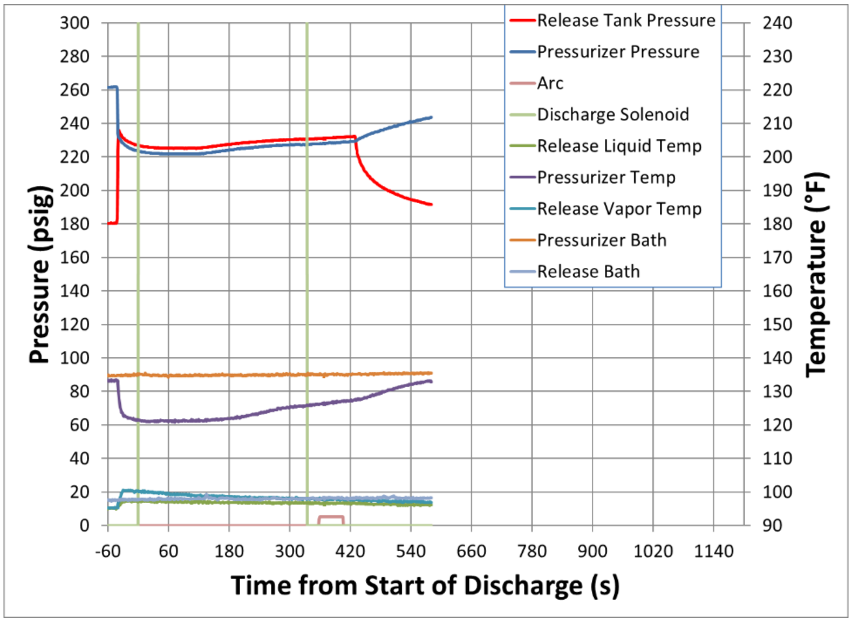


Figure 537 – RI_30 Pressurizer and Release Tank Pressure and Temperatures

Figure 538 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at location A, where ignition started. Locations B, C, and D show only slightly increased temperatures up to the 18-inch level. The higher temperatures from 60 inches to 92 inches reflect the buoyant rise of the hot gases from the flaming at location A.

The delayed peak in temperature at location B, 18-inch, level was due to a burning piece of cheesecloth that draped across the thermocouple bead.

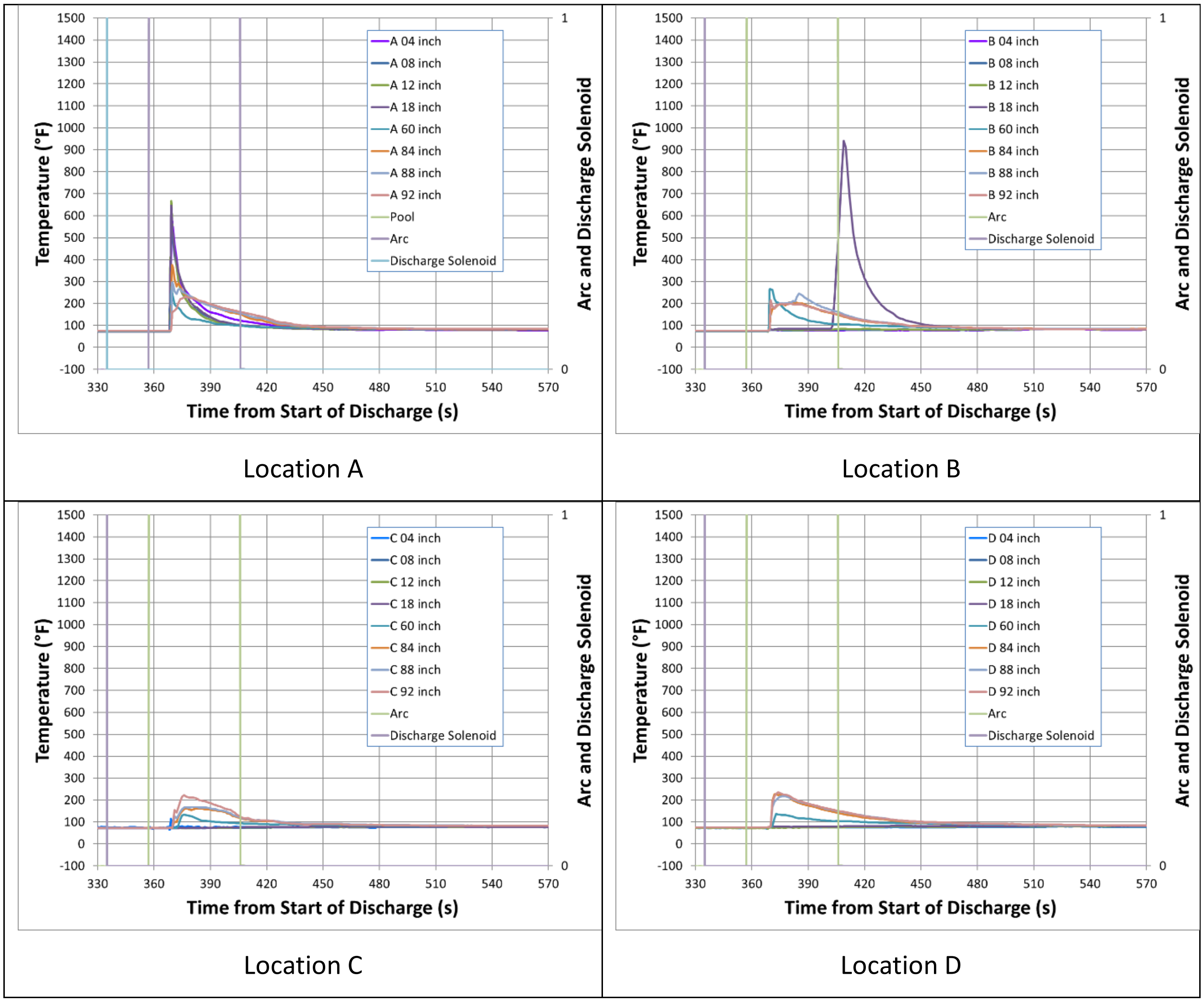


Figure 538 – RI_30 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 3 seconds. Figure 539 shows the ignition at the 6-inch arc in front of the door. There is an initial blue flame (premixed), while the dominant yellow color signifies a diffusion flame. The second frame shows that the gases were pushed out of the cooler to mix with room air. Four deflagration vents burst due to the ignition event.

Figure 539 – RI_30 Ignition event

Figure 540 shows the room pressure transit during the ignition event. This was the first test to record at 50 Hz recording speed able to capture the pressure transient. For reference 1 mmHg pressure is equivalent to 2.78 Lb/ft ^{2}.

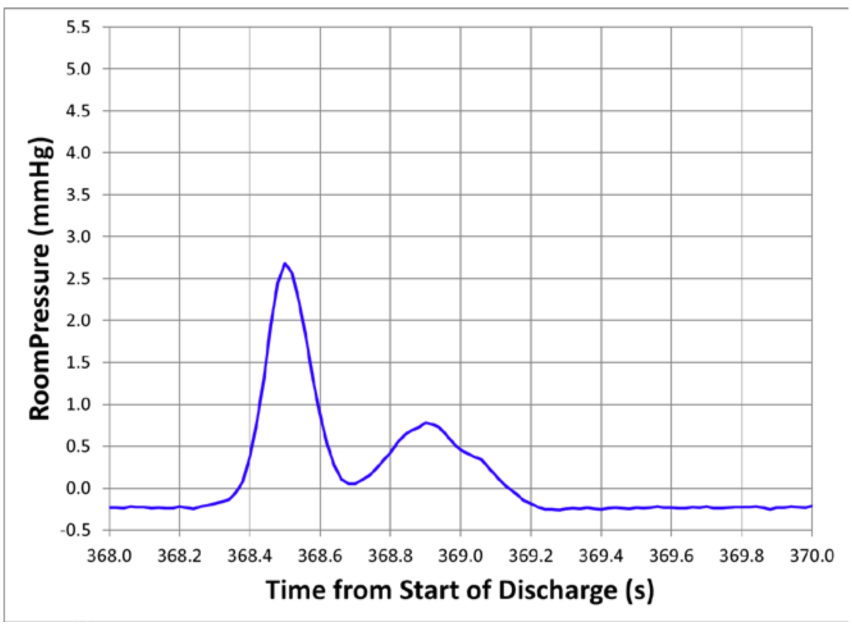


Figure 540 – Room Pressure during ignition event

Test RI_31 (100 grams; Internal Release)

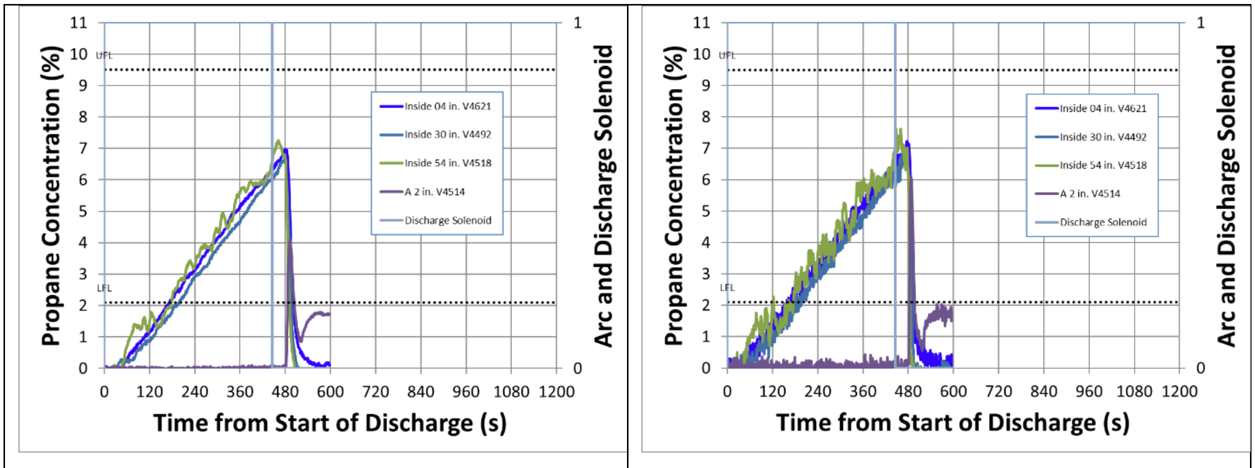
Test RI_31 was performed without ignition sources to measure propane concentrations and verify door gasket seal integrity. This concentration test showed a concentration above LFL at the electric arc location and was followed by an igniter test later in the program (RI_32).

Table 114 – RI_31 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location	Maximum Concentration (%)	
Planned	100	07:27	0.224	Evaporator Return Bend	9.2 0.12	Calculated with no leakage and well mixed Well mixed in test room
Measured	103	07:25	0.231		7.3 7.6 6.3	Internal Internal Deconvoluted Electric Arc Location

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 541 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording.



Concentrations	Deconvoluted Concentrations

Figure 541 – RI_31 Concentrations

Figure 542 shows the concentrations generated in RI_31 and RI_24 are nearly identical showing that there has been no degradation in the cooler door gaskets from previous igniter tests.

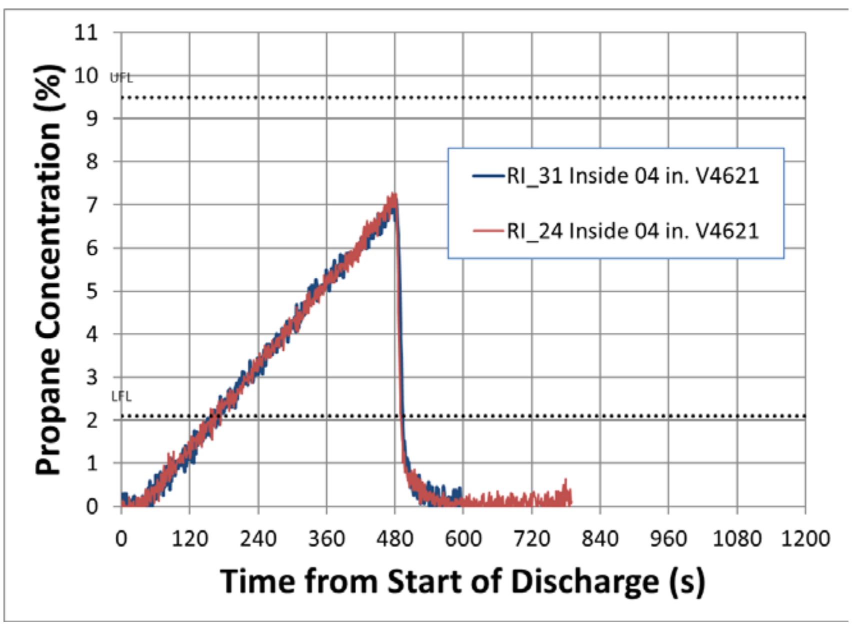


Figure 542 – Compare RI_31 and RI_24 Concentrations

Figure 543 shows the measured concentrations at the eight locations specified by 2-89 CDV. There was a period of 43 seconds when some concentrations were above the LFL of propane. Final propane concentrations at the floor level were between 1.3% and 2.0%. Concentrations at the high level were negligible.

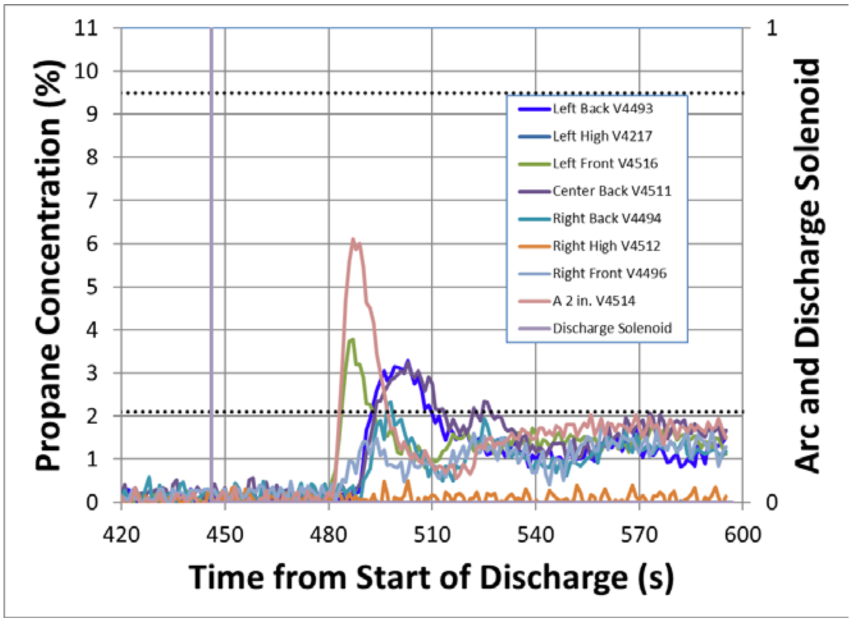


Figure 543 – RI_31 Concentrations at 8 locations surrounding cooler

Figure 544 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

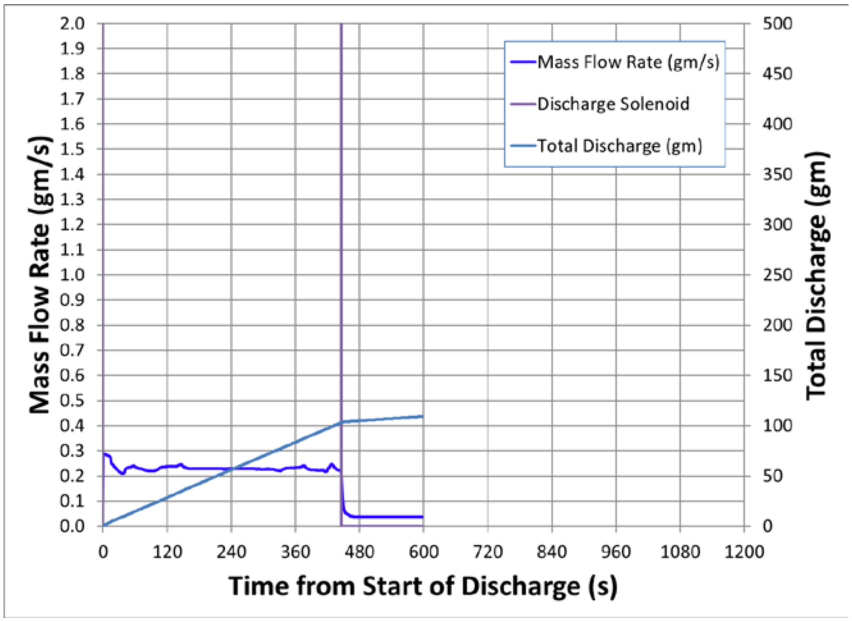


Figure 544 – RI_31 Mass Flow

Figure 545 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

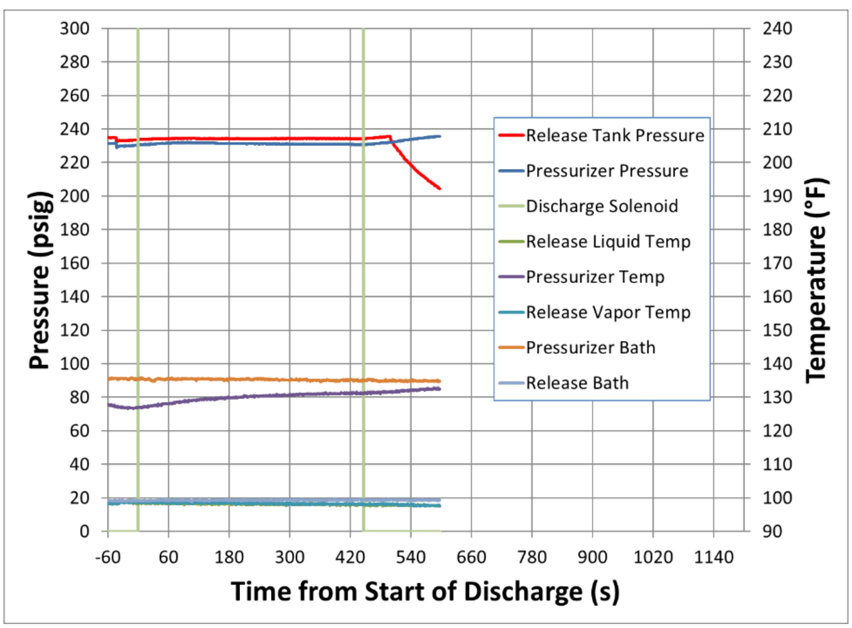


Figure 545 – RI_31 Pressurizer and Release Tank Pressure and Temperatures

Test RI_32 (100 grams; Internal Release, with Arc Igniters)

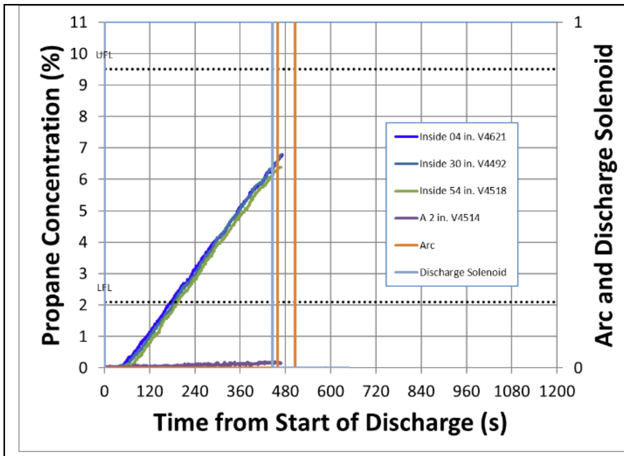
Test RI_32 was performed with ignition sources and resulted in ignition at the arc location. Just prior to the door opening, the internal concentrations were higher than stoichiometric conditions at 7.0%. Initial flaming at the electric arc was blue in color (pre-mixed) while later stages were yellow in color (diffusion flame). Four of the six deflagration vents were burst by the ignition.

Table 115 – RI_32 Summary

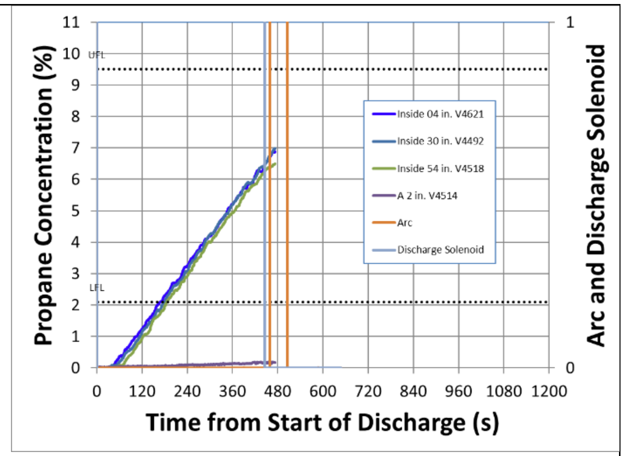
	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	100	07:27	0.224	Evaporator Return Bend
Measured	102	07:26	0.229	

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 546 shows the cooler internal concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations



Deconvoluted Concentrations

Figure 546 – RI_32 Concentrations

Figure 547 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

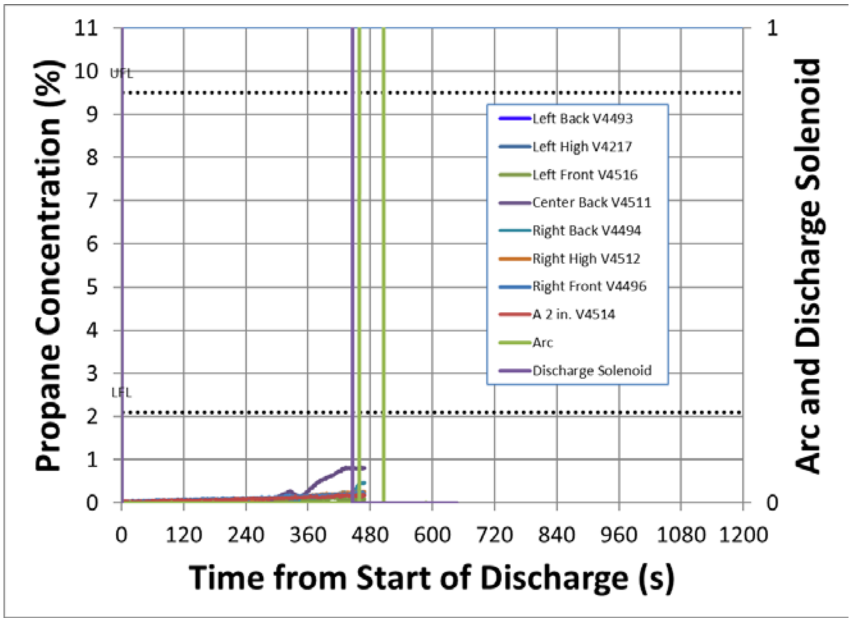


Figure 547 – RI_32 Concentrations at 8 locations surrounding cooler

Figure 548 compares the concentrations at the interior sensor (4-inch level) from tests RI_31 and RI_32 to show that concentrations were similar to within a few tenths of a percent relative to the discharge time. The data for test RI_32 looks choppy by comparison due to the difference in data acquisition rates (1 Hz vs. 50 hz).

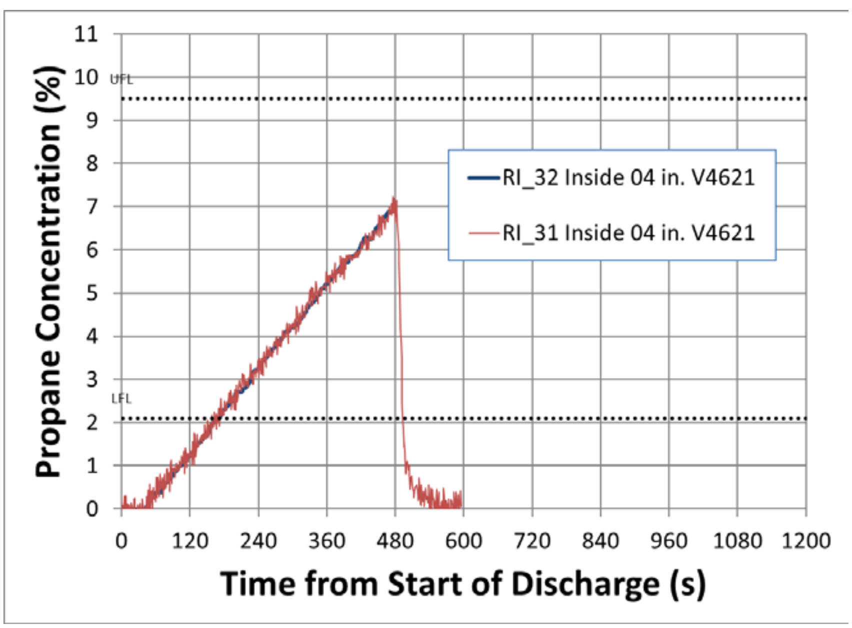


Figure 548 – RI_32 to RI_31 Concentration Comparison

Figure 549 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

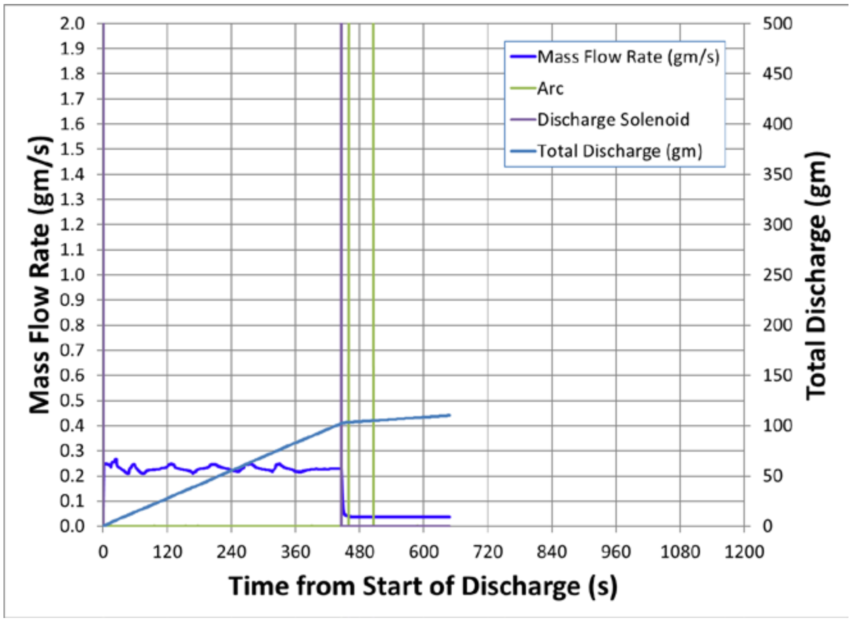


Figure 549 – RI_32 Mass Flow

Figure 550 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

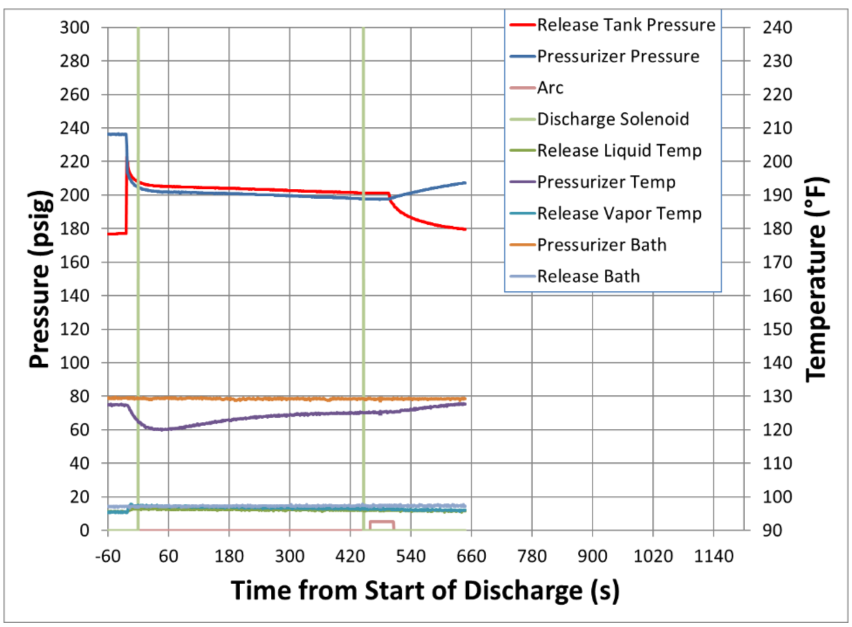


Figure 550 – RI_32 Pressurizer and Release Tank Pressure and Temperatures

Figure 551 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at location A, where ignition started. Locations B, C, and D show only slightly increased temperatures up to the 18-inch level. The higher temperatures from 60 inches to 92 inches reflect the buoyant rise of the hot gases from the flaming at location A.

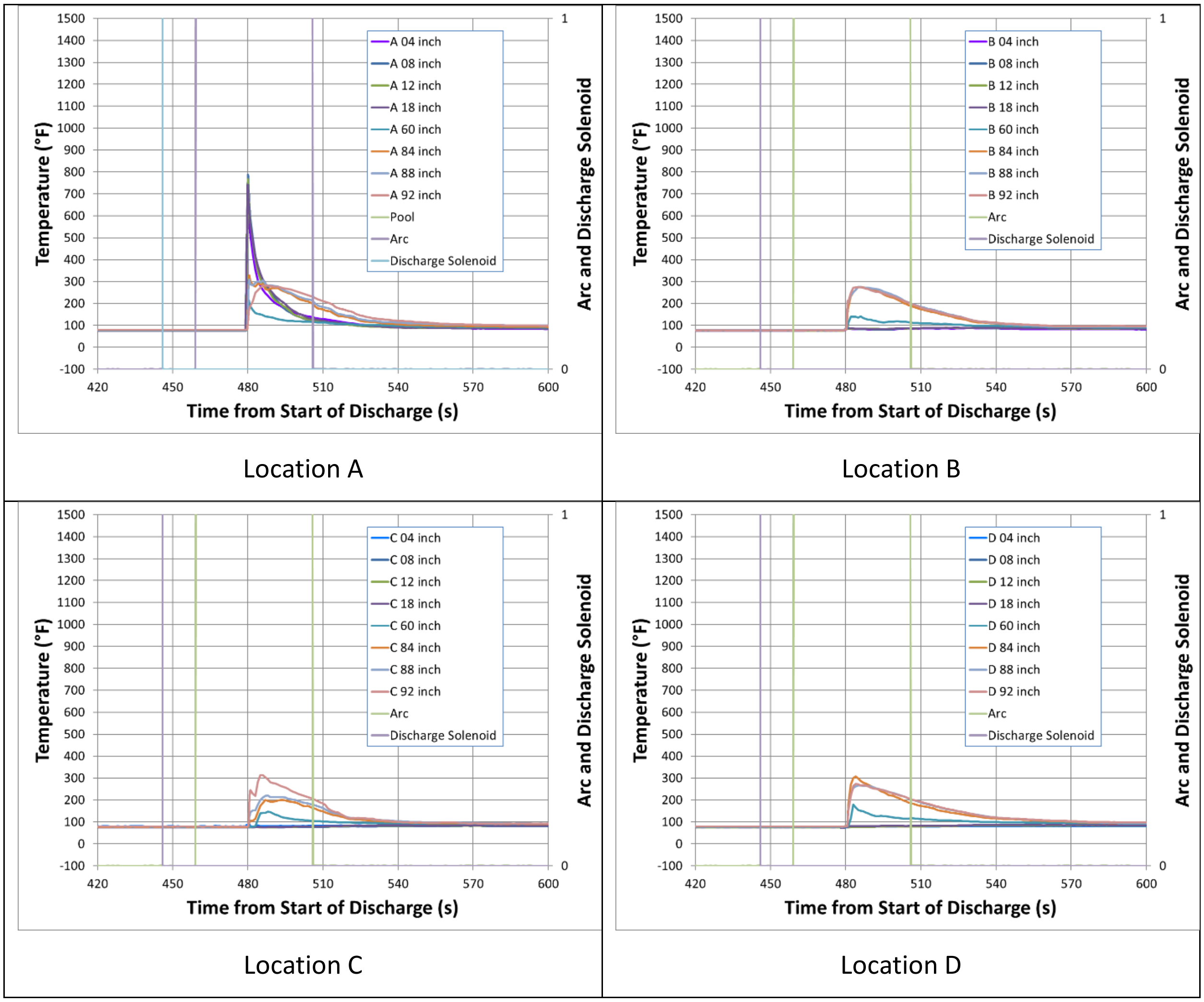


Figure 551 – RI_32 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 4 seconds. Figure 552 shows the ignition at the 6-inch arc in front of the door. There is an initial blue flame (premixed), while the dominant yellow color signifies a diffusion flame. The second frame shows that the gases were pushed out of the cooler to mix with room air. Two deflagration vents burst due to the ignition event and two others melted from the heat.

Figure 552 – RI_32 Ignition event

Figure 553 shows the room pressure transit during the ignition event. This was the first test to record at 50 Hz recording speed able to capture the pressure transient. For reference 1 mmHg pressure is equivalent to 2.78 Lb/ft².

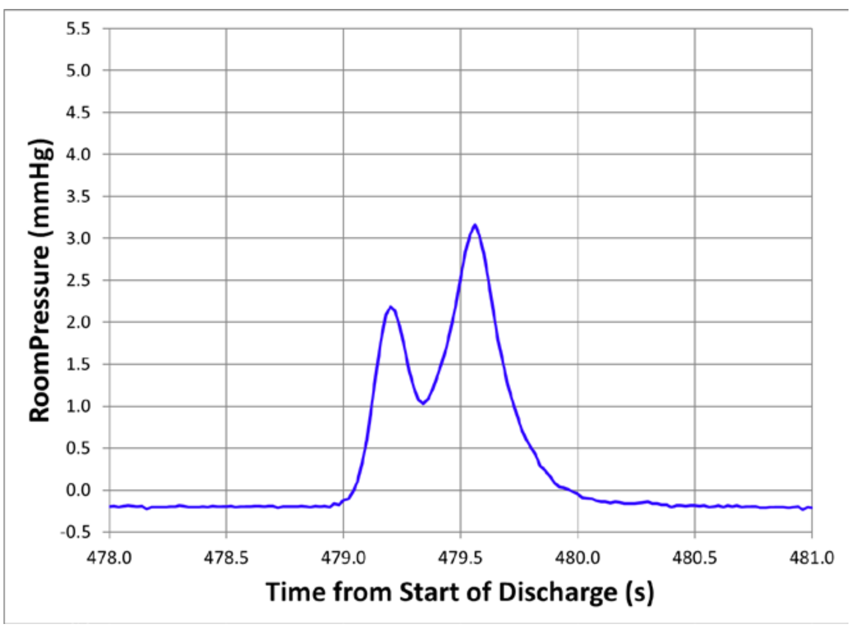


Figure 553 – Room Pressure during ignition event

Test RI_33 (125 grams; Internal Release)

Test RI_33 was performed without ignition sources to measure propane concentrations and verify door gasket seal integrity. This concentration test showed a concentration above LFL at the electric arc location and was followed by an igniter test later in the program (RI_34).

Table 116 – RI_33 Summary

<table>
<tr><th></th><th>Discharge Amount (g)</th><th>Duration of Discharge MM:SS</th><th>Discharge Rate (g/s)</th><th>Leak Location</th><th colspan="2">Maximum Concentration (%)</th></tr>
<tr><td rowspan="2">Planned</td><td rowspan="2">125</td><td rowspan="2">09:18</td><td rowspan="2">0.224</td><td rowspan="5">Evaporator Return Bend</td><td>11.5</td><td>Calculated with no leakage and well mixed</td></tr>
<tr><td>0.15</td><td>Well mixed in test room</td></tr>
<tr><td rowspan="3">Measured</td><td rowspan="3">130</td><td rowspan="3">09:17</td><td rowspan="3">0.233</td><td>8.9</td><td>Internal</td></tr>
<tr><td>9.1</td><td>Internal Deconvoluted</td></tr>
<tr><td>7.9</td><td>Electric Arc Location</td></tr>
</table>

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 554 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording.

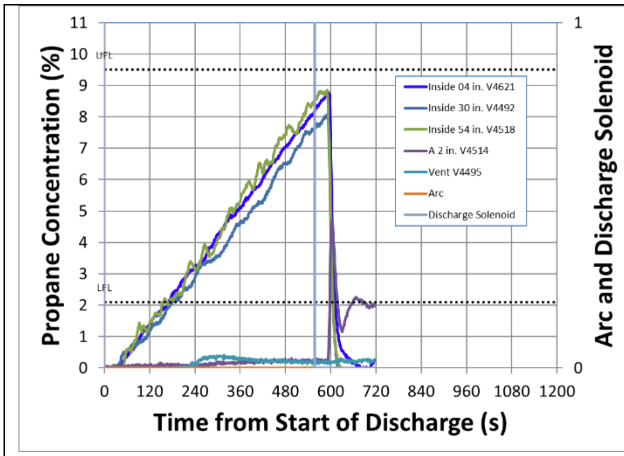
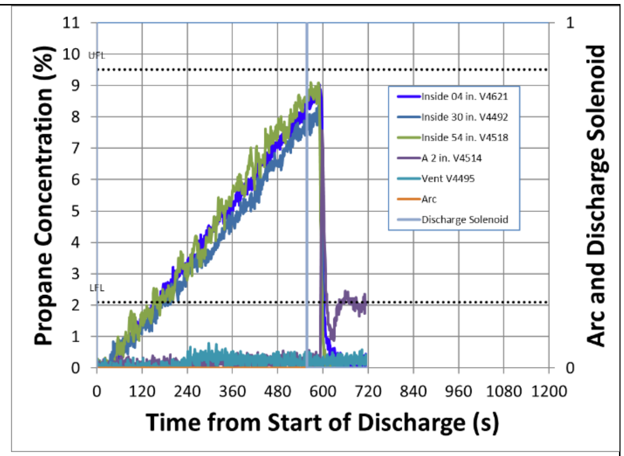
	
Concentrations	Deconvoluted Concentrations

Figure 554 – RI_33 Concentrations

Figure 555 shows the concentrations generated in RI_33 is higher than in RI_25 meaning some slight improvement in the cooler door gasket seal had occurred.

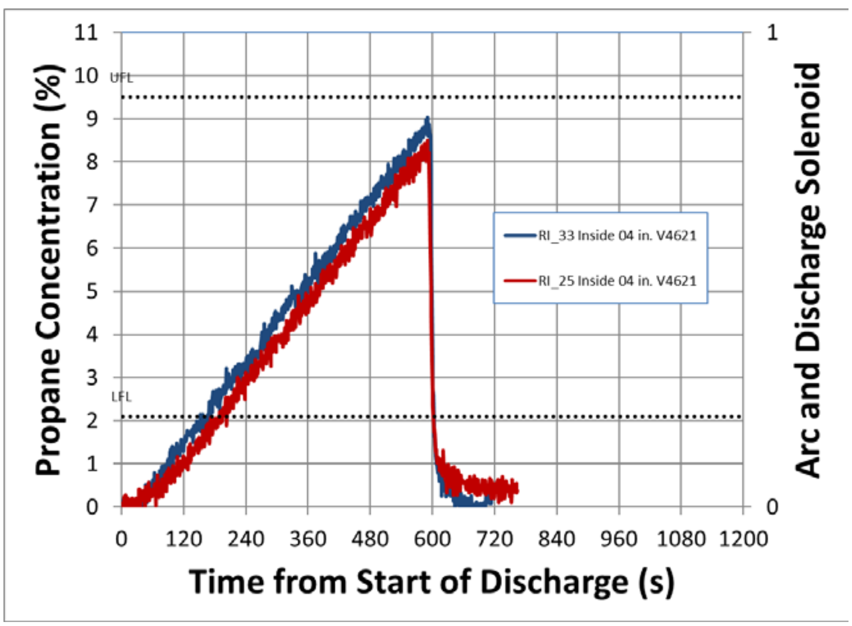


Figure 555 – Compare RI_33 and RI_25 Concentrations

Figure 556 shows the measured concentrations at the eight locations specified by 2-89 CDV. There was a period of 43 seconds when some concentrations were above the LFL of propane. Final propane concentrations at the floor level were between 1.5% and 2.5%. Concentrations at the high level were just within the detectable range of the concentration sensors (0.0% to 0.4%).

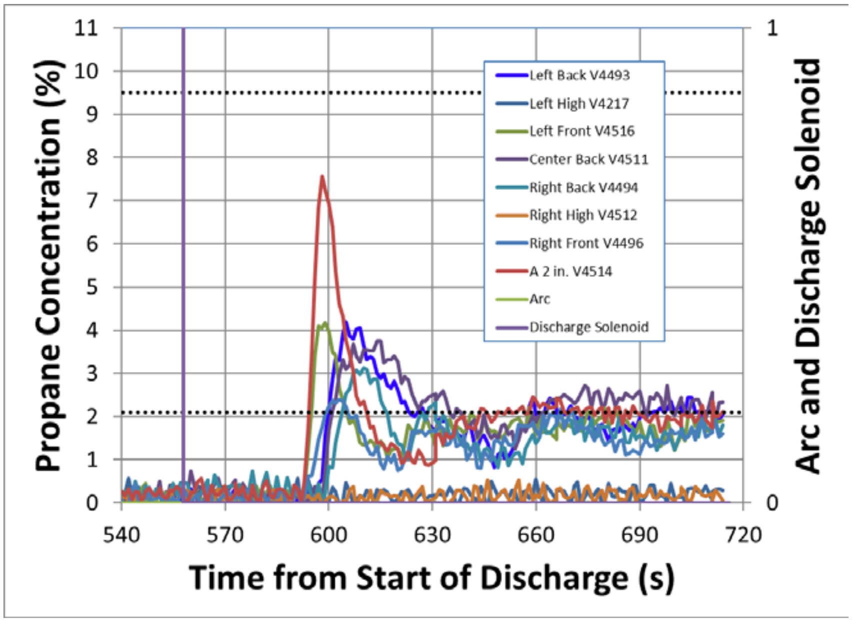


Figure 556 – RI_33 Concentrations at 8 locations surrounding cooler

Figure 557 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

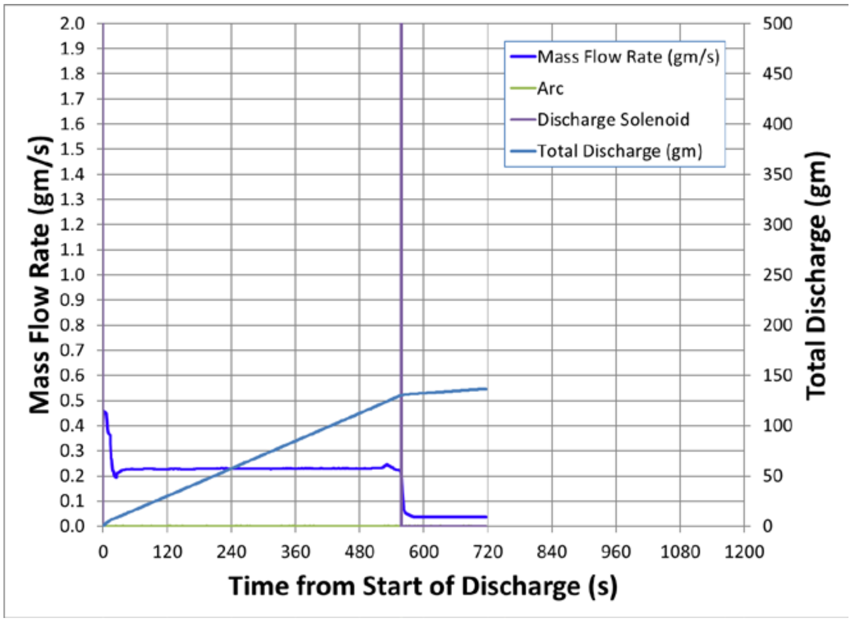


Figure 557 – RI_33 Mass Flow

Figure 558 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

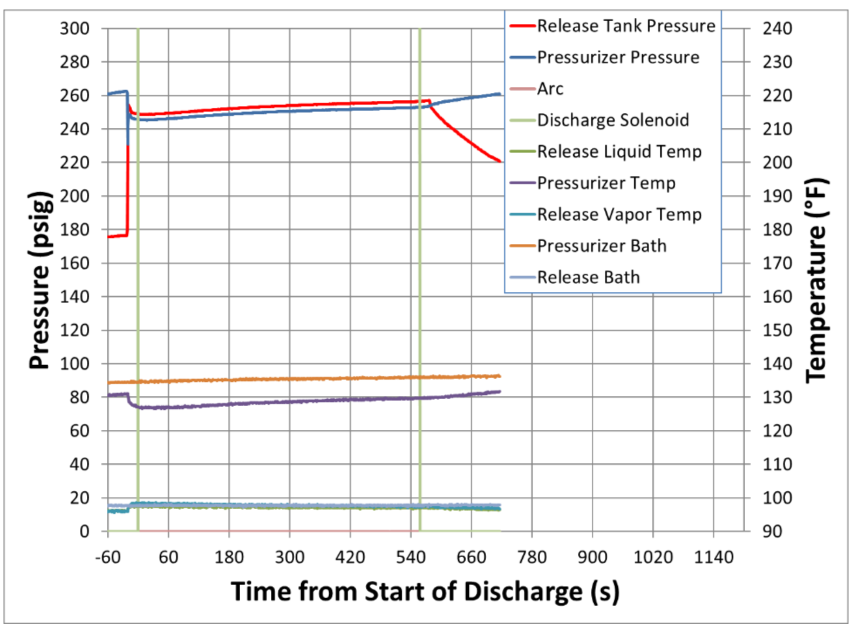


Figure 558 – RI_33 Pressurizer and Release Tank Pressure and Temperatures

Test RI_34 (125 grams; Internal Release, with Arc Igniters)

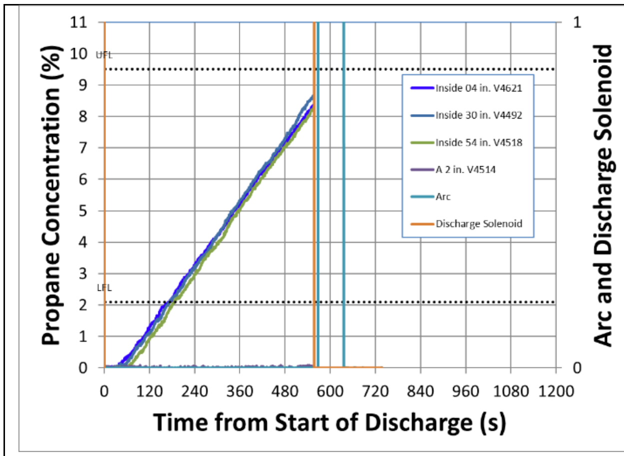
Test RI_34 was performed with ignition sources and resulted in ignition at the arc location. Just prior to the door opening, the internal concentrations were higher than stoichiometric conditions at 7.0%. Initial flaming at the electric arc was blue in color (pre-mixed) while later stages were yellow in color (diffusion flame). One of the six deflagration vents were burst by the ignition and four others were melted open by the hot gases.

Table 117 – RI_34 Summary

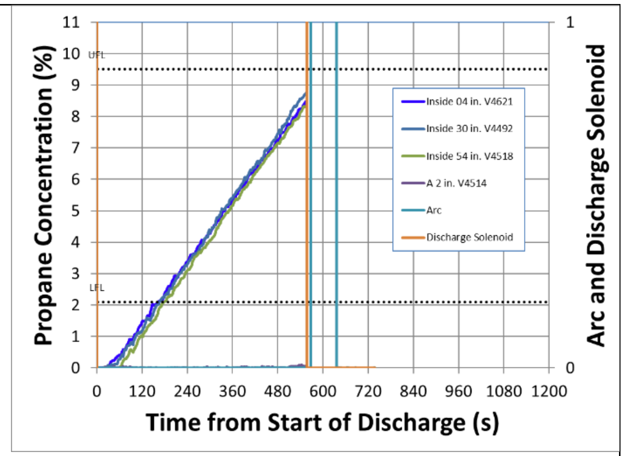
	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	125	09:18	0.224	Evaporator Return Bend
Measured	128	09:18	0.229	

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 559 shows the cooler internal concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations



Deconvoluted Concentrations

Figure 559 – RI_34 Concentrations

Figure 560 shows the measured concentrations at the eight locations specified by 2-89 CDV. All concentrations were low prior to the door opening with the exception of the right-side high location.

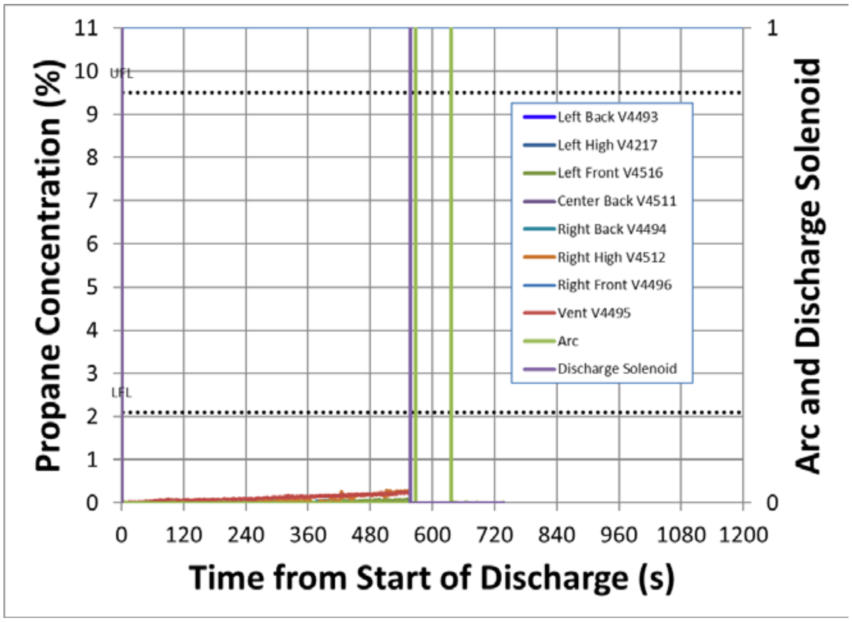


Figure 560 – RI_34 Concentrations at 8 locations surrounding cooler

Figure 561 compares the concentrations at the interior sensor (4-inch level) from tests RI_33 and RI_34 to show that concentrations were similar to within a few tenths of a percent relative to the discharge time.

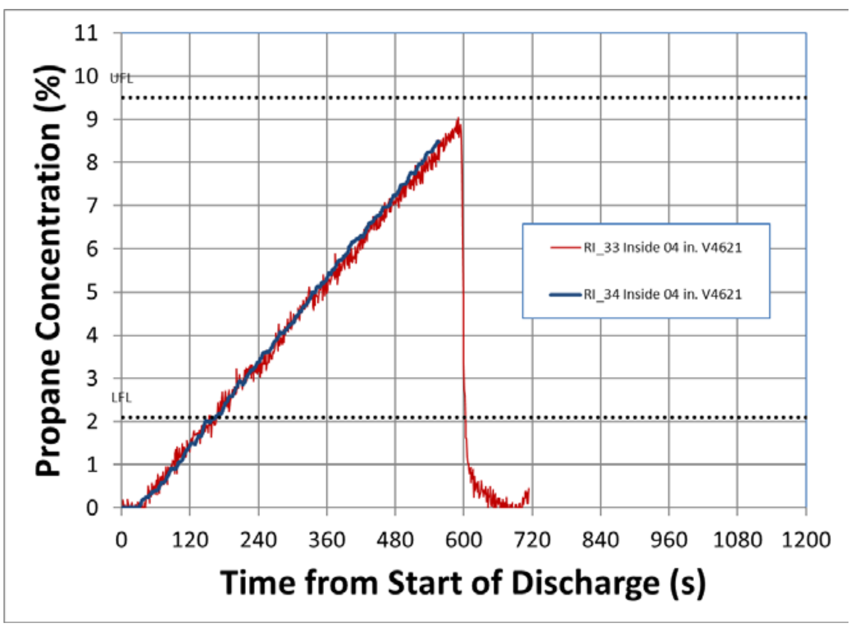


Figure 561 – RI_34 to RI_33 Concentration Comparison

Figure 562 shows the mass flow rate and total mass flow. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

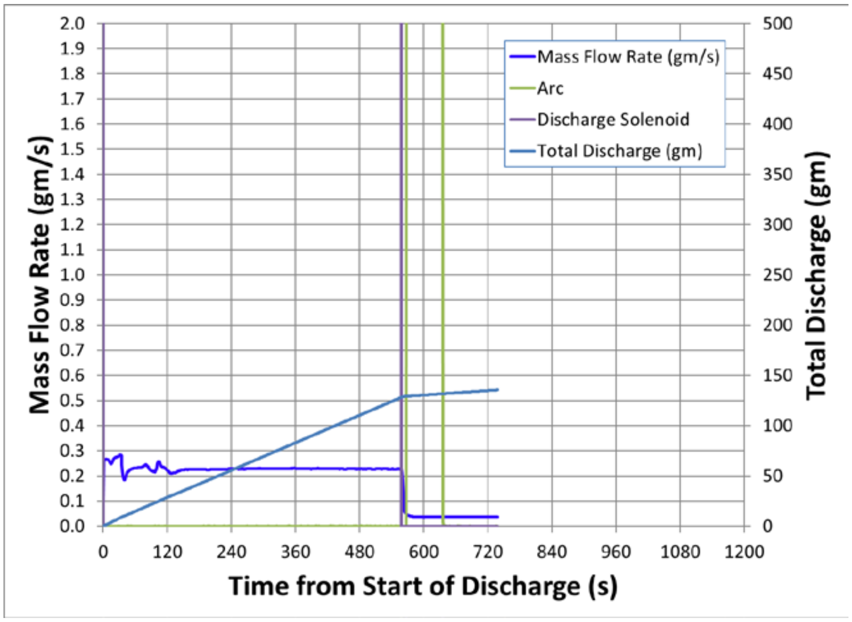


Figure 562 – RI_34 Mass Flow

Figure 563 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

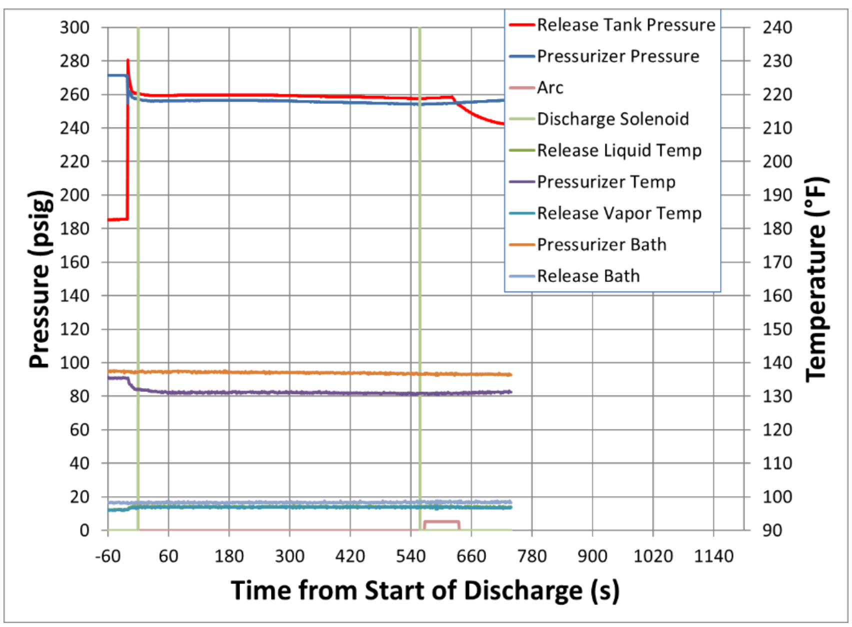


Figure 563 – RI_34 Pressurizer and Release Tank Pressure and Temperatures

Figure 564 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at location A, where ignition started. Locations B, C, and D show only slightly increased temperatures up to the 18-inch level. The higher temperatures from 60 inches to 92 inches reflect the buoyant rise of the hot gases from the flaming at location A.

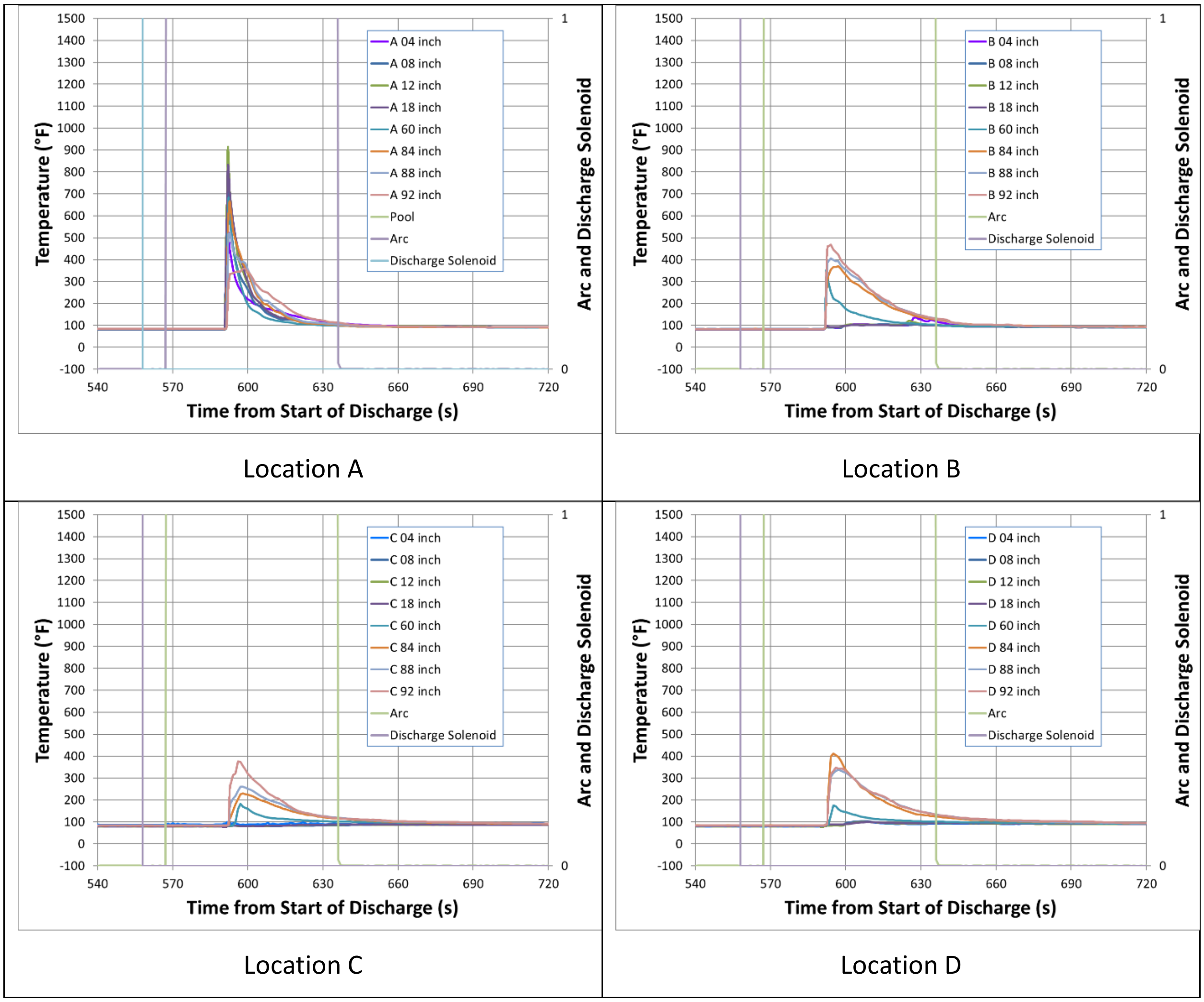


Figure 564 – RI_34 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 5 seconds. Figure 565 shows the ignition at the 6-inch arc in front of the door. There is an initial blue flame (premixed) which quickly transitioned to a diffusion (yellow) flame. The second frame shows that the gases were pushed out of the cooler to mix with room air. One deflagration vent burst due to the ignition event and four others melted from the heat.

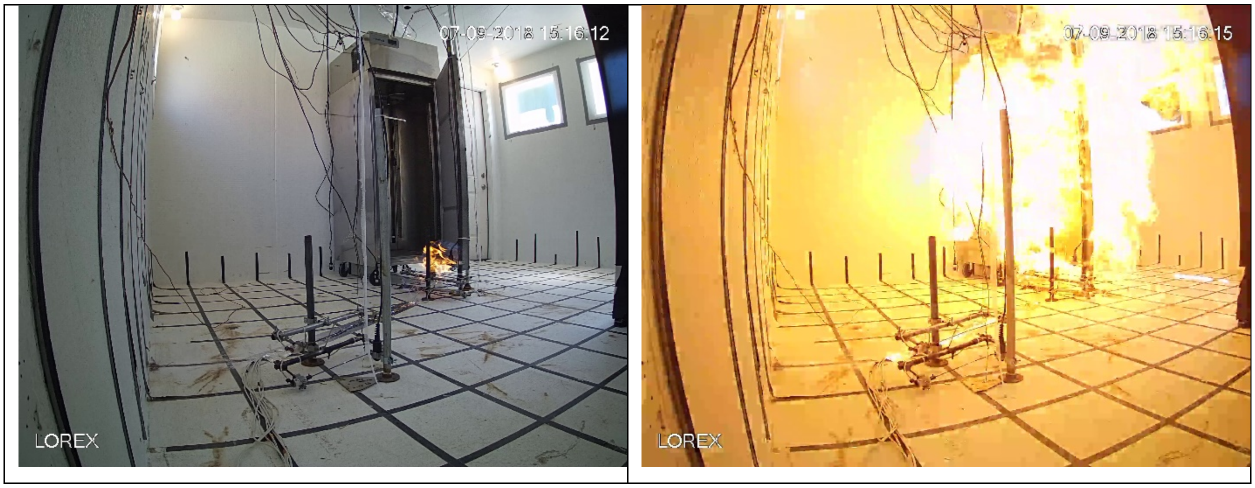


Figure 565 – RI_34 Ignition event

Figure 566 shows the room pressure transit during the ignition event. For reference 1 mmHg pressure is equivalent to 2.78 Lb/ft².

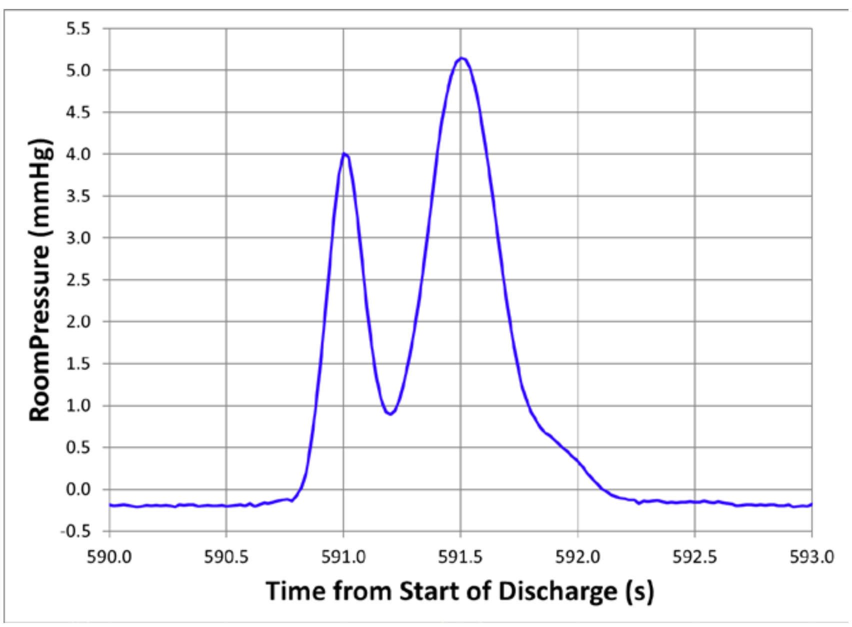


Figure 566 – Room Pressure during ignition event

Test RI_35 (150 grams; Internal Release)

Test RI_35 was performed without ignition sources to measure propane concentrations prior to the conduct of test RI_36. The key parameters and results of this test are summarized in the following table.

Table 118 – RI_35 Summary

<table>
<tr><th></th><th>Discharge Amount (g)</th><th>Duration of Discharge MM:SS</th><th>Discharge Rate (g/s)</th><th>Leak Location</th><th colspan="2">Maximum Concentration (%)</th></tr>
<tr><td>Planned</td><td>150</td><td>11:10</td><td>0.224</td><td rowspan="2">Evaporator Return Bend</td><td>13.9</td><td>Calculated with no leakage and well mixed</td></tr>
<tr><td>Measured</td><td>153</td><td>11:10</td><td>0.229</td><td>10.5
10.7
8.5</td><td>Internal
Internal Deconvoluted
Electric Arc Location</td></tr>
</table>

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 567 shows propane concentrations and deconvoluted values inside the cooler from the start of the discharge to the end of data recording. The internal sensors show steadily increasing trends up to the point that the center door is opened. The final concentration before the door is opened is between 10.0% and 10.5%. This value is above the Upper Flammability Limit (UFL) of propane (9.5%).The lowest sensor (at 4 inches) shows slightly larger concentrations than the sensors at 30 and 54 inches. As the door opens the sensor at 54 inches decreases the fastest, followed by the 30-inch level, while the 4-inch sensor decreased at the slowest rate.

Figure 568 focuses on the time from just before the discharge completion (670 s) to just after the door begins to open (700 s).

The sensor at the electric arc location (A 2 in.) shows a slight increase prior to the door opening, most likely due to door gasket leakage onto the floor near the cooler. This leakage accounts for the peak concentrations being less than the calculated well-mixed value. After the door is opened, the arc location increases to a value above the LFL of 2.1% and peaks at 5.3% (8.2% deconvoluted).

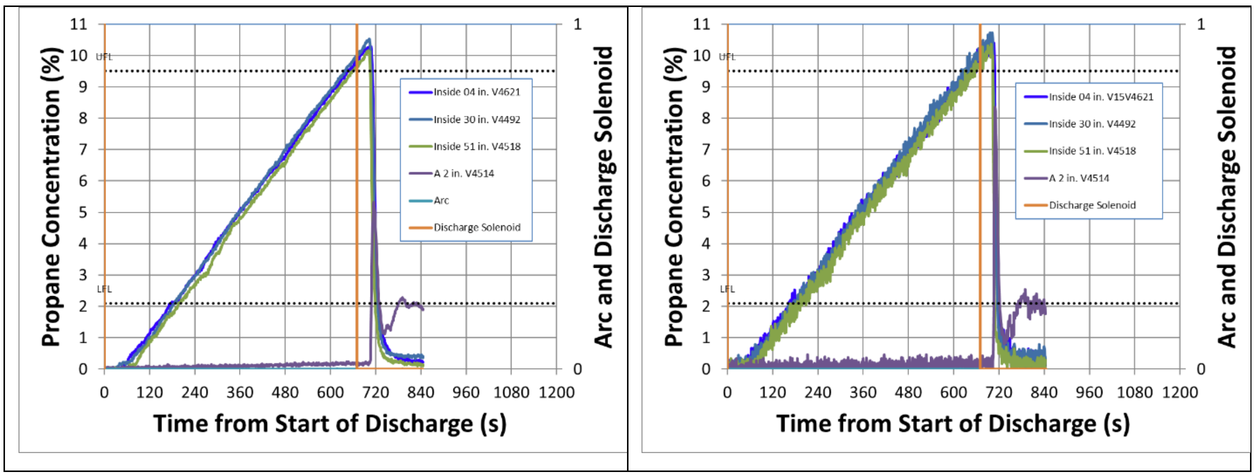
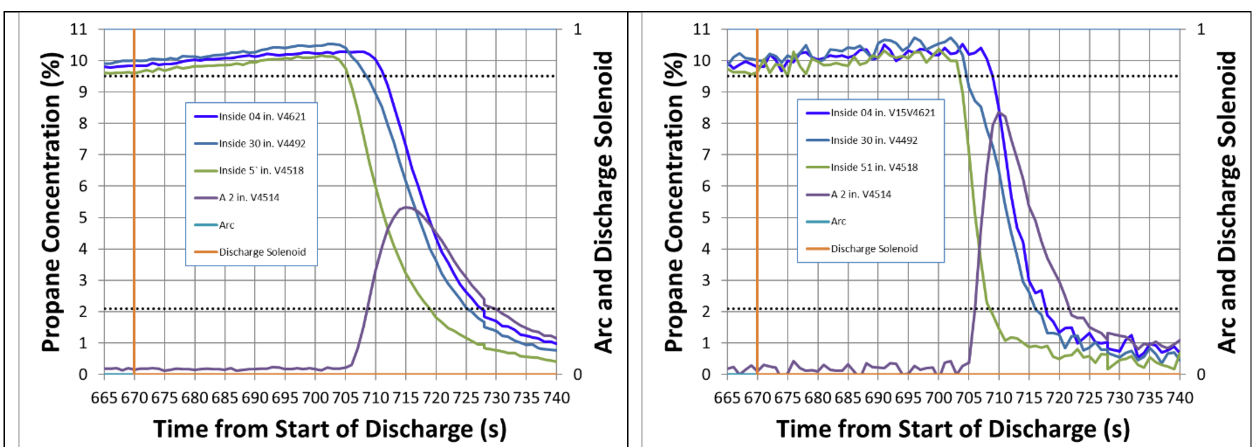


Figure 567 – RI_35 Concentrations



Concentrations	Deconvoluted Concentrations

Figure 568 – RI_35 Concentrations (Discharge Completion to after Door Opens)

Figure 569 focuses on the concentrations after completion of the discharge. The graphs show some concentrations at the 2-inch level near the LFL, while concentrations at higher locations are well below the LFL. At 146 seconds after the door opening, two of the sensors show concentrations slightly above the LFL of 2.1%. All other concentrations are below the LFL.

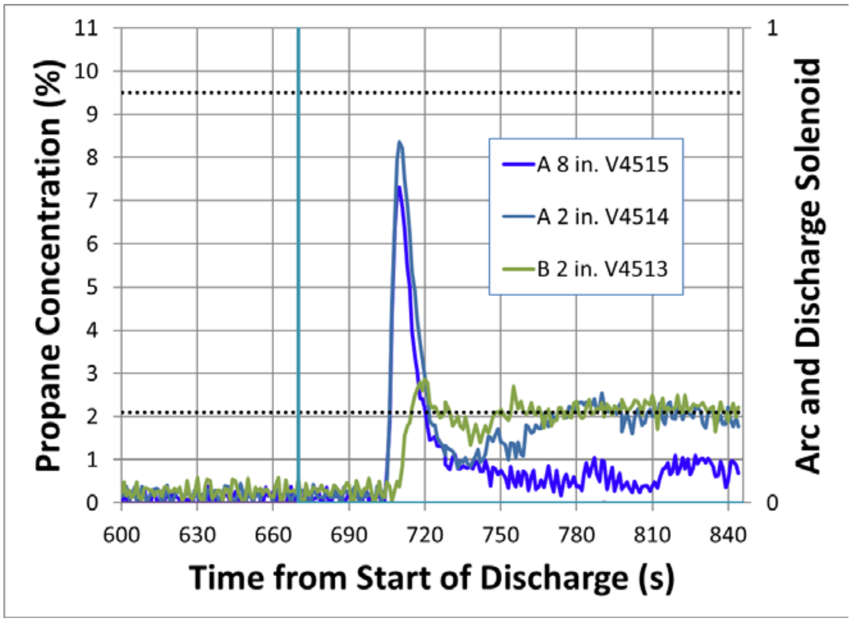


Figure 569 – RI_35 Concentrations after Discharge Completion

Figure 570 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

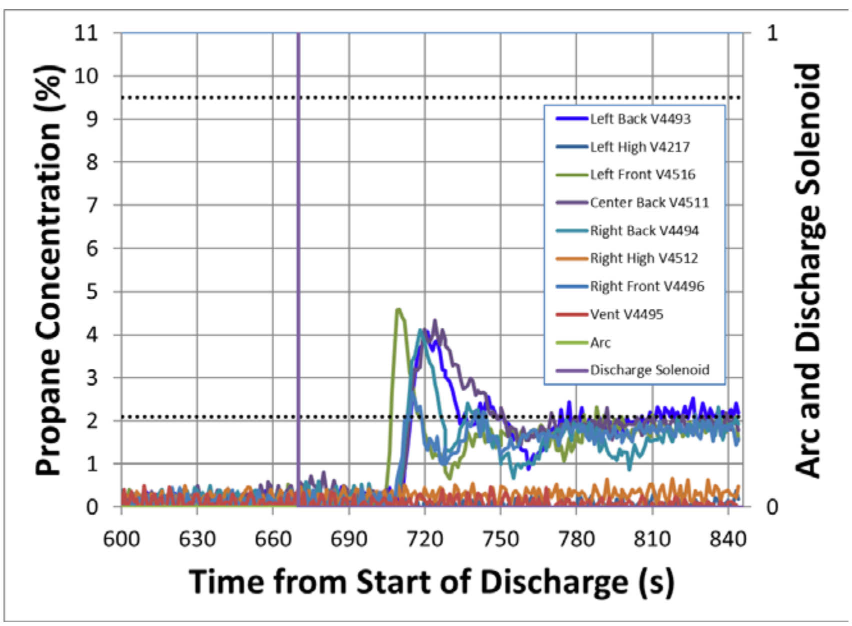


Figure 570 – RI_35 Concentrations at 8 locations surrounding cooler

Figure 571 shows the mass flow rate and total mass flow. The operator adequately controlled mass flow, but constant attention was required due to the low initial mass in the pressurizer tank. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

The spikes following the completion of the discharge are due to venting the discharge system in preparation for replacing the pressurizer tank for additional tests.

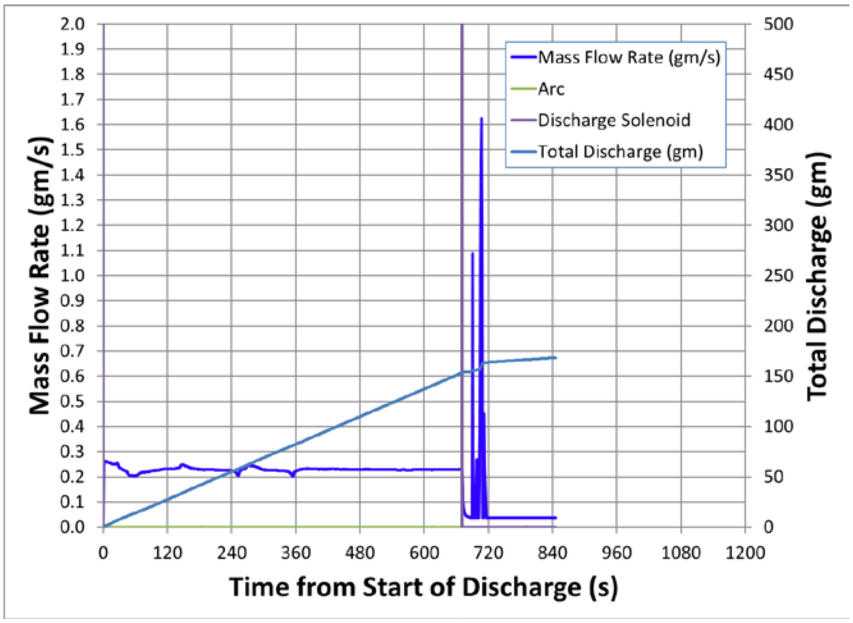


Figure 571 – RI_35 Mass Flow

Figure 572 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis). The slight increase in pressure following the start of the discharge is an indication of the low mass of liquid remaining in the pressurizer. Heat transfer from the pressurizer bath was able to more than compensate for the loss of mass into the release tank.

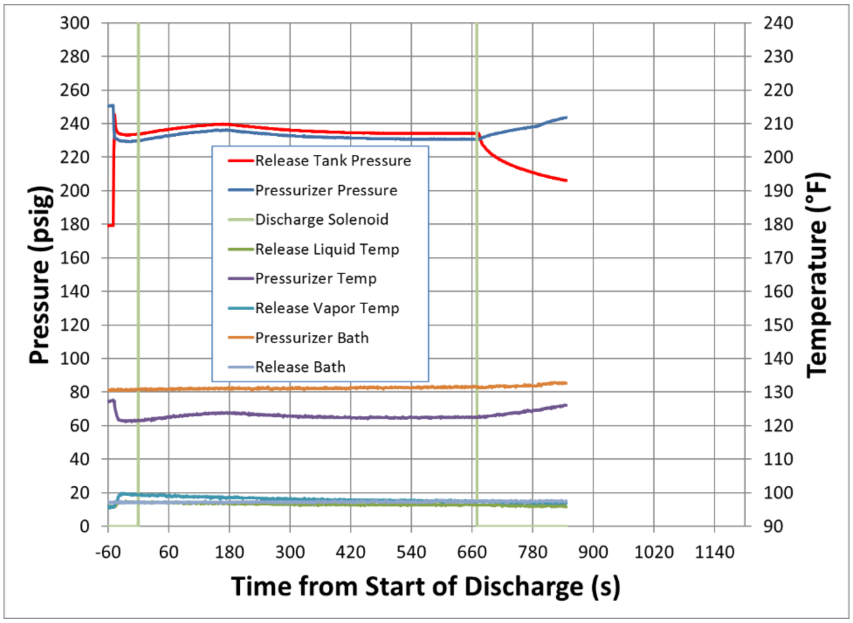


Figure 572 – RI_35 Pressurizer and Release Tank Pressure and Temperatures

Test RI_36 (150 grams; Internal Release, with Arc Igniters)

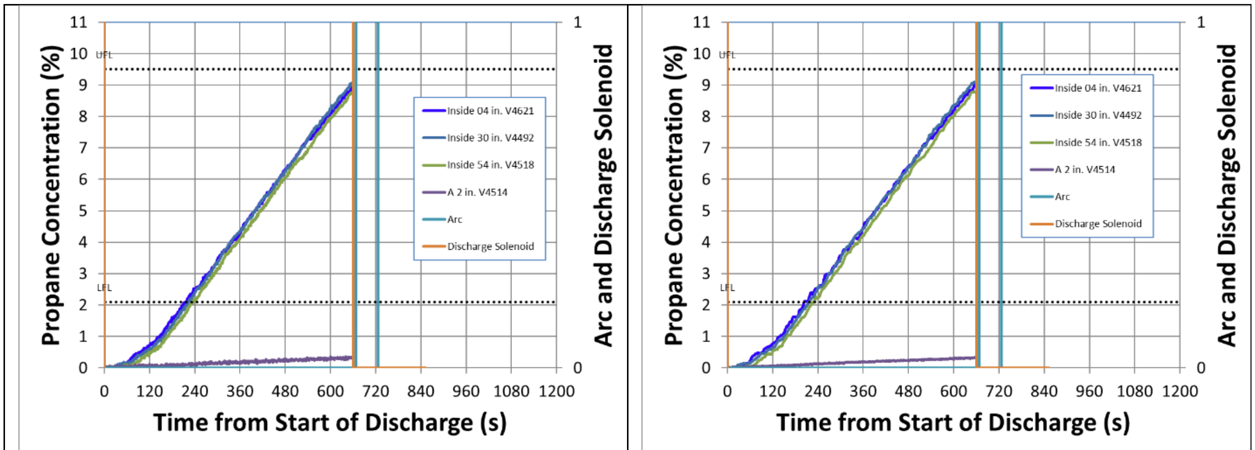
Test RI_36 was performed with ignition sources and resulted in ignition at the arc location. Just prior to the door opening, the internal concentrations were higher than the UFL for propane (9.5%). Because of these high concentrations, the resulting flaming was orange in color indicating a diffusion flame. Diffusion flames are typically orange in color due to insufficient oxygen to support complete combustion of propane.

Table 119 – RI_36 Summary

	Discharge Amount (g)	Duration of Discharge MM:SS	Discharge Rate (g/s)	Leak Location
Planned	150	11:10	0.224	Evaporator Return Bend
Measured	149	11:01	0.225	

Per procedure, the door of the cooler remained closed for 30 seconds after completion of the release. The door was then opened to a 60° angle in 3.0±0.5 seconds. Data was recorded for a minimum of 2.5 minutes following completion of the discharge.

Figure 573 shows the cooler internal concentrations measured up to the point that combustion products caused a false measure of propane concentration.



Concentrations	Deconvoluted Concentrations

Figure 573 – RI_36 Concentrations

Figure 574 shows the measured concentrations at the eight locations specified by 2-89 CDV. All these exterior sensors show a slight increase in concentration prior to the door opening due to leakage from the door gaskets.

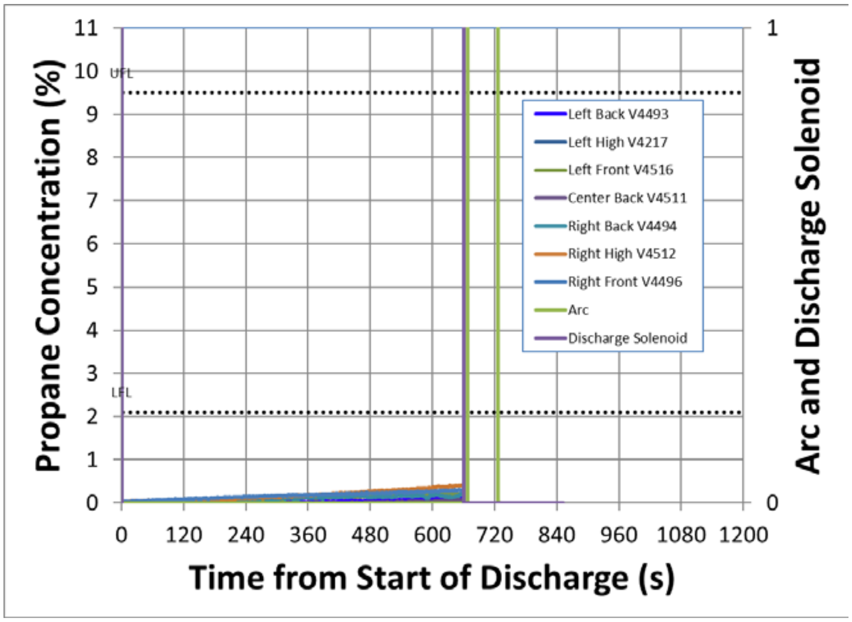


Figure 574 – RI_36 Concentrations at 8 locations surrounding cooler

Figure 575 compares the concentrations at the interior sensor (4-inch level) from tests RI_35 and RI_36 to show that concentrations were similar to within a few tenths of a percent relative to the discharge time.

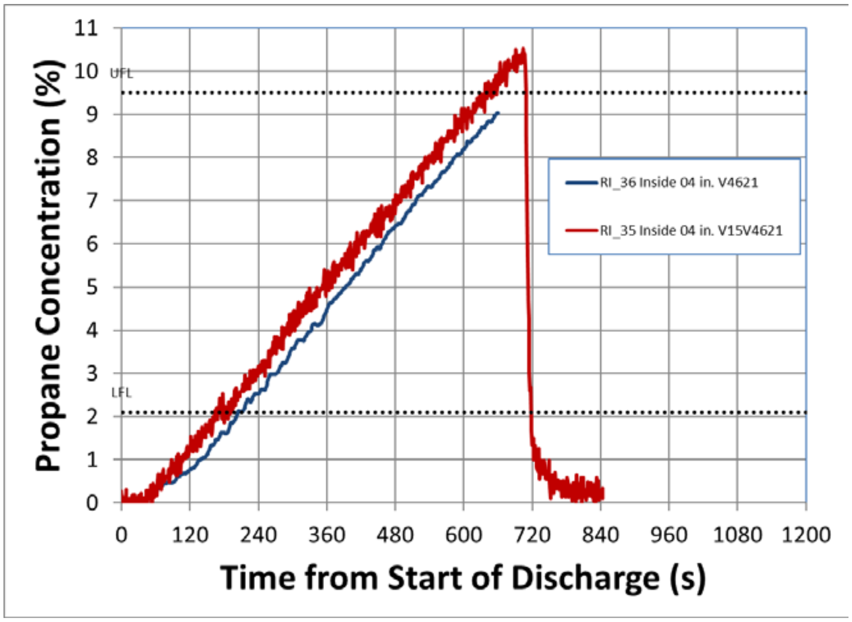


Figure 575 – RI_36 to RI_35 Concentration Comparison

Figure 576 shows the mass flow rate and total mass flow. Flow was initially low followed by the operator throttling up the flow rate to a constant level for the remainder of the discharge. The small flow rate following closure of the discharge solenoid is not an actual flow. Instead it is a relic of the mass flow sensor linear calibration zero offset. Flow rates after closure of the discharge solenoid were not used to calculate the total mass release.

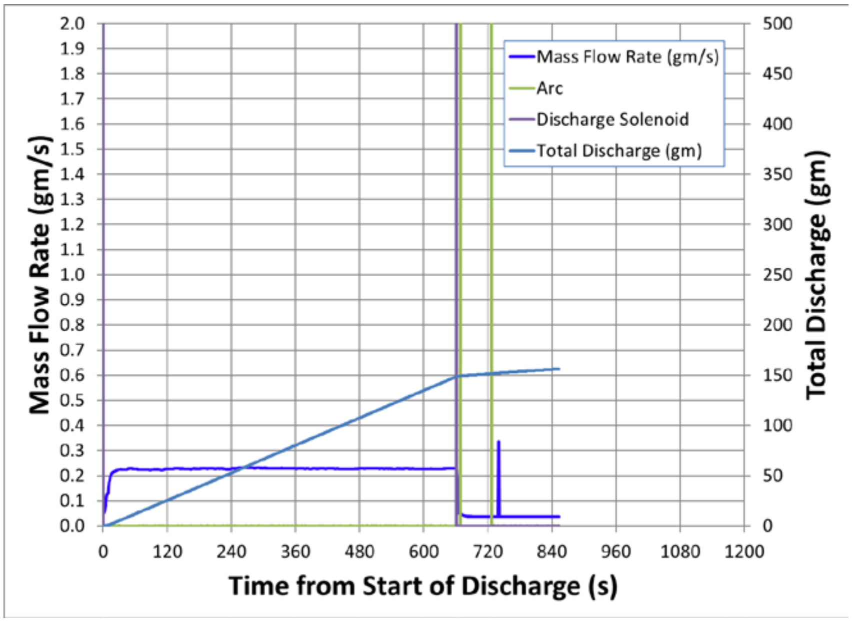


Figure 576 – RI_36 Mass Flow

Figure 577 shows the pressurizer and release tank pressures (left axis) and temperatures (right axis).

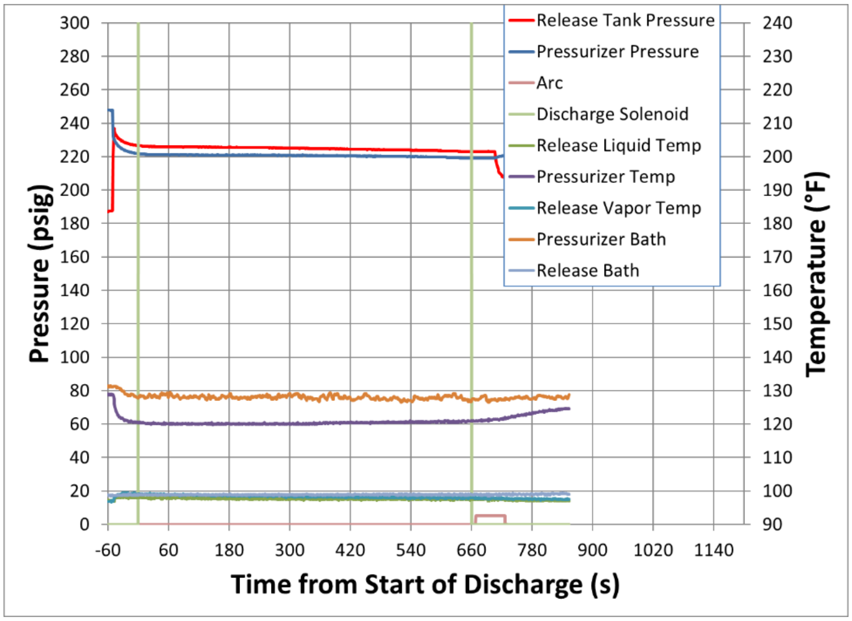


Figure 577 – RI_36 Pressurizer and Release Tank Pressure and Temperatures

Figure 578 shows the temperatures developed at the various locations following ignition. The highest temperatures were recorded at the floor level at location A, where ignition started. Locations B, C, and D show only slightly increased temperatures up to the 18-inch level. The higher temperatures from 60 inches to 92 inches reflect the buoyant rise of the hot gases from the flaming at location A.

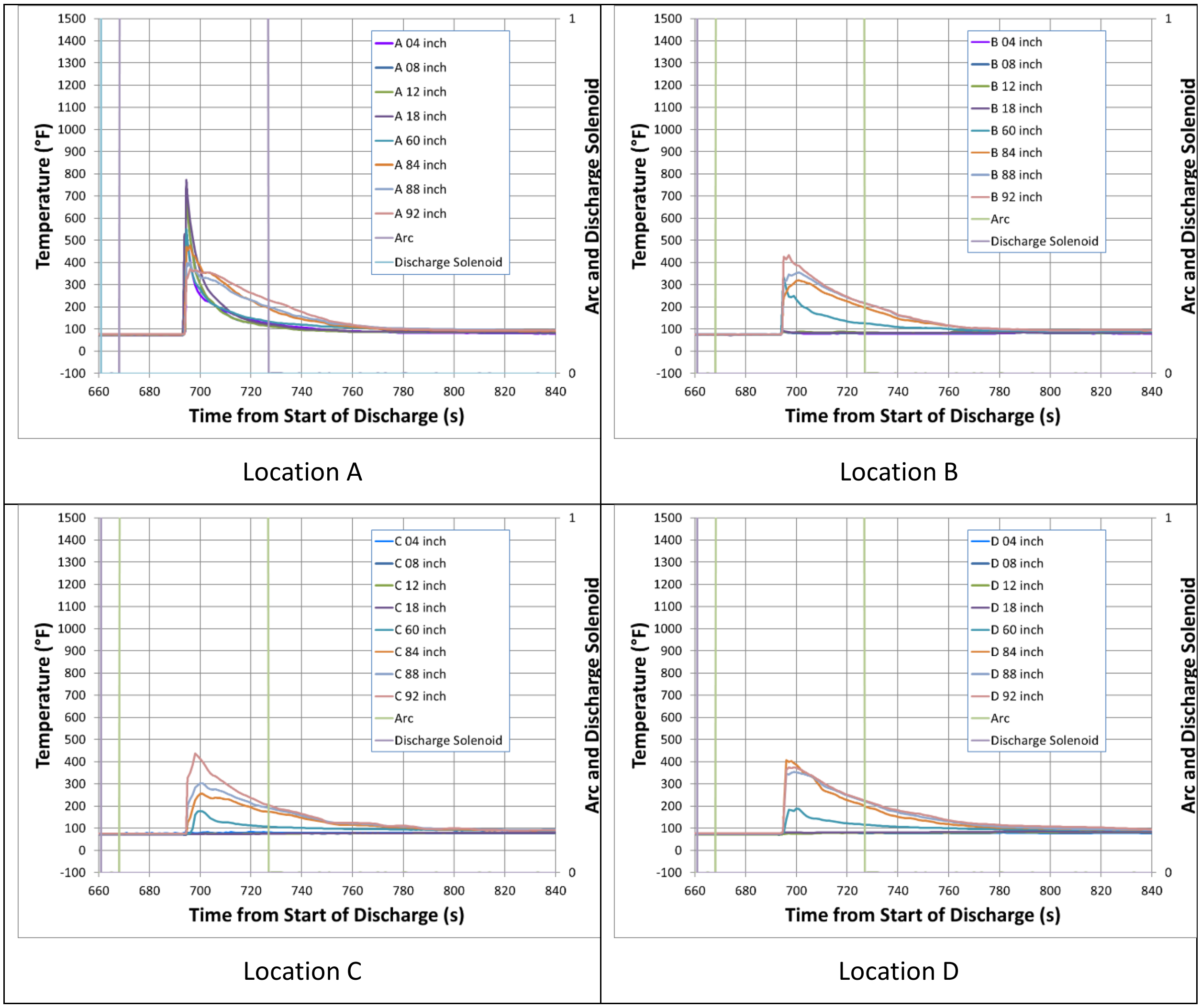


Figure 578 – RI_36 Temperatures at Locations A, B, C, and D

The videos show that the propane flaming endured for 3 seconds. Figure 76 shows the ignition at the 6-inch arc in front of the door. There a small amount of blue flaming (premixed), while the dominant yellow color signifies a diffusion flame. The second frame shows that the flames spread almost entirely in the vertical direction. One deflagration vent burst due to the initial flaming and three others were melted by the hot gases.

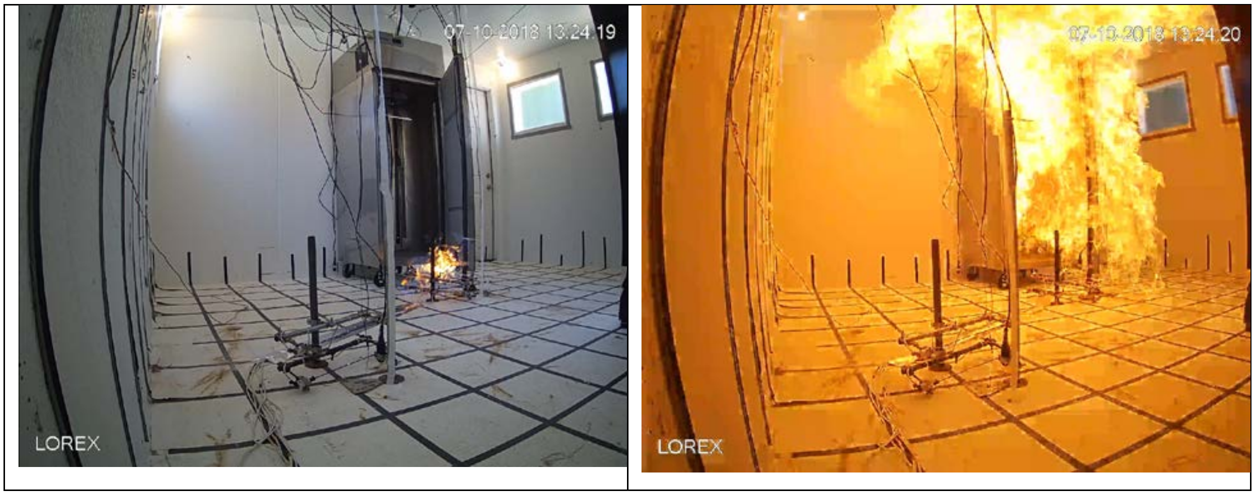


Figure 579 – RI_36 Diffusion flames and buoyant rise of hot gases

Figure 580 shows the room pressure transit during the ignition event. For reference 1 mmHg pressure is equivalent to 2.78 Lb/ft².

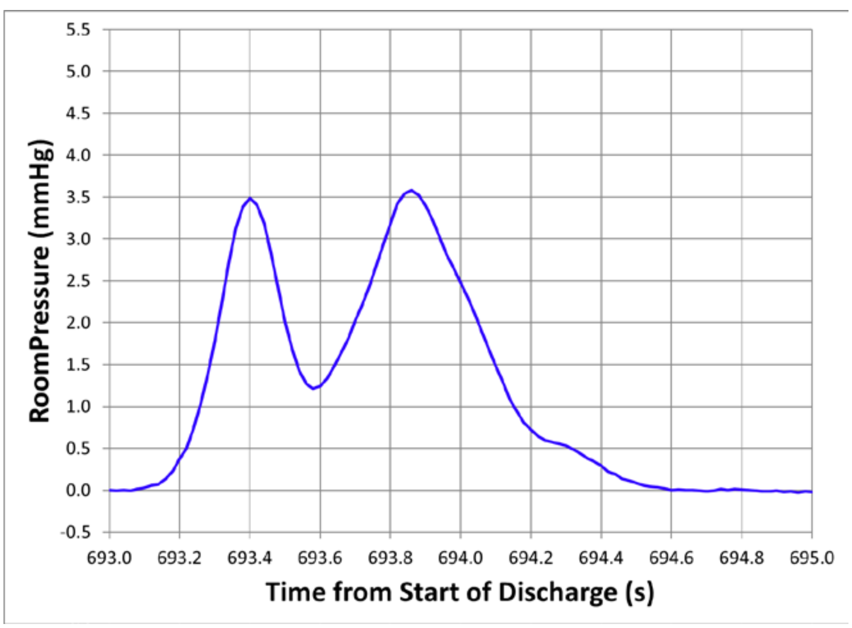


Figure 580 – Room Pressure during ignition event

Appendix F Mass Flow Control Validation

Mass flow between 6.8 and 40 g/s

The mass flow meter supplied by the manufacturer was calibrated for 0-150 kg/hr (0-41.67 g/s). This meter was matched with a PLC control system and the data acquisition system. This appendix documents the interaction of the meter with the data acquisition system. The output of the meter was a 4 to 20 ma signal linearly matched with the calibrated range of the meter as shown in Figure 581

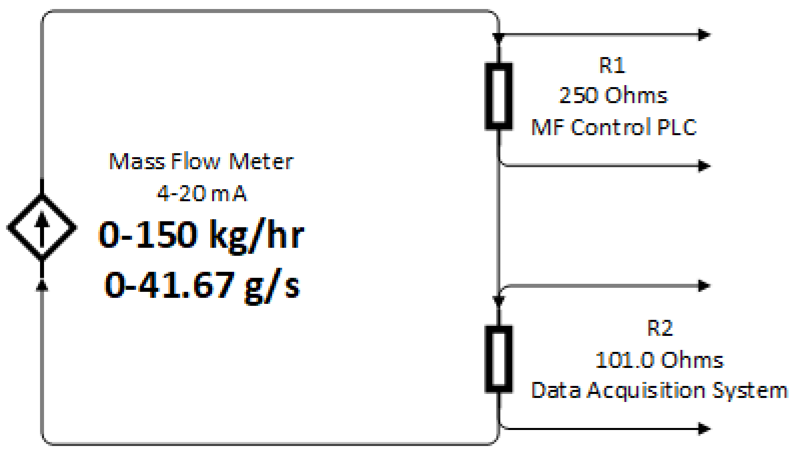


Figure 581 – Current loop from the mass flow meter

For Task 1 and Task 2 testing, excluding the reach-in cooler tests, the mass flow rate signal was converted to grams per second according to equation 1.

$$\dot{m} = \frac{(V - 0.404)}{(2.02 - 0.404)} 41.667 \qquad \text{Eqn. 1}$$

Where:

$\dot{m}$ is the mass flow rate in grams per second, and

V is the voltage across resister R2 (101.0 ohms)

Accuracy of this measurement was dependent on the calibration of the meter and the conversion in the data acquisition system. The combined accuracy of the resistor and data input channel was less than 0.1%. The rated accuracy of the mass flow meter from the calibration sheet was ±0.5% of reading. These The factors combine by a root sum square method, given that the uncertainties are independent. So at 20 kg/h the combined accuracy is 0.51% = sqrt[(0.5%)^2 + (0.1%)^2)]

Mass flow between 0.2 and 0.6 g/s

The reach-in cooler testing required flow rates in the range of 150 g to 397 g in 670 seconds or 0.224 to 0.593 g/s (0.81 to 2.13 kg/hr.). These flows were less than the lowest calibration point of 5 kg/hr. contained in the manufacturer's calibration report. The manufacturer provided information to change the span of the mass flow meter from 150 kg/hr. down to 7.2 kg/hr. (2 g/s). Calibration by the manufacturer was not possible due to the time constraints on the project. The revised mass flow current loop is shown in Figure 582.

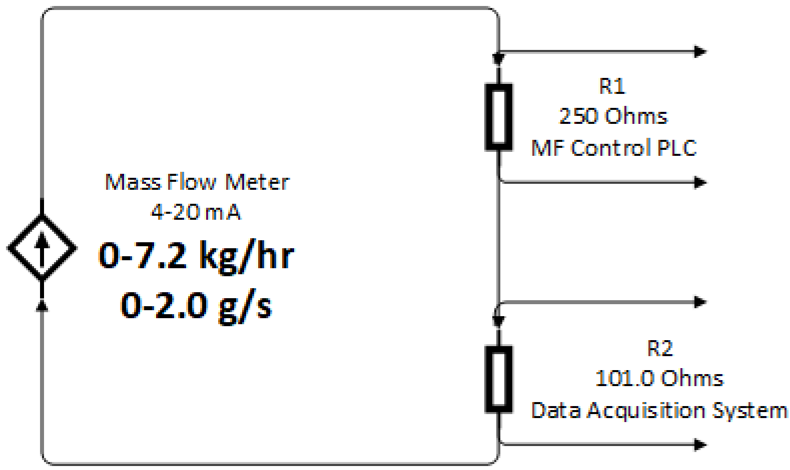


Figure 582 – Mass Flow Meter modification for the reach-in cooler test series

A separate calibration was performed using the test setup shown in Figure 8. Water was flowed through the discharge system and collected in a bucket. The bucket weight was recorded on a scale with an accuracy of ±0.05g. The flow rate voltage signal was recorded by the data acquisition system at the rate of 1 Hz.

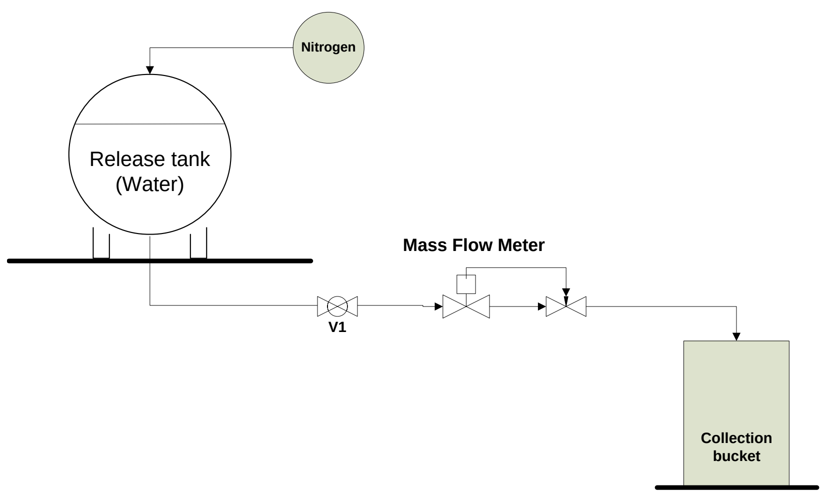


Figure 583 – Test Set up for Validation of Mass Flow Meter and Controller

Table 120 reports 25 trials of the low flow system. The flow rates were performed in a random order, but the table has been sorted in increasing order of the target flow rate. The columns in this table have the follow meanings.

Column Name	**Purpose**
Test#	The test number
Flow Rate (g/s)	The target flow rate planned before the test.
Measured Mass (g)	The measured mass collected in bucket during the flow period
Actual Time to Flow (s)	The time in seconds for the duration of collection in the bucket
Actual Flow Rate (g/s)	The measured mass (g) divided by the actual time of flow
Average Volt signal (V)	The average voltage signal recorded in the data acquisition system during the flow period

Table 120 – Low Mass Flow Calibration Summary

Test#	Target Flow Rate (g/s)	Measured Mass (g)	Actual Time to Flow (s)	Actual Flow Rate (g/s)	Average Voltage signal (V)
Trial 19	0.125	100.1	625	0.160	0.503
Trial 22	0.125	99.1	625	0.159	0.503
Trial 23	0.125	98.8	647	0.153	0.500
Trial 20	0.167	128.2	649	0.198	0.534
Trial 21	0.167	127.5	646	0.197	0.534
Trial 24	0.167	126.7	633	0.200	0.537
Trial 12	0.200	155.6	644	0.242	0.563
Trial 3	0.200	156.0	644	0.242	0.564
Trial 5	0.200	151.8	648	0.234	0.563
Trial 11	0.224	170.4	648	0.263	0.582
Trial 15	0.224	171.0	647	0.264	0.582
Trial 6	0.224	166.2	651	0.255	0.581
Trial 8	0.224	170.0	649	0.262	0.581
Trial 13	0.350	256.7	658	0.390	0.683
Trial 4	0.350	256.1	661	0.387	0.682
Trial 9	0.350	254.2	657	0.387	0.683
Trial 14	0.530	380.2	663	0.573	0.828
Trial 17	0.530	377.7	662	0.571	0.828
Trial 18	0.593	416.0	653	0.637	0.880
Trial 7	0.593	415.3	664	0.625	0.875
Trial 8A	0.593	416.2	662	0.629	0.879
Trial 1	0.650	461.3	669	0.690	0.925
Trial 10	0.650	456.4	659	0.693	0.927
Trial 2	0.650	462.4	667	0.693	0.927

Prediction Interval

The low flow rate data in Table 120 was loaded into Minitab to calculate the prediction interval for mass flow rate and total mass flow. The following graphs report the calculation of those intervals.

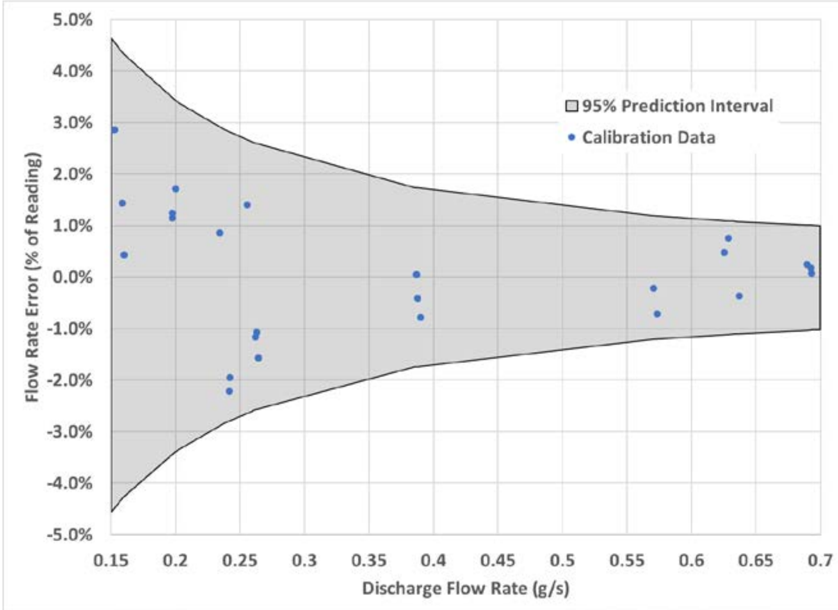


Figure 584 – Prediction Interval for low mass flow rates

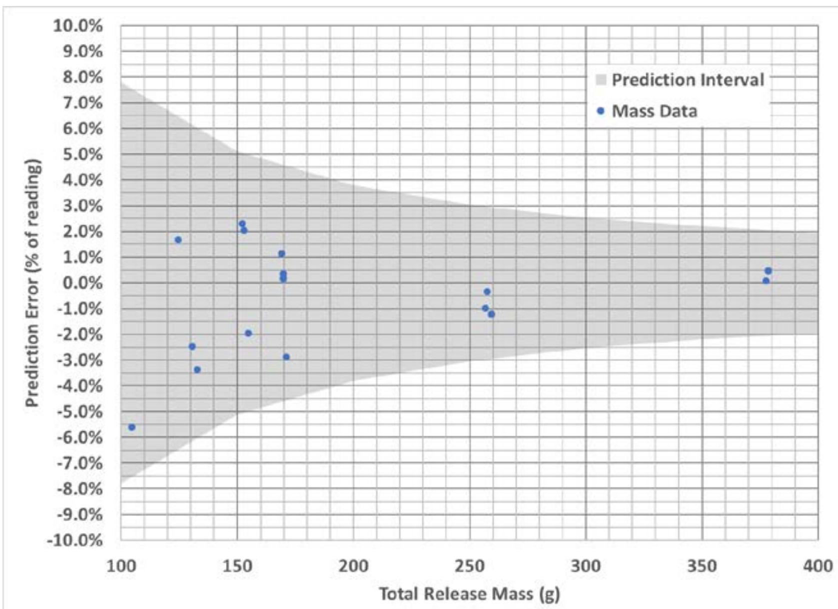


Figure 585 – Prediction interval for total mass flow at low mass flow rates

Appendix G Propane Measurement Uncertainty

Measuring propane concentration in this project was based on the principle of partial pressures of mixed gases. In other words, as propane is mixed into a volume of air it displaces air (and oxygen) in proportion to the volume percentage of propane. This aspect of propane (and any gas near ideal gas behavior) is as much a property of propane as any other property (e.g. conductivity, IR absorption, density, or index of refraction of the gas mixture). A electrochemical oxygen sensor was selected for this project base on the relatively fast response time and low cost, as compared to the Henze-Hauck conductivity sensors used in the AHRTI 9007-1 project.

The Apogee SO-220 sensor measures absolute Oxygen concentration. Use of this sensor is planned as a proxy for propane concentration. The manufacturer supplies correction for absolute pressure, temperature, and humidity.

Measurement of propane concentration using the Apogee sensor involves the following assumptions:

1. Barometric pressure, cell temperature, and humidity at the sensor remain constant throughout the validation. To prevent condensation of water vapor, the Apogee sensor is equipped with a heater to maintain a non-condensing gas mixture at the diffusion membrane.
2. At 100% propane concentration (0% oxygen concentration) the sensor output is 2% of the value measured at 20.95% oxygen concentration (per specifications).
3. At 0% propane concentration the sensor output is in the range of 12 to 13 mV (per specifications).
4. Oxygen concentration is known to be 20.95% by volume
5. The SO-220 sensor output has stabilized.
6. Propane concentration at the sensor displace all atmospheric gases in proportion to their initial concentrations. In other words, if the local propane concentration is x, then the local oxygen concentration has changed to $(1 - x) * 20.95\%$. This relationship provides a means to infer propane concentration by solving for x.

Note that these assumptions become invalid if any other gas were introduced to the sensor. For example, combustion results in reduction of oxygen, increases in carbon dioxide, and increase in water vapor.

With these assumptions, then the following equations are derived to determine propane concentration. Equations 3 and 4 in the SO-220 manual can be converted into the following form to determine Oxygen concentration:

$$O_2 = O_{2,init}\left(\frac{S - S_{zero}}{S_{init} - S_{zero}}\right) \qquad \text{Eqn. 1}$$

Where:

O_2	Is the Oxygen Concentration based on signal output (% by volume)
$O_{2,init}$	Is the Initial Oxygen Concentration (20.95% by volume)
S	Is the Sensor output (mV)
S_{zero}	Is the Sensor output at 0% Oxygen (based on Nitrogen) (mV)
S_{init}	Is the Sensor output at 20.95% Oxygen (mV)

The expression in parentheses in Eqn. 1 is the same as the $(1 - x)$ in assumption #6 above. Solving for x gives the following equation

$$x = \left(\frac{S_{init} - S}{S_{init} - S_{zero}}\right) \qquad \text{Eqn. 2}$$

Where:

x	Is the Propane Concentration (% by volume)

The other aspect of validating the sensor response is to correlate the sensor output to the actual concentration input to the sensor. In this case, the $x_{indicated}$ in equation 2 is based on manufacturer's claim of a linear response of the sensor to absolute oxygen concentration.

In the ideal case, x should be equal to measured mix of gases from the mass flow controllers or x_{input}, calculated as shown in equation 3.

$$x_{input} = \left(\frac{S_{nitrogen}}{S_{nitrogen} + S_{air}}\right) \qquad \text{Eqn. 3}$$

Where:

$S_{nitrogen}$	Is the recorded flow rate of nitrogen
S_{air}	Is the recorded flow rate of air

The manufacturer of this sensor also provides a temperature correction. The effect in all tests was small with the exception of tests where the sensor was rapidly cooled by an impacting mist of propane liquid. The final conversion equation for propane concentration including temperature correction is shown in Equation 2.

$$x = \left(\frac{S_{init} - S}{S_{init} - S_{zero}}\right) \times 100\% - \sum_{i=0}^{3} \frac{C_i T^i}{0.2095} \qquad \text{Eqn. 2}$$

Where:

C_i	Constants provided by Apogee Instruments for the SO-200 series sensor
T^i	Measured temperature (°C) raised to an integer power
0.2095	Ambient Oxygen volume fraction

The constants are listed in Figure 11.

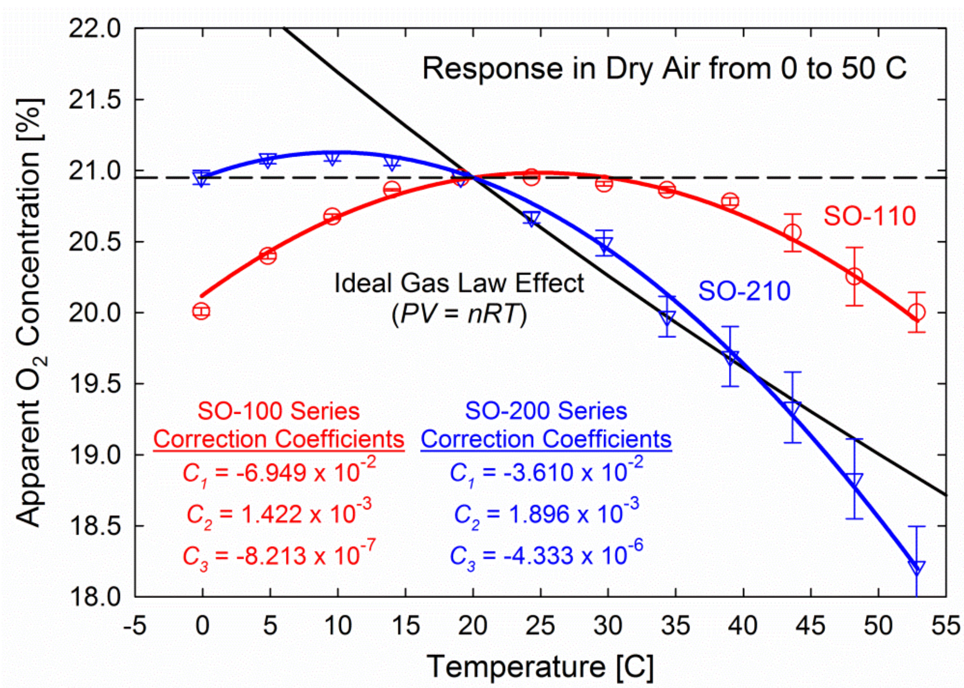


Figure 586 – Temperature Correction Constants (Apogee Instruments: SO-100-200-manual)

Manufacturer's Uncertainty

The relevant sections of the SO-220 instrument are shown in Figure 587. This information is extracted to create a prediction interval chart according to these specifications.

SPECIFICATIONS

	SO-100 Series Slower Response Higher Output	SO-200 Series Faster Response Lower Output
Response Time (time required to read 90 % of saturated response)	60 seconds	14 seconds
Measurement Range	0 to 100 % O_2	
Sensitivity (at sea level, 101.3 kPa)	52-58 mV in 21 % O_2; 2.6 mV per % O_2; 26 µV per 0.01 % O_2	12-13 mV in 21 % O_2; 0.6 mV per % O_2; 6 µV per 0.01 % O_2
Output at 0 % O_2	5 % of output at 20.95 % O_2 or 2.5 ± 1 mV	2 % of output at 20.95 % O_2 or 0.2 ± 0.1 mV
Measurement Repeatability	less than 0.1 % of mV output at 20.95 % O_2	
Non-linearity	less than 1 %	

Figure 587 – SO-220 Extracted Specifications from Apogee Instruments

Sensor serial #4217 was selected for use in generating the data shown in Table 121. The

Table 121 – Manufacturer's specification for sensor #4217

Concentration (%)	Signal (mV)	Signal Low (mV)	Signal High (mV)	PI Low (%)	PI High (%)
0.0%	13.45	13.43	13.46	-0.10%	0.10%
1.5%	13.25	13.24	13.26	1.40%	1.60%
2.0%	13.18	13.17	13.20	1.90%	2.10%
3.0%	13.05	13.04	13.06	2.90%	3.10%
4.0%	12.92	12.91	12.93	3.90%	4.10%
5.0%	12.79	12.77	12.80	4.90%	5.10%
6.0%	12.65	12.64	12.67	5.90%	6.10%
7.0%	12.52	12.51	12.54	6.90%	7.10%
8.0%	12.39	12.38	12.40	7.90%	8.10%
9.0%	12.26	12.25	12.27	8.90%	9.10%
10.0%	12.13	12.12	12.14	9.90%	10.10%
20.0%	10.81	10.80	10.82	19.90%	20.10%
30.0%	9.49	9.48	9.51	29.90%	30.10%
40.0%	8.18	8.16	8.19	39.90%	40.10%
100.0%	0.27	0.26	0.28	99.90%	100.10%

The data in Table 121 was then used to create a graph of the prediction interval as shown in Figure 588. The graph show the accuracy in terms of percent of reading (% rd.) By converting the manufacturers statements that the accuracy ranges from ±7% rd. at concentrations as low as 1.5%. The accuracy improves to ±1% rd. at concentrations near 10%.

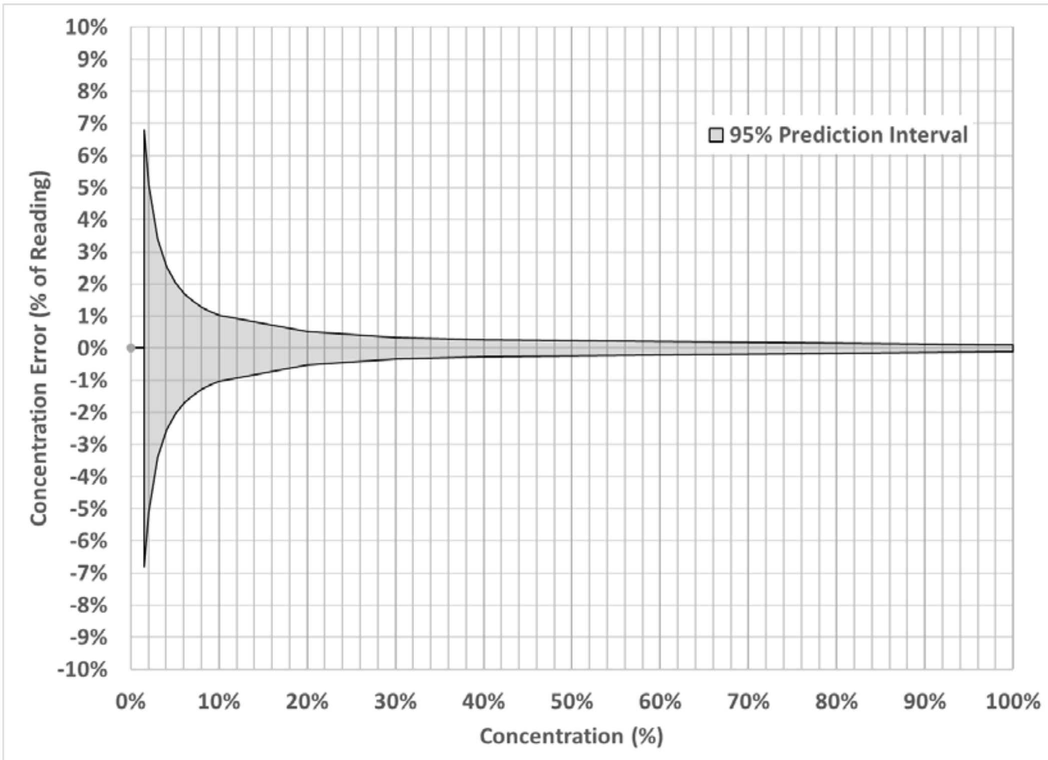


Figure 588 – Prediction interval for sensor #4217

Appendix H Test Instrumentation and Equipment

Table 122 summarizes the instrumentation and equipment used in the Task 1 and Task 2 test programs. The following sections provide more detail on each item in the table.

Table 122 - Instrumentation

Instrumentation Name	Model	Manufacturer	Range	Accuracy
Thermocouple [1]	GG-K-24-SLE	Omega	minus 200 °C to 1250 °C	±2 °C
Thermocouple [1]	TJ36-CAXL-18U-48	Omega	minus 200 °C to 1250 °C	±2 °C
Concentration Sensor [2]	220	Apogee	0-100% by volume	±5% of Rd. at 2% concentration ±1% of Rd at 10% concentration
NI Data Acquisition System [1]	NI Data Acquisition System	National Instruments	Multi-Range	±0.1%
Pressure Transducer [1]	TD1000	Transducers Direct	0-500 psig	±0.5%
Pressure Transducer [1]	226A	MKS Instruments	0-100 mmHg	±0.5 mmHg
Mass Flow Control System [2]	Mass Flow Control System	Hallfield Controls	0-300 kg/hr	±0.4 % of Rd. at between 6.8 and 40 g/s
				±4% of Rd.at 0.2 g/s ±1.5 of Rd. at 0.5 g/s
Scale [1]	7000xl	Doran	0-500 lbm	±0.2 lbm
Temp/Hum/Pres probe [1]	4247	Traceable Products	10.0-95.0 %RH 1.00 kPa – 110.0 kPa	±3 %RH ±0.4 kPa

[1] – Accuracy from suppliers information

[2] – Accuracy from in-house validation/calibration

Instrumentation

Thermocouple wire

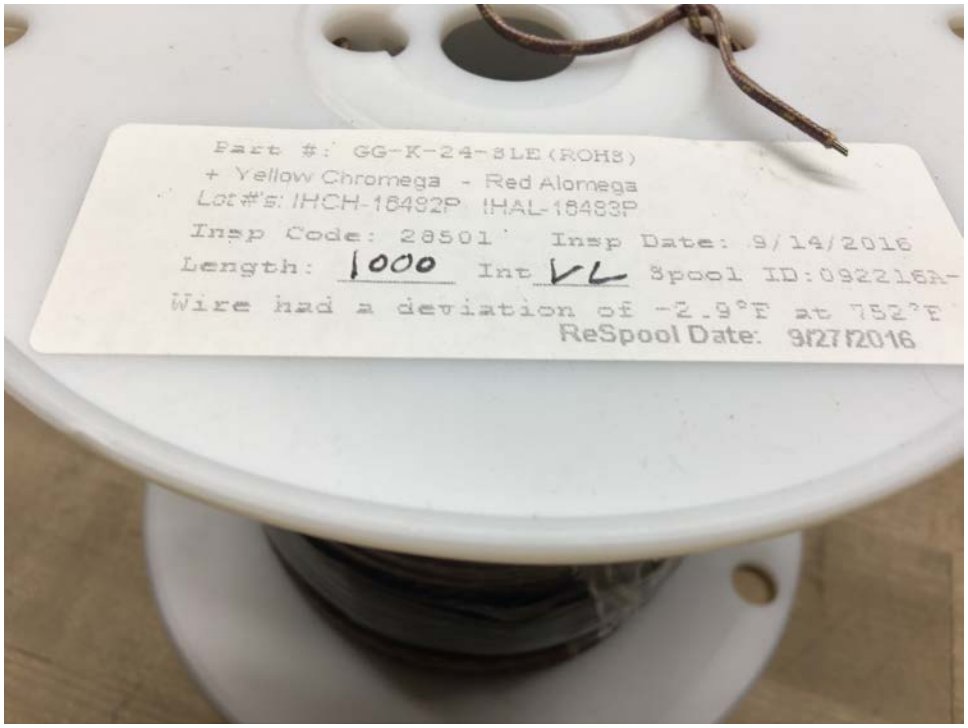


Figure 589 - GG-K-24-SLE

24-gauge Type K thermocouple wire was used to create bare bead TC's for use in various monitoring locations. The response time is 3.0 seconds (63% of step change). Reference: http://www.omega.com/techref/ThermocoupleResponseTime.html

Thermocouple, shielded probe

Figure 590 - TJ36-CAXL-18U-48

Ungrounded 1/8 inch diameter type K thermocouples were used to measure temperatures in the release and pressure tanks as well as the surrounding water baths.

Concentration Sensor

Figure 591 – Apogee Model 220 Oxygen Sensor

The oxygen sensor was used to measure propane concentration because of the displacement of oxygen by propane (prior to any combustion gases that can skew the results).

NI Data Acquisition System

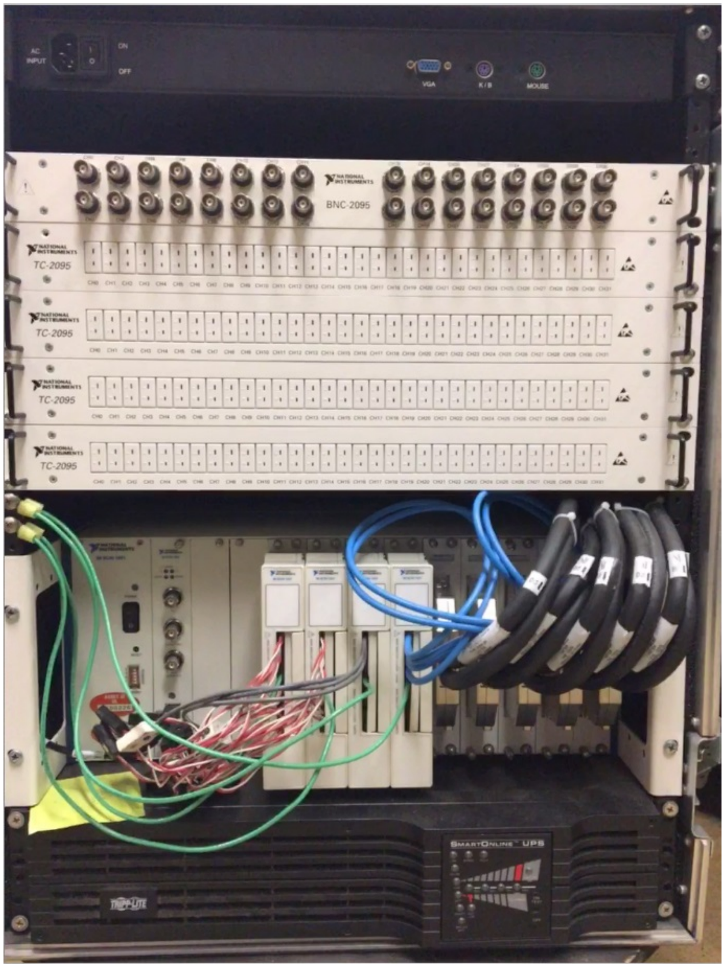


Figure 592 - NI Data Acquisition System

The data acquisition system contains four TC-2095 32-channel cold-junction compensated thermocouple input panels; One BNC-2095 32 channel channel cold-junction compensated thermocouple input panel, and four SXCI-1327 modules supporting up to 300 V inputs.

Pressure Transducer, 0-500 psig

Figure 593 - TD1000

Pressure transducers were used on the Release and Pressurizer tanks.

Pressure Transducer, 100 Torr

Figure 594 – MKS Model 226A; 100 Torr

The 100 Torr pressure transducer was used to monitor the pressure difference between the test room and equipment room.

Mass Flow Control System

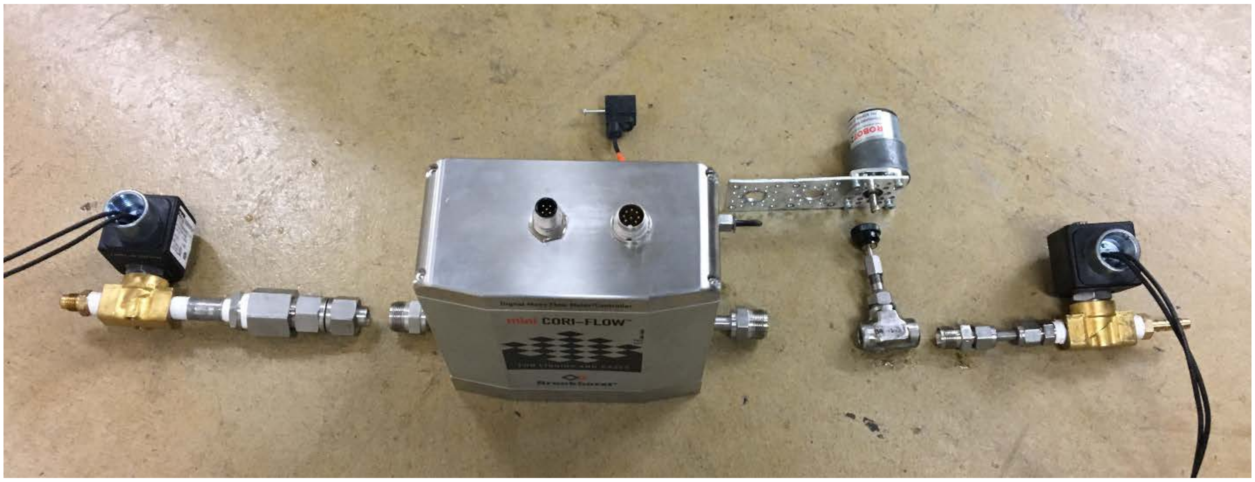


Figure 595 - Mass Flow Control System Components

Shown from left to right are 1) emergency stop solenoid; 2) Coriolis mass flow meter; 3) metering valve and DC motor operator; and 4) discharge stop solenoid.

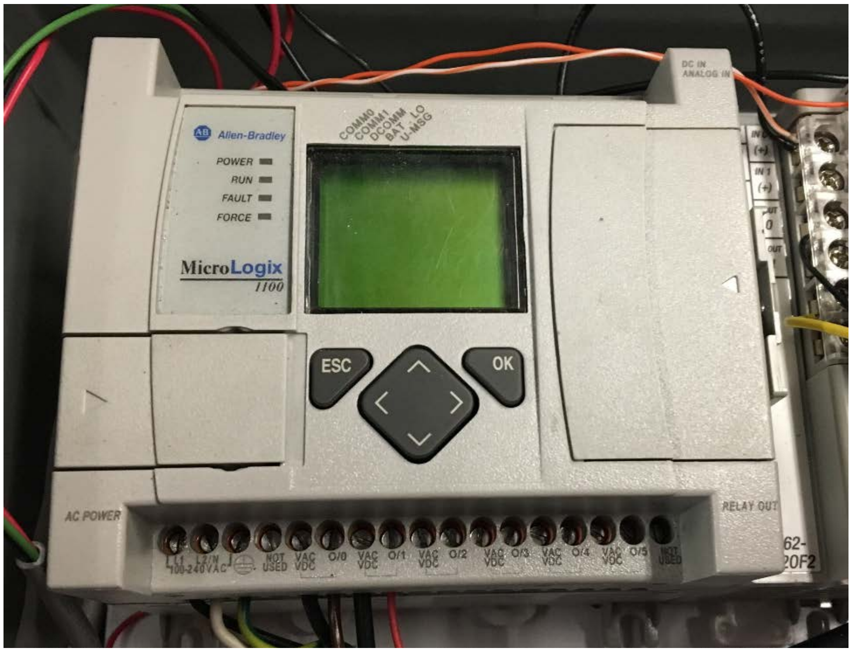


Figure 596 – Mass Flow System Programmable Logic Controller (PLC)

The PLC was programmed with controls to start, stop, measure, totalize the propane flow. The PLC output a calibrated flow signal to the data acquisition system.

Scale, 0-500 lbs

Figure 597 - SCL\7000xl

The 7000xl scale was used to record release and pressurizer tank weights before and after filling and also after release weight.

Temp/Hum/Pres probe

Figure 598 – Traceable Model 4247

Handheld temperature humidity probe used to determine humidity and barometric pressure at the beginning of each test.

AHRTI Supplied Equipment

AHRTI Supplied Equipment	Manufacturer
PTAC	Goodman
Mini-Split Indoor Unit	Daikin
Single Door Reach-in Cooler	Welbilt
Three Door Reach-in Cooler	Hussmann

PTAC

Figure 599 – PTAC Unit

Mini-Split Indoor Unit

Figure 600 – Mini-split indoor unit

Single Door Reach-in Cooler

Figure 601 – Single Door Reach-in Cooler

Three Door Reach-in Cooler

Figure 602 – Three Door Reach-in Cooler

Appendix I Test Procedure

Pre-Test Checklist

Initial Safety

- Combustible gas sensors operating in the equipment room.
- Test room purged and refrigerant concentration sensors show less than minimum detectable concentration in the test room, space below and above the test room.
- Oxygen analyzer shows comparable Oxygen concentrations in the test room, underfloor, and outside air (20.95% ideal; comparison within ±0.20%)
- All rooms in the structure show less than minimum detectable combustible gas concentration.
- Test room cleared of any items or debris not required for the test.
- Sprinkler system setup and piping system is dry.
- Fire extinguishers present and charged.

Test Room Preparation

- Gas monitoring shows all propane and combustion products have been removed.
- Sample pump operating and oxygen concentration is at 20.95% ± 0.05% based on a dried sample (0% humidity)
- Equipment checks show all instrumentation operational (Thermocouples, Heat Flux gages, concentration sensors, video cameras, pressure sensor, infrared camera).
- Test room ambient in the range of 60-80 °F.
- Deflagration vent plastic sheets are in place and outside shutters closed.
- Ignition indicators (cheesecloth strips) in place
- Propane discharge tubing located at position required by the test plan
- Electric arc gapped and tested for operation.
- Concentration sensors and electric arc in position according to the test plan.
- Test Marquee positioned and is clear in the camera view.
- Cameras positioned and focused.
- Verify sufficient battery power and memory for high speed cameras.
- Test room doors closed and sealed. Outside door unlocked
- Test Clock operation verified and reset to zero time.
- Test room initial barometric pressure, temperature, and humidity recorded.
- Heat flux water bath energized and circulating water
- Close the test room damper
- Stop the HVAC system

Discharge Preparation

- Release tank and Pressurizer charged with propane masses required by the test plan.
- Tank and discharge manual valves closed except for one valve in the line connecting the pressurizer to the release tank.
- Propane charges recorded on the tank charging log.
- Release and Pressurizer tanks immersed in water baths.
- Release tank at 118 ± 3 °F and stable
- Pressurizer tank at 125 ± 3 °F and stable
- Venting solenoid in place and connected
- E-stop energized to allow propane flow
- All solenoid and air operated valves checked for proper operation.
- Discharge needle valve set for desired flow rate.

Control Room Preparation

- Camera views correct and ready to record.
- Data acquisition prepared with test information and ready to record in the correct mode (10 Hz or 1 Hz depending on the test plan).
- All sensors in use have current calibrations or validations.
- Refrigerant sensors adequately warmed up.
- Oxygen analyzer connected to the test room
- All oxygen sensors show stable conditions (±1% of 20.95% values)
- All thermocouples in the test room are at stable conditions

Final Safety Briefing

- All personnel briefed on the test procedure.
- Equipment room and utility rooms are evacuated of all personnel except for one operator in the equipment room. (This person in contact with the control room through radio)
- Radio checks completed.
- External monitoring personnel in place to clear all persons near the test facility (walking path clear)
- Outside strobe light energized
- Fire suppression team from Building 3 is available in case of uncontrolled fire.
- Barricade and warning signs in place.
- Sprinkler hose connected (dry and ice free)
- Two water-based fire extinguishers are fully charged and placed in accessible locations.

Test Operation

Warning

In case of a malfunction or unexpected fire, de-energize all solenoid valves and ventilate the test room. If the tank charging room can be entered, then close all manual tank isolation valves.

Identify an assembly point in case of evacuation. (standby generator)

If fire continues in the test room activate the sprinkler head in the test room.

If fire is observed in the tank charging room or utility room then first open all breakers to that room prior to starting sprinkler flow. Call Security at X4-2000

If fire occurs in the control room, disconnect all electric power to the test facility, evacuate the control room using extinguishers to suppress the fire if possible. Call Security at X4-2000.

If these means fail to suppress the fire, use the hose streams and building 3 staff to put out the fire. Call Security at X4-2000.

- Alert all testing personnel and Building 3 staff that a propane discharge test is about to begin.
- Verify all traffic (foot and otherwise) are clear of the test facility.
- Strobe light energized.
- Open the deflagration vent shutters as required by the test plan.
- Open manual valves in the discharge path
- Start the data recording system at 10 Hz or 1 Hz as required by the test plan.
- Start recording on video cameras
- Verify that needle valve (mass flow rate) and total mass are set in the mass flow control system
- Start the High-speed cameras.
- Simultaneously:
    - Start the test clock
    - Start the refrigerant flow
- At completion of the planned discharge perform the following actions
    - Verify that refrigerant flow has stopped
    - Energize the electric arcs If required by the test plan (ignition test)
- Continue recording data for at least two minutes or until all signs of ignition have ceased and take the following actions:
    - Stop data recording
    - Stop video recording
    - De-energize the electric arc
- Push the E-stop control (close propane shutoff)
- Vent the line between the E-stop valve and the mass flow control system stop solenoid
- Ventilate the test room
- Open the supply damper in the test room.
- Pre-set the mass flow needle valve for the next test in the series

Post-Test Checklist

- Inform the Building 3 staff to stand down from their backup positions.
- Turn off exterior strobe
- Remove barricades and warning signs.
- Enable the HVAC system and open the damper into the test room
- Close deflagration vents
- Repair plastic vent covers as needed.
- Disable the sprinkler head.
- De-energize power to the electric arc by a second means of disconnect.
- Check the health of measurement equipment:
    - Electrode wires and insulators
    - Thermocouple arrays
    - Propane sensors
    - Video cameras
    - Heat flux sensor
- Take photos of anything pertinent in or outside the test facility.
- Take photos of the deflagration vents post-test condition
- Upload photos and data acquisition files to a secure location