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Composite Overwrapped Pressure Vessel (COPV) Energetic Rupture and Intentional Burst Test Series

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May 2025

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Final Report for

Composite Overwrapped Pressure Vessel (COPV) Energetic Rupture and Intentional Burst Test Series

Produced by

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Office of Safety and Mission Assurance for Pressure Systems

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1.0 Introduction

The National Aeronautics and Space Administration's (NASA's) Office of Safety and Mission Assurance for Pressure Systems has a requirement to develop, maintain, and reuse lightweight pressure vessels for ongoing and future space missions. These tanks are called Composite Overwrapped Pressure Vessels (COPVs) and are lightweight pressure vessels capable of storing a large variety of pressurized gases in different volumes. However, the lightweight requirement comes at an increased risk of tank rupture due to the materials used in manufacturing. These include carbon fiber, fiberglass, plastic, and/or aluminum.

To mitigate and analyze this risk, NASA has developed a fragmentation software package to predict fragmentation effects from a COPV rupture event. As with all software simulation packages, real-world data is required to refine the results, making the simulation more representative of the rupture event. Therefore, NASA partnered with the US Army's Combat Capabilities Development Command (DEVCOM) Aviation and Missile Center (AvMC) at Redstone Arsenal, AL to perform intentional rupture and burst testing to help feed the software program with real-world data to further refine the fragmentation parameters. This testing was conducted at the AvMC Intentional Detonation Facility (also known as the "Snake Pit") from 8-22 AUG 2024.

The overall objective of the test series was to execute a twenty-six (26) shot test matrix on (6) different COPVs, where the tanks would produce fragments via an intentional rupture event or a natural burst event. The tanks would be remotely filled with pressurized gaseous nitrogen (N_2) at a controlled fill rate to ensure that the COPVs would not exceed the individual temperature thresholds due to gas compression. High speed cameras placed around the test area would record the fragmentation events to obtain velocity magnitudes and vectors. Additionally, blast overpressure sensors were placed near the tanks for majority of the shots to obtain blast overpressure curves of each event.

This test report will go into further detail of this overarching test series, including test setup descriptions, test methodology and data analysis techniques, as well as a reporting of the final data recorded by each test event.

2.0 Traditional Fragmentation Test Methodology

For purposes of Department of Defense (DoD) fragmentation (frag) analysis, the standards that instruct the test execution are published in a document called the "Test and Data Reduction Procedures for Munitions" and was developed by an inter-agency (Army, Marine Corps, Navy, Air Force) group called the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME).

The test type in these series of tests is more commonly known as fragmentation arena testing. It centers around the fragmenting asset (typically warhead) being broken up into polar zones (relative to its central axis) and physically capturing the actual fragments, as well as their velocities. The data captured is then used to build a virtual model of the fragmentation, also known as a ZDATA file. The fragments are physically captured within large stacks of fiberboard material, called frag bundles. The velocities are recorded using what are called velocity panels in conjunction with high-speed video cameras. The velocity panels are thin (~16 gauge) panels of metal (steel or aluminum) placed at accurately measured positions around the fragmenting charge and are recorded with cameras. The cameras will record an initial flash (when the munition is initially detonated) and will record each fragment hit on the panels, which results in a duration of flight. Based on the location of the frag hit, the distance travelled can be derived and combined with the duration of flight to provide an average velocity. See Figure 1 below for a schematic of a standard horizontal arena test.

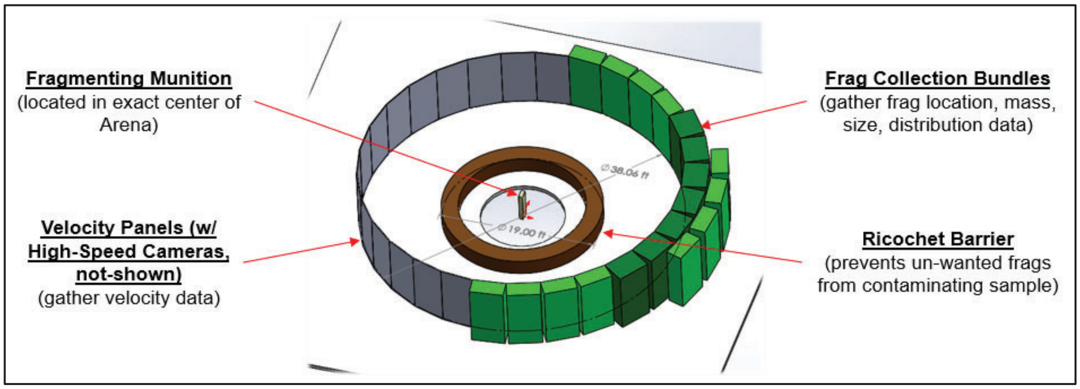


Figure 1: JTCG/ME Standard Horizontal Arena Test

One of the most important assumptions that is made when conducting arena testing is that the fragmenting round is axi-symmetric, meaning it breaks up identically in zones relative to its central axis. Another way of describing this is that, if the nose is polar 0° and the tail is polar 180° and we caught a frag (of unique size/shape) in a bundle at 82°, there would be another identical frag of same properties striking the velocity panel at 82° on the other side of the arena. Below, in Figure 2, is an illustration of this assumption. Relative to the image, effectively, all of the same type (size/shape/quantity) of frags that are caught in the green frag bundle are assumed to also impact the blue velocity panel.

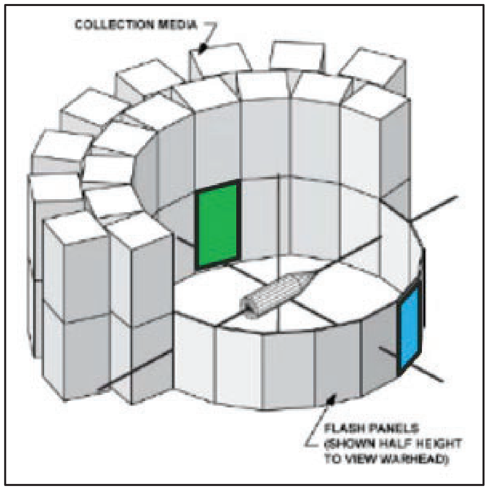


Figure 2: Illustration of Axi-Symmetry in Arena Test

This assumption of axi-symmetry is a decent assumption in the field of warheads, as the case breaks up similarly each time due to the fast-moving detonation wave and fracture mechanics of fragmenting warheads.

3.0 NASA COPV Rupture Test Methodology

In the case of COPV fragmentation, the axi-symmetric assumption is no longer valid. The high-pressure Nitrogen inside will force the case to open, but the fragments that emanate will not be the same in the various polar zones around them. Therefore, the NASA and DEVCOM AvMC team had to collaborate on the best way to attempt to capture similar data for the COPV fragmentation study. It was decided that the most important data to capture from these tests was fragment velocity and direction. Therefore, the baseline fragment capture method was to orient each of the COPVs vertically (so that the vertical axis was polar angle 0°) and to film each burst event with various vantage points of high-speed cameras. Each high-speed camera view would be distance calibrated and synced so that velocity and angle for each fragment could be derived from the aggregate of the data.

Blast overpressure effects were also of interest to the NASA team, so the AvMC team instrumented a number of the tests with different types of sensors to measure these effects.

After each test, the test area was canvassed to attempt to recover fragments that had been scattered, to obtain their mass and physical dimensions. Due to the high number of tests that were conducted in such a short time, the team focused mainly on larger frags, as smaller ones were much harder to track which test they belonged to.

Based on the different types of COPV tanks that were requested for testing, the NASA and AvMC team came up with two main test styles that were to be executed.

The first test type that was conducted was called the intentional rupture test. During this type of test, AvMC test personnel would install an explosive cutting charge to the outside of the COPV at a NASA designated location. The COPV would then be remotely pressurized to a NASA designated filling level and then sealed inside with ball valve. The AvMC team would then remove the filling hose, wire in the initiator's firing leads, and retreat to the control room. Once at the control room, the AvMC team would begin the firing sequence, which would simultaneously trigger the Phantom® high-speed cameras and the blast overpressure data acquisition system with the initiation of the explosive cutting charge. The result was that the COPV would rupture, its fragments would fly away, and all the high-speed videos and blast overpressure data would be recorded and saved.

The second test type that was conducted was called the pressurize-until-burst test. During this type of test, no energetics were used. The high-speed cameras would be set up with a special type of acoustic trigger that sends the requisite camera trigger pulse based off a loud noise event. The AvMC team would hook up the COPV to the filling tubing and would remotely pressurize the tank until it burst, or until leaks formed that prevented it from being filled further. If the COPV burst, the resulting fragments would fly away and the loud noise event would trigger the high-speed video to record the event. Due to the uncertainty of the burst time, no blast overpressure sensors were used for these tests.

Those are the two main types of tests that were conducted during this test series. As the test series was being conducted, the recovered data consequently encouraged various minor changes to increase the fidelity of the data capture. These minor changes from test-to-test are described in more detail in the remainder of this report.

4.0 Test Setup Summary

As this test series was quite involved, it will help to understand the layout of the test area, as well as the details surrounding various sub-systems utilized to conduct it. The following sections detail each of these setups and subsystem details.

4.1 Test Area Layout

The location that each of the burst or rupture tests took place was in the center of a 60ft x 60ft square concrete pad in the lower area of the test area. At the center of the concrete pad is a 10ft diameter pit of sand to prevent excess fragmentation from damaging the concrete surface. This pad is typically used by the AvMC test team to conduct JTCG/ME compliant fragmentation arena testing. It was also chosen as the ideal spot for this COPV rupture testing because it has the largest area of flat undisturbed ground at the test site. As described in the previous section, each COPV would be filled with N_2 while at its designated rupture location and would subsequently be oriented vertically for each test. A combination of sand and plywood was used to provide a stable platform for the tanks to rest on until tested. See below in Figure 3 for a picture of the concrete pad and some of the more important test setup features.

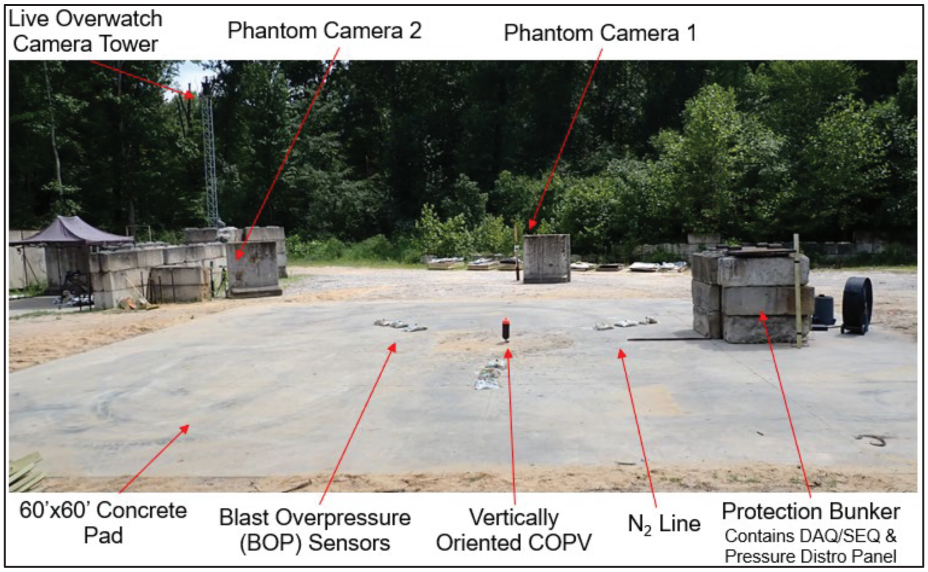


Figure 3: COPV Test Area Layout

4.2 N2 Filling & Heat Mitigation

A significantly hazardous operation of this test series was the remote filling process of the gaseous nitrogen into the COPVs. Due to the hazardous nature of handling these COPVs once pressurized, it was decided that the COPVs would be filled at their desired rupture location. To accomplish this, the AvMC team decided to park the NASA-loaned nitrogen supply truck near the Snake Pit's control room and proceed to run ¼" stainless steel pressure tubing from the supply truck all the way down to the rupture location down-range. This distance was approximately 600ft and was routed in such a way to minimize any range vehicles from accidentally rolling over it. See below in Figure 4 for a schematic of this overall pressure filling system.

Figure 4: Schematic of COPV N_2 Fill System

As seen in the above figure, once the pressure fill tubing reaches the test area, it initially goes to a designated protected area that contains an AvMC-built pressure distribution panel (PDP). The PDP is comprised of a remote-actuated ball valve and a pressure transducer. The remote-actuated ball valve allows the AvMC test team to quickly start or stop the flow of pressure into the COPV tank as desired. The pressure transducer was installed down-range from the ball valve and was intended to be the digital means of determining how much pressure the COPV has stored in it in real time. This pressure transducer was a Honeywell Sensotec Model Z bridge transducer with a max range of 10,000 psi and it was calibrated at AvMC the week prior to testing. If the pressure transducer had been placed closer to the COPV, there was a greater chance that it would have been destroyed in the pressurize-until-burst tests, hence why it was installed at the PDP. See Figure 5 below for a picture of the pressure distribution panel (PDP).

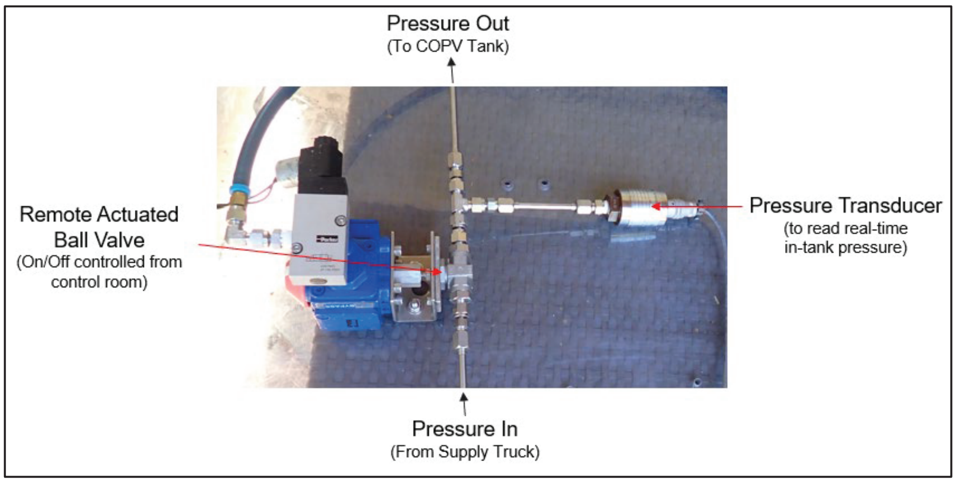


Figure 5: Pressure Distribution Panel (PDP)

Due to the various materials and construction of the COPV tanks, each one came with a not-to-exceed surface temperature. One of the major contributors to the COPV surface temperature heating is from gas compression during the pressurization process. To mitigate this factor, AvMC installed a flow-rate control needle valve at the outlet of the nitrogen supply truck and used it to maintain a controlled pressure-rise rate during the filling process. The desired pressure rise rate to minimize potential for excessive heating was deemed to be around 100psi per minute. During each tank fill, this needle valve would need slight adjustment to maintain this desired fill rate, which is why it was positioned at the tank truck next to the control room. Next to the needle valve, the AvMC team also installed a ball valve to allow for venting of the pressure line. This vent valve was utilized to bleed out the remaining nitrogen in the fill lines after the COPVs would be sealed off. This ensured that the AvMC team members removing the fill lines from the COPV would be protected from a high-pressure purge event. See Figure 6 below for an image of the fill control and vent valves.

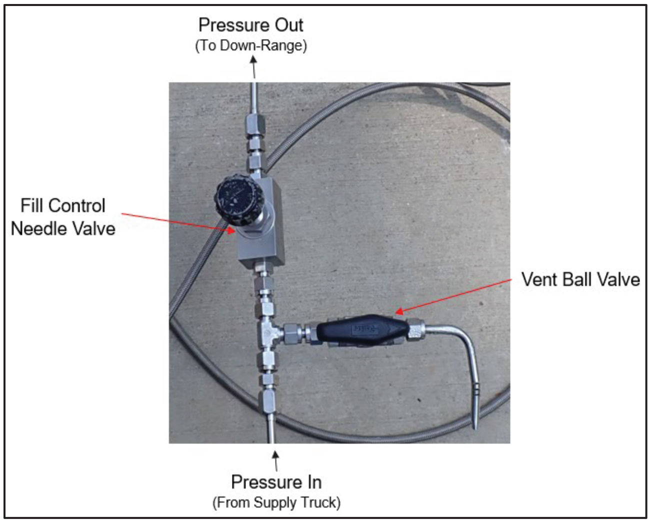


Figure 7: Fill Control and Vent Valves

Apart from the COPV pressurization causing the surface to heat, the other factor that had to be addressed was that of environmental inputs and direct sunlight. The lowest "not-to-exceed" surface temperature among all of the tank types was approximately 120°F. Unfortunately, this testing was conducted outside during unfavorable conditions; the humid, hot month of August in Huntsville, AL. Ambient outside temperature through the weeks of testing was between 80° to 90°F. To mitigate the tanks from heating close to the critical surface temperature, an EZ-Up tent was placed over the COPVs and a hi-volume fan was positioned to blow air across the tank during the pressurization phase. This kept direct sunlight from radiatively heating the tanks and actively cooled the tanks via convective cooling. See Figure 7 below for a picture of this heat mitigation system as installed.

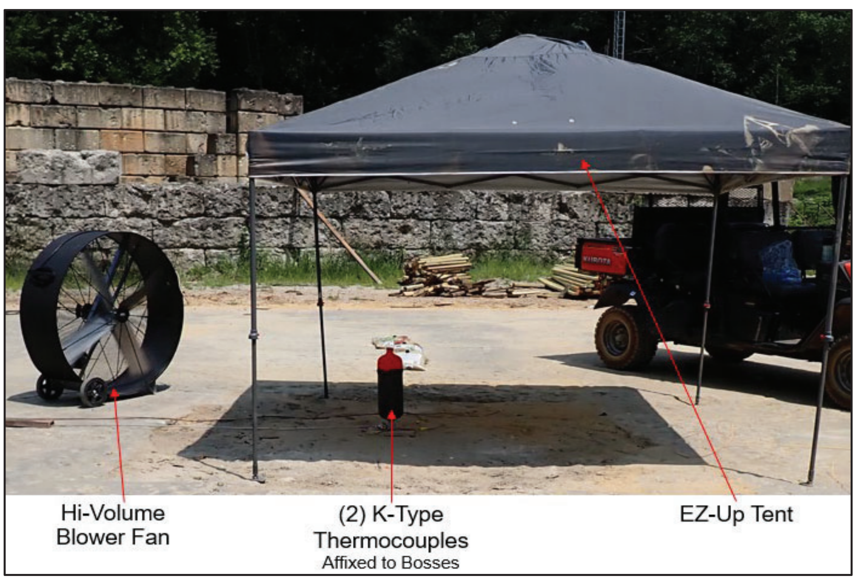


Figure 6: Heat Mitigation System for COPV

In order to continuously monitor the surface temperature during the filling process, two K-type thermocouples were installed on the outside of the COPV and were able to be read real-time during the fill process. If the data readout on these thermocouples began to approach the critical temperature, mitigations were made to either lower the fill rate or stop the fill process altogether until safer temperatures were met.

4.3 DAQ and Protection Bunker

The AvMC team utilized their custom-built data acquisition (DAQ) system for gathering and recording all data (thermocouples, pressure transducers, etc.), remotely actuating the on/off fill valve, as well as sending the precise triggers to the detonator (on the rupture tests) and the Phantom high-speed cameras. The main DAQ chassis is a National Instruments cRIO-9049 and there were various cards added to it to allow for the various data and control channels to function properly. Effectively, it was the central hub of this entire test series. Physically, it was all packaged into a large Pelican® case and, for the duration of the test series, was required to physically reside near the rupture location. Test personnel could communicate and control all subsystems from it via local network.

Due to the nature of this test series, fragments from the COPVs could be launched vertically and, on descent, impact this critical piece of equipment. Therefore, a protective bunker was erected using concrete ecology blocks and a thick steel plate roof to house and protect these critical components. Apart from the DAQ system, this protective bunker also housed the pressure distribution panel (PDP), a network switch, as well as other needed tools and supplies for conducting the test series. See below in Figure 8 for pictures of the outside and inside of this protection bunker.

Figure 8: Equipment Protection Bunker, Outside (L), Inside (R)

4.4 Energetic Rupture Mechanism

In lieu of any sort of mechanical rupture mechanism, the team was instructed to utilize an explosive-based system to initiate the cuts in the COPVs. Prior to the test series, the NASA personnel responsible for delivering the COPVs pre-marked each one with a desired rupture line that were decided upon based on various design considerations. The goal of the energetics was to instantaneously cut the tank open at the desired line and allow the expanding gasses to fragment the tanks and propel the fragments away. The desire was to choose an energetic that wasn't too powerful that it would absolutely destroy the tanks but powerful enough to penetrate the composite overwrap and rip the tanks open. The AvMC team utilized one of two different energetics for most of these tests.

The first type of rupturing energetics used was a loop of 50 grain/foot (3.24 gram/ft) detonating cord surrounding the COPV. This energetic is typically used in mining or demolition applications for carrying detonation waves between mining holes or demo charges. The det cord was purchased from Ensign-Bickford Aerospace & Defense (EBAD)® and the tradename for the product is PRIMACORD® 10. The cord has a flexible textile outer jacket with a core of the high explosive pentaerythritol tetranitrate (PETN). See Figure 9 below for an image of det cord.

Figure 9: 50 gr/ft Det Cord on Spool

The initiator that was used to start the detonation event within the det cord is called an RP-81 and is an Exploding Bridgewire (EBW) detonator manufactured by Teledyne RISI®. These detonators contain approximately 450mg of HMX and have an equivalent output of a standard #8 blasting cap. They require a high voltage electrical pulse of around 3,500 volts in order to fire, which makes them inherently safe to operate around. The firing system used to fire the RP-81s is called an FS-43 firing system and it's also manufactured by Teledyne RISI®. See Figure 10 below for a schematic of an RP-81 detonator.

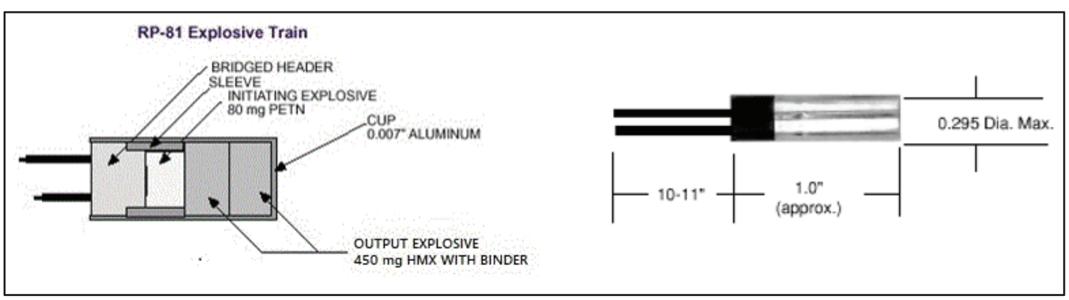


Figure 10: RP-81 Detonator Schematic

For this test series, the det cord was wound in a loop around the COPVs and the two ends of the cord were taped together in the same axial direction. This loop was taped to the COPV at the desired location, as designated by paint from the NASA customer. At the joined end of the det cord, the RP-81 detonator was affixed such that the detonation wave from the end of the detonator would transition into the axially oriented energetics inside the det cord. This detonation wave would travel down both ends of the cord, ultimately running around each side of the COPV and meeting on the very back side of the loop, completing the detonation process. The explosive energy released by the detonation, in most cases, was sufficient enough to cut through the COPV tank. See Figure 11 below for a schematic and picture of how this det cord was installed on each tank.

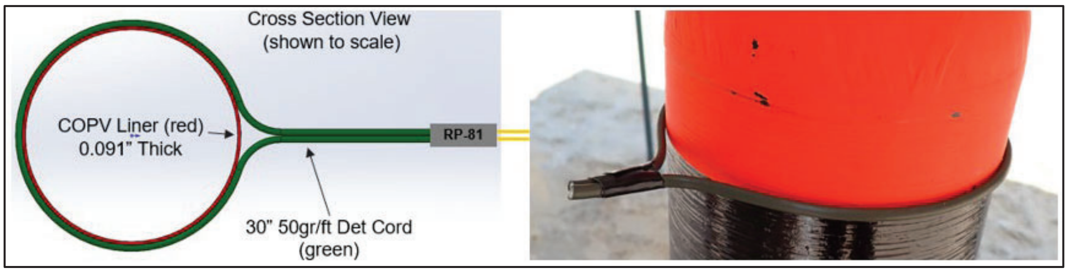


Figure 11: Det Cord Installation Schematic (L), and Implementation (R)

The other type of energetic rupture mechanism used is called flexible linear shaped charge, also referred to in this report as flex linear or FLSC. Flex linear is a specifically designed cutting charge, most commonly used in building demolition or explosive ordinance disposal (EOD) operations. The cross section of flex linear is a 90 degree V-shape of extruded RDX-based explosive surrounded by a dense malleable metal sheath, typically copper or lead. The shape of the V is created so that, upon detonation of the core material, the inner apex of metal inside the V forms a cutting jet shaped charge that cuts through whatever is underneath it. Depending on the core loading, this jet has the potential to penetrate multiple inches of steel. For this test series, 125 grain/ft (8.1 gram/ft) flex linear was implemented, which was the smallest that the AvMC team had available. The flex linear was installed in a similar manner to the det cord, wrapped around the COPV at the desired cut line and taped in place. In order to start the detonation process, the AvMC team used a small ball of C-2 plastic sheet explosives and pressed the RP-81 into that. Similar to the detonation train in the det cord, the RP-81 would transfer the detonation wave into the ball of C-2, which would then transfer into each side of the loop of flex linear, subsequently wrapping around both sides of the COPV and completing on the back side of the tank. See Figure 12 below for a schematic of flex linear shaped charge and an example of how it was installed on the COPVs for this test series.

Figure 12: Flex Linear Shaped Charge Cross Section (L) and Implementation for Test (C) (R)

4.5 Phantom® High-Speed Cameras

In order to capture the burst or rupture events and obtain fragment velocities, the AvMC team placed four (4) Phantom® high-speed cameras around the test pad and synced the trigger with the burst event. Three (3) of the four (4) cameras were placed near the same level as the tank at 0°, 45°, and 90° around the tank. The fourth camera was placed on a hill and provided a wider-angle isometric view of the burst events. See Figure 13 below for a map layout of where each of the cameras (colored blue) were placed around the test area.

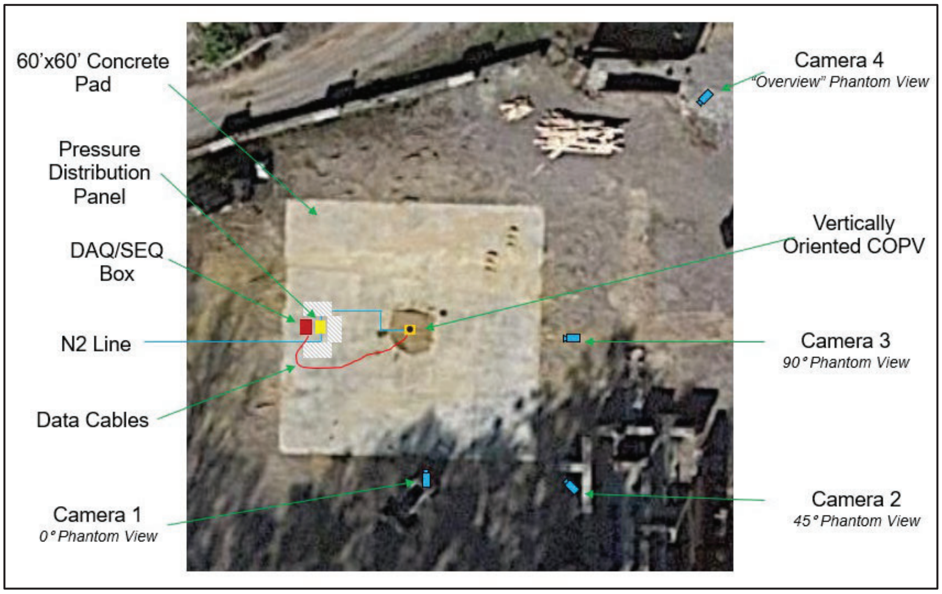


Figure 13: Phantom Camera Layout Map

Referencing the camera locations and nomenclature from the above image, below in Table 1 is a detailed list of cameras and settings used throughout the test series.

Table 1: List of Cameras and Settings Used for Testing

Camera #	Camera Model	Color Output	Resolution	Framerate	Lens
1	Phantom® V2512	Monochrome	512 x 800	25,722 fps	Nikon® 24-85mm
2	Phantom® VEO410	Color	448 x 800	12,000 fps	Nikon® 24-85mm
3	Phantom® VEO710	Monochrome	448 x 800	17,000 fps	Sigma® 24-70mm
4	Phantom® V2640	Color	2048 x 1952	6,600 fps	Nikon® 80-200mm

Each camera was set up behind a barricade wall (to protect them from fragmentation) and the view angle was bounced around the wall using a mirror. See below in Figure 14 for an example of this barricade and mirror system, as well as the resulting camera image.

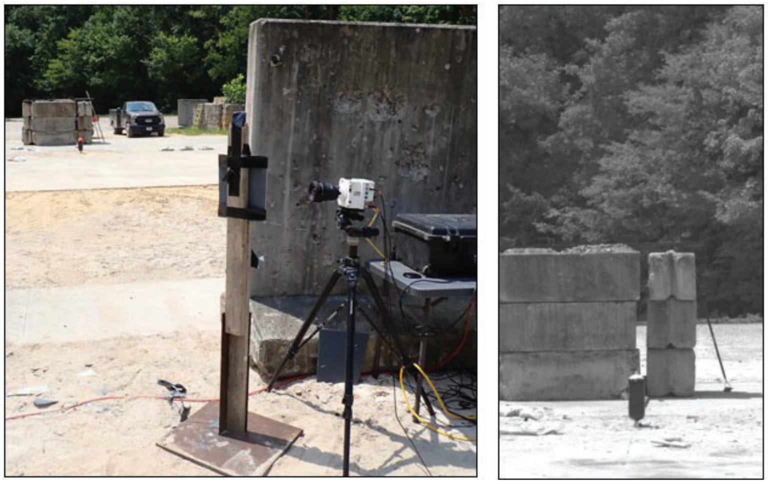


Figure 14: Phantom Camera Protection & Resultant Image

A special test method was used to calibrate each of the phantom cameras to allow for post-test distance and velocity measurements. A calibration tool was fabricated to allow the team to calibrate distance measurements in both horizontal and vertical directions for each camera view. Two (2) wooden 2x4s were screwed together at 90° and a strip of black Gorilla Tape® was applied at precise locations on each board such that the outside edges of the tape were exactly 72 inches apart. This tape distance was true in both horizontal and vertical planes. At the beginning of each test day, after the phantom cameras were setup and views were dialed in, one of the test team members would hold the calibration tool at the center of the test pad and a snapshot would be taken on the camera software for each camera view. Once these snapshots were taken, the camera and lens settings for each view would remain untouched for the remainder of the day, to ensure that the calibration values would remain valid. The team would then proceed to test throughout that day and then repeat the calibration process at the beginning of the next day. The calibration snapshots would be saved but not touched until post-test data reduction efforts. Within the Phantom® video software, there is a feature that allows the user to select between two known points and input the distance. This results in a value of inches/pixel for that specific video. This value is then applied to all views of that camera from that day. This will then allow the user to determine distance and velocity from objects moving in each camera view. See Figure 15 below for an image of this calibration tool and an example snapshot.

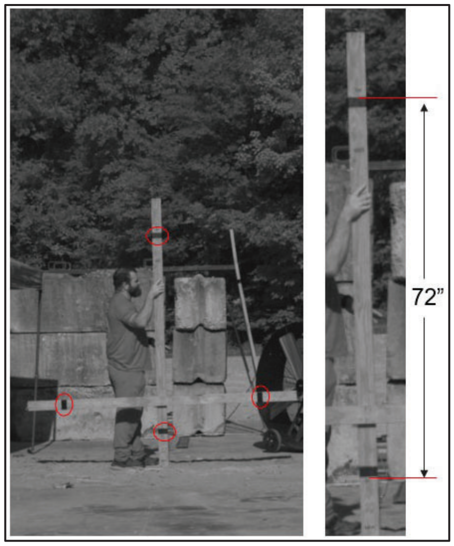


Figure 15: Calibration Tool and Example Snapshot

Depending on the type of test, one of two different camera triggering systems were used. For the intentional rupture testing, the digital trigger sequencer that's built into the Data Acquisition System (DAQ) was used to simultaneously trigger the cameras, the data recorder, and the detonator initiation system. For the pressurize-until-burst testing, the team had no idea when the tank would eventually burst so a passive camera trigger system was used for these tests. The MIOPS® camera trigger system is a commercially available product that has various built-in features to allow for different external inputs to tell a camera to trigger. In this case, the test team used its acoustic trigger feature that will sense a loud noise event and subsequently send the trigger pulse to the cameras. Within the acoustic trigger feature, a sensitivity level is set based on how loud the event is expecting to be. In order to properly dial this ideal sensitivity level in, the system was studied during the intentional rupture testing to get the sensitivity level dialed in to a reliable zone. This acoustic trigger feature ended up successfully triggering cameras for each of the pressurize-until-burst tests, resulting in full data capture throughout the whole test series. See below in Figure 16 for a picture of the MIOPS® acoustic trigger system and how it was implemented with the high-speed cameras.

Figure 16: MIOPS Acoustic Trigger System (L), and Implementation (R)

See Appendix A for techniques used in conjunction with the high-speed video footage to calculate 3-dimensional velocity magnitude and direction.

4.6 Blast Overpressure Sensors

Since these COPVs would be rupturing and quickly purging the entire tank of pressurized nitrogen, blast overpressure measurements were taken for majority of the tests. Two different methods of blast overpressure measurement were utilized.

The first type of measurement device used is the commercially available Black Box Biometrics Inc's Blast Gauge System®. The AvMC test team refers to these devices as BOP sensors. These BOP sensors were developed for soldiers to wear during combat operations to passively collect data on blast overpressure events for tracking traumatic brain injury trends. As such, BOPs are incredibly rugged, battery powered, and store all blast overpressure event data using an onboard storage system. The sensors are programmed to automatically and passively record the pressure waveform when they experience a pressure event greater than 0.5 psi. One downside of this system is that they are factory calibrated so it's hard to verify that the data that they've recorded is accurate. These devices were used for COPV tests 1-16. For some of the tests, the BOP sensors were tied to sandbags (to limit movement from blast wave) and placed at ground level in three (3) different arrays of three (3) sensors at differing distances from the tank. For some of the later tests, when additional blast overpressure measurement devices were used, they were mounted to a 3 ft tall post at similar distances from the tank. See below in Figures 17 and 18 for images of the BOP sensor features as well as how they were implemented for this test series.

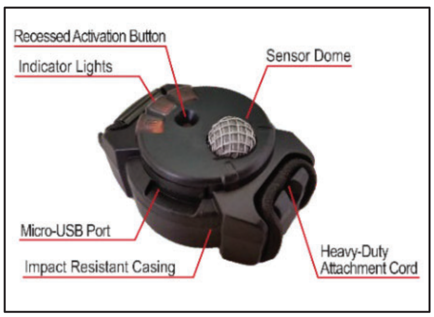


Figure 17: Black Box Biometrics Inc's Blast Gauge System (BOP Sensor)

Figure 18: BOP Sensor Implementation Methods: Mounted to Sandbag (L), BOP Sensor Array (C), Mounted to Poles (R)

The second type of blast overpressure measurement used is the PCB Inc's piezoelectric pencil gauge system. The AvMC team refers to these as pencil gauges. Effectively, it's a long aluminum rod with a pointed tip and a piezoelectric pressure sensor mounted on a machined flattened surface of the rod that runs the length. When a blast wave passes down the length of the gauge, any disruptions caused by wrapping around the shaft are dissipated by the point on the front and the resultant pressure wave recorded by the sensor is a true representation of pressure versus time. These gauges are the industry standard for measuring free field blast overpressure events. These pencil gauges were AvMC calibrated to NIST standards within 1 calendar year of their use. The gauges utilize a PCB signal conditioner system to provide excitation voltage to the sensor and the resultant data is recorded on AvMC's National Instruments Data Acquisition (DAQ) chassis at 1 million samples/second. These sensors were used for tests 10-16 of this COPV test series. Each pencil gauge was mounted to a 4ft tall pole with an adjustable ball joint arm and, as recommended, each of the pencils were aimed directly at the source of the overpressure event (the COPV tank). Six (6) pencil gauges were utilized for each test, in two (2) arrays of three (3) sensors each. See Figure 19 below for an image of the mounting setup and sensor array for these pencil gauges used in this test series.

Figure 19: Pencil Gauge Mounting Hardware (L), Sensor Array (R)

It is significant to note the difference in how each of these blast overpressure measurement devices capture data. The concept is most easily described as either "front-on" measurement verses "side-on" measurement and it directly has to do with how the sensor is oriented relative to the pressure wave. "Side-on" measurement implies that the sensing surface is parallel with the direction that the pressure wave is travelling. Pencil gauges directly measure in "side-on" configuration because the sensing surface is on the side of the shaft and the pressure wave passes by the sensor un-interrupted as it expands. "Front-on" measurement implies that the sensing surface is perpendicular to the direction the pressure wave is travelling. When this happens, the pressure wave is interrupted by the flat surface and results in higher-than-normal pressure readings. This phenomenon is known as compression stacking. This is worth mentioning because some of the tests had the BOP sensors oriented in this front-on configuration. All of the tests that had BOP sensors attached to sandbags were technically in side-on configuration and should have negligible compression stacking effects. However, on the tests where the pencil gauges were also used, the AvMC team improperly mounted the BOP sensors to the same mounting arm such that the sensing surface was directly facing the pressure source. For these tests, it is highly likely that compression stacking occurred on the BOP sensors and the resulting BOP pressure data will read higher values than the data recorded on the nearby pencil gauge. See Figure 20 below for a visual schematic showing the difference between front-on and side-on configuration, as well as a picture of this BOP/pencil mounting method.

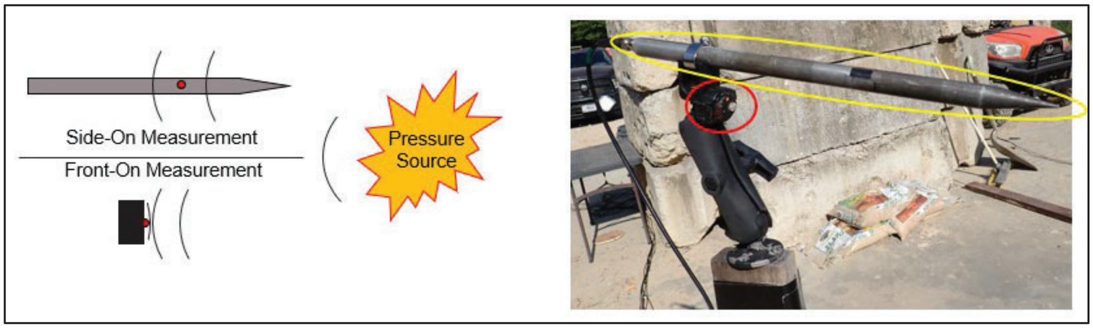


Figure 20: Side-On vs Front-On Measurement (L), Pencil/BOP Combo Mount (R)

One additional point to mention about the pressure data recorded in this test series is that the software that configures the BOP sensors before use was improperly configured and resulted in a lack of data capture for a number of the COPV tests. When the lead test engineer configured and powered on the BOP sensors prior to the test series, the BOPs were set in a mode called "personnel-mode". Post test series, the team leaned the BOPs should have been set in a mode called "structure-mode." Between the two modes, there is no difference in how the data is collected. However, personnel-mode has a sleep feature that is used to conserve battery life on each sensor. When in personnel-mode, if the sensor hasn't detected any movement within 30 minutes, it will "go to sleep" and it will then "wake up" when movement is detected. Thus, if the sensor was in sleep mode when the pressure wave passed by, it will not record it. This was the case for a large number of the tests that were conducted in this test series. If the BOP sensors had been moved or adjusted prior to the shot (such as adjusted position, etc.), they successfully recorded data. As the test series continued, the test team stopped adjusting the BOPs for each test, as they were staying in their desired position from shot-to-shot. In those cases, the BOP sensors failed to record. Conversely, had the sensors been configured in structure-mode, the BOPs would have not gone to sleep and the team would have recorded data successfully for every test. Therefore, in the final data reporting for each test, this explains why there are many tests with no BOP sensor data reported.

4.7 Overwatch Camera Locations and Meteorology Stations

In addition to all of the data acquisition sensors and phantom cameras, the test area utilized four (4) overwatch cameras placed at different vantage points around the test site. Each camera tower is approximately 30ft tall and has a networked Speco Pan-Tilt-Zoom (model O4P30X) camera mounted at the top. These cameras all network back to a Network Video Recorder (NVR) system that is in the control room. Additionally, the Pan-Tilt-Zoom features can all be controlled from the control room for ease of scanning the test area and adjusting the view for each shot.

To obtain accurate weather conditions during each test shot, the test team utilized a dual-meteorology station setup that was mounted to one of the camera towers. The weather stations were Columbia Weather Systems Inc's Orion Weather Stations®. Two of these weather stations were mounted to the same camera tower at different heights. One was mounted near the bottom of the tower at around 5ft above ground level (AGL) and the other was mounted near the top at around 30ft AGL to gather both current weather conditions and also differences in ground level versus tree-top level conditions for each test. These weather stations were networked back to a control station in the control room and were recording 1 sample/second data during the entire test series. While each weather station records a large variety of meteorological data, the data that the team was most concerned about for each test was temperature, relative humidity, and 3-second-rolling-average wind speed and direction. See below in Figure 21 for a map of where each tower was located around the test area, as well as a picture of one of the weather stations.

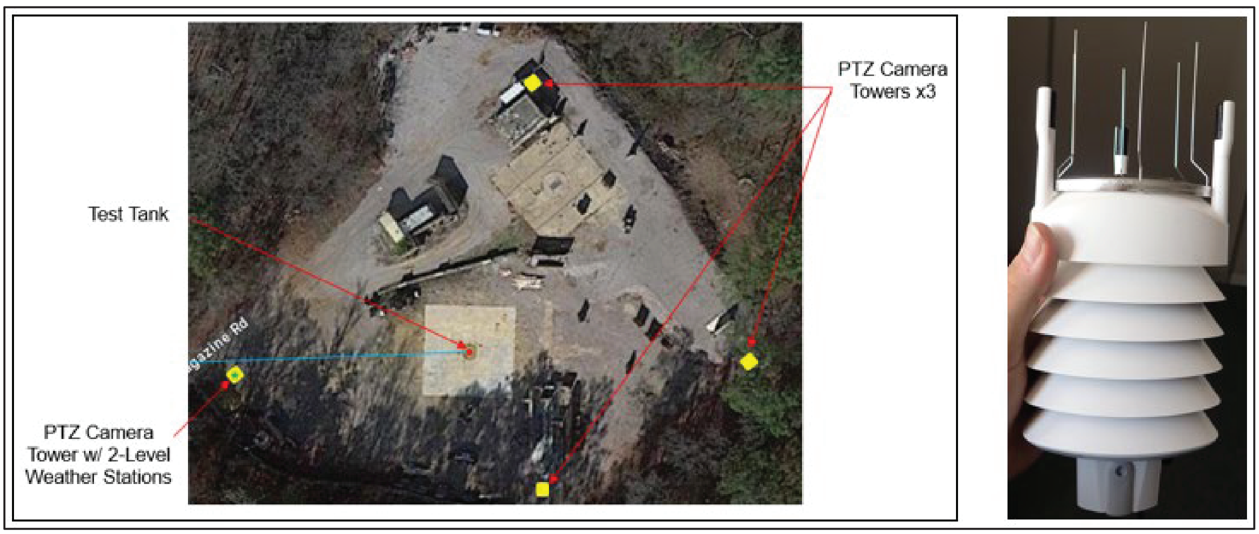


Figure 21: Camera Tower Location Map (L), Orion Weather Station (R)

5.0 Overall Test Matrix

5.1 COPV Details

In all, six (6) different Composite Overwrapped Pressure Vessels (COPVs) were tested in this test series. The first one tested was manufactured by General Dynamics and was considered a Type III COPV (contains an aluminum liner with a carbon fiber composite overwrap). The volume of this General Dynamics tank is 8.2L (2.16 Gal), has a rated working pressure of 4,300 psi and a design burst pressure of 6,450 psi. See Figure 22 below for an image of this General Dynamics COPV.

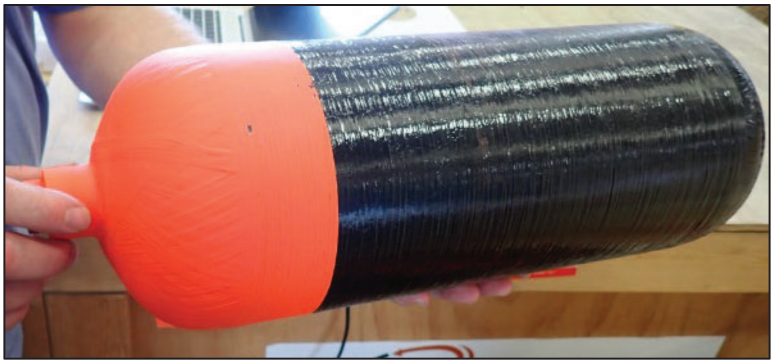


Figure 22: General Dynamics Type III COPV

The next type of COPV tested was manufactured by Xperion and was considered a Type IV COPV (contains a plastic liner with a fiberglass and carbon fiber composite overwrap). The volume of this Xperion tank is 46L (12.15 Gal), has a rated working pressure of 2,900 psi and a design burst pressure of 6,525 psi. See Figure 23 below for an image of these Xperion COPVs.

Figure 23: Xperion Type IV COPVs

The next type of COPV tested was manufactured by Infinite Composites and was considered a Type IV COPV (contains plastic liner with a carbon fiber composite overwrap). The volume of this Infinite Composites tank is 1.9L (0.5 Gal) and is the smaller variant of the Infinite Composites tanks tested in this series. Since there is another model of Infinite Composites tanks being tested, this variant will be referred to as Infinite Composites Small COPV. This tank has a working pressure of 4,496 psi and a design burst pressure of 8,992 psi. See Figure 24 below for an image of this Infinite Composites Small COPV.

Figure 24: Infinite Composites Small Type IV COPV

The next type of tank tested was manufactured by Cimarron and was considered a Type V COPV (contains no inner liner, except for metallic bosses, and is purely a carbon fiber composite overwrap). The volume of this Cimarron tank is 113.6L (30 Gal), has a rated working pressure of 500 psi and a design burst pressure of 1,000 psi. See Figure 25 below for an image of this Cimarron COPV.


Figure 25: Cimarron Type V COPV

The next type of tank tested was manufactured by HyPerComp and was considered a Type V COPV (contains no inner liner and is purely a carbon fiber composite overwrap). The volume of this HyPerComp tank is 128.7L (34 Gal), has a rated working pressure of 50 psi and a design burst pressure of 100 psi. The reason the rated pressure levels are so low is because this particular model was designed and intended for high cycle usage. By rating the tank at a lower pressure level, they could get a longer life cycle out of each tank before wear and tear occurs. In actuality, these tanks can hold higher pressures than this. See Figure 26 below for an image of this HyPerComp COPV.

Figure 26: HyPerComp Type V COPV

The final tank tested was manufactured by Infinite Composites and is also a Type IV COPV (plastic inner liner with carbon fiber composite overwrap). The volume of this tank is 113.6L (30 Gal) and will be referred to as the Infinite Composites Large COPV for the remainder of this report. The rated working pressure of this Large COPV is 500 psi and the design burst pressure is 1,000 psi. See Figure 27 below for an image of this Infinite Composites Large COPV.

Figure 27: Infinite Composites Large Type IV COPV

5.2 Test Matrix and Description

A limited number of COPV assets of each type/manufacturer were provided for testing by the customer. See below in Table 2 for a consolidated list of how many tests of each type of tank, sorted by manufacturer.

Table 2: COPV Test Series Matrix (Sorted by Manufacturer)

Designation	COPV Type	Volume	Rated Working Pressure	Designed Burst Pressure	# of Rupture Tests	# of Pressure Until Burst Tests
General Dynamics	III	8.2L (2.16 Gal)	4300 psi	6450 psi	8*	0
Xperion	IV	46L (12.15 Gal)	2900 psi	6525 psi	6	3**
Infinite Comp. Small	IV	1.9 L (0.5 Gal)	4496 psi	8992 psi	3	0
Cimarron	V	113.6L (30 Gal)	500 psi	1000 psi	0	2***
HyPerComp	V	128.7L (34 Gal)	50 psi	100 psi	0	2***
Infinite Comp. Large	IV	113.6L (30 Gal)	500 psi	1000 psi	0	2***
				TOTALS	17	9

* (1) shot will be fired horizontally with frag capture bundles

** Will be shot very last and with a modified Pressure Distribution Panel (due to the high pressures required)

*** Will be utilizing (1) "Stepped Increase to Burst" procedure

As seen above, a total of twenty-six (26) tests were executed during this test series. Due to various factors, the actual order that each test was executed varied. See Table 3 below for the actual chronological order of tests executed and the details surrounding each one.

Table 3: COPV Test Series Matrix (Sorted by Test #)

Test #	Tank Mfr	Date	Rupture Mechanism	Data Setup
1	**General Dynamics** (8.2L Type III)	8/8/24	50 gr/ft Det Cord	Phantom Cameras Only
2		8/13/24		
3				
4				
5				
6		8/14/24	Conical SC	
7			125 gr/ft Flex Linear Shaped Charge	
8	**Xperion** (46L Type IV)			
9				
10		8/15/24		
11				Phantom Cameras and Pencil Gauges
12				
13				
14	**Infinite Comp Small** (1.9L Type IV)			
15		8/19/24		
16				
A	**No Tank** (Bare Energetics for Pressure Comparison)			
B				
C			50 gr/ft Det Cord	
17	**General Dynamics** (8.2L Type III)	8/20/24		Frag Capture Arena w/ Cams

Test #	Tank Mfr	Date	Burst Process	Data Setup
18	**Cimarron** (113.6L Type V)	8/21/24	Pressure Rise until Burst	Phantom Cameras Only
19	**HyperComp** (128.7L Type V)			
20	**Infinite Comp Large** (113.6L Type IV)			
21	**Cimarron** (113.6L Type V)		Stepped Pressure Increase until Burst	
23	**Infinite Comp Large** (113.6L Type IV)			
22	**HyperComp** (128.7L Type V)	8/22/24		
24	**Xperion** (46L Type IV)		"Intensified" Pressure Rise until Burst	
25				
26				

Ideally, the AvMC team would have organized this test matrix such that each tank type would have been tested individually before moving to the next manufacturer's tank. However, there were many factors that necessitated the seemingly random nature of the executed test matrix.

The first of these factors is the difference between rupture and burst testing. Seventeen (17) of the twenty-six (26) tests were conducted as intentional rupture tests and the remaining nine (9) tests were conducted as intentional burst tests. The tank filling procedures for each of those types of tests were slightly different and the intentional rupture tests required energetics to initiate, while the burst tests did not. Therefore, it was decided that the team would conduct all of the energetic rupture tests first before moving to burst tests.

The second of the driving factors was that some of the energetic rupture tests required more instrumentation or different physical setups relative to others. For example, the early General Dynamics tank shots had no pencil gauges present, requiring less setup time. Later, the pencil gauges were added to the test setup, which added to the test complexity and were used continuously until the next major configuration change. Finally, the entire layout of the test was changed for a fragment capture-style test in shot seventeen (17). The order of test operations here was optimized to streamline the test execution style while ensuring that all data was captured successfully.

The final driving factor within the pressurize-until-burst tests was to minimize damage potential of the pressure filling system. The lower magnitude pressure burst tests were prioritized first because there was a lesser probability of fill tubing damage from the burst event, which would have required replacement, costing extra range time and resources. The higher magnitude pressure burst tests were prioritized last because there was a high probability of fill tubing damage and also the installation and usage of a pressure intensifier to boost the tank pressures beyond the supply truck's limits.

6.0 General Dynamics Type III Test Results

The first set of test results that will be discussed are from the General Dynamics tests. All eight (8) of the tests conducted on this tank were intentional energetic rupture tests. See Table 4 below for a breakdown of the test matrix executed on this style of COPV.

Table 4: General Dynamics COPV Test Matrix

Test #	Date/Time	Desired Fill Pressure	Energetic Used	Rupture Location
1	8/8/24 @ 1408	4300 psi	50gr/ft Det Cord	At Dome/Cylinder Taper
2	8/13/24 @1042			At Dome/Cylinder Transition
3	8/13/24 @ 1204			At Dome/Cylinder Transition
4	8/13/24 @ 1320			At Dome/Cylinder Transition
5	8/13/24 @ 1531		50gr/ft Det Cord*	At Boss
6	8/14/24 @ 1116		Conical Shaped Charge	At Boss
7	8/14/24 @ 1320		125gr/ft Flex Linear Shape Charge	At Boss
17	8/20/24 @ 1025		50gr/ft Det Cord	At Dome/Cylinder Taper

* Failed to rupture tank. Required emergency demil via remotely fired gun

Test 1 was the first time a COPV was attempted to be filled with the AvMC team's new remote fill system. The AvMC team struggled to maintain the proper fill rate, which caused the fill process to take longer than desired. Though the test ultimately succeeded, the team decided to reconfigure the remote fill system to allow more control on fill rate for future tests.

Tests 2 through 4 all worked as intended, with the 50 gr/ft det cord working as the cutting charge.

On Test 5, upon initiation of the detonation train, the det cord functioned properly but failed to rupture through the thicker material on the head boss of the COPV. This rupture failure caused a hazardous situation where the COPV was damaged and still contained pressure. Per the risk assessment of this situation a remotely fired standalone gun system was implemented to safely impact and vent the tank and eliminate personnel exposure. The damaged tank was impacted by a 7.62mmx39mm ball round and subsequently vented the contained pressure appropriately. However, due to this non-ideal setup, no fragment velocity capture was obtained for the test.

For Test 6, through discussions with the NASA customers, the AvMC team opted to shoot a copper conical shaped charge at the filled tank at the desired rupture location. This munition is a small pre-cursor shaped charge from an Army missile system. This method proved successful at punching a very precise hole through the tank and venting the pressure, but the tank didn't fragment into pieces. It was then decided that the team would utilize flexible linear shaped charge for future rupture tests.

Test 7 worked as intended, with the 125 gr/ft flex linear working as the cutting charge.

Finally, Test 17 also worked as intended, with the 50 gr/ft det cord working as the cutting charge. The fragment arena bundles were indeed successful in capturing the main fragments, allowing the team to recover the two halves of the COPV that came apart for further analysis.

The following sections detail the data and results gathered from each of the respective tests.

6.1 Test 1 – Det Cord Rupture @ Dome Taper

Test 1 was an energetic rupture test on the General Dynamics COPV, with det cord being the energetic rupture mechanism placed at the dome/cylinder taper, the most likely location this tank would rupture, based on tank design and geometry.

The fill process for test 1 began on 8/8/24 at 1206 CDT and took approximately 1hr and 35mins to fill to the desired pressure. As described above, the AvMC team was having trouble maintaining a consistent fill rate during this particular fill. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,324 psi. The head boss temperature ended at 103°F.

The energetic rupture test event occurred at 1408 CDT under partly cloudy skies, 86.7°F, 65% relative humidity, and a wind-speed of 4.2 mph SSE. The det cord successfully ruptured and separated the tank, as desired. See Figure 28 below for images of the tank during and after test.

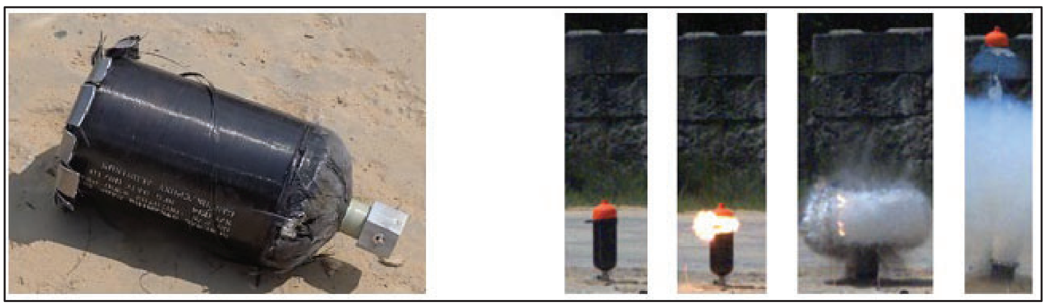


Figure 28: Test 1 General Dynamics Tank Post-Test (L) and During Separation (R)

Essentially, the top boss separated in-tact and was propelled upwards. The rest of the tank and valve components were driven down into the sand pit so no velocity calculations were generated for them. Though the top boss was not recovered, the mass was estimated to be 1,080 grams (based on the pre-test mass subtracted by the remaining post-test frags) and was estimated to be approximately 6.5" diameter and 7" long. See Table 5 below for a chart of the test's frag velocity summary.

Table 5: Test 1 Fragment Velocity Summary

Test 1					
Cutter:	*50 gr/ft Det Cord*		**Pressure:**	*4324 psi*	
Location:	*At Dome/Cylinder Taper*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Boss*	*1080*	*Ø6.5x7*	560	2.1

As mentioned above, the bottom boss, broken valve and valve knob were all found in the sand pit and recovered for post-test evaluation. Sizes and masses were taken of each of these items but aren't worth reporting on since no velocity calculation was done on them. See below in

Figure 29 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frags.

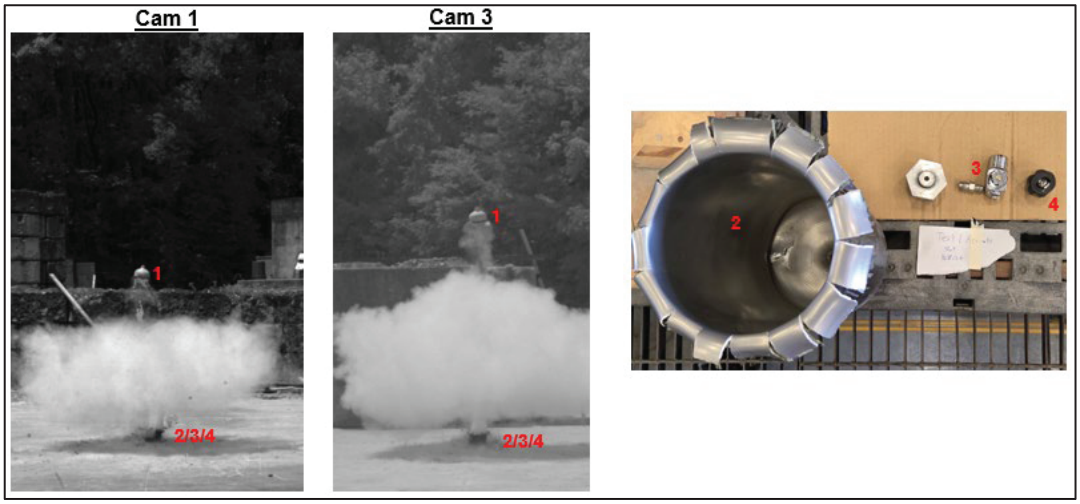


Figure 29: Test 1 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

The BOP sensors all recorded successful pressure curves for this test. Based on the length and strength of the det cord, the net explosive weight of the energetics was 6.9 grams of PETN and the COPV tank contained 8.2L of gaseous nitrogen at 4,324 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 30 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	4.17	10ft
H1	4.6	
H2	4.64	
I2	3.63	12.5ft
J1	3.37	
J2	3.34	
I3	2.97	15ft
K1	2.18	
K2	2.47	

Figure 30: Test 1 Blast Overpressure Results

6.2 Test 2 – Det Cord Rupture @ Dome Transition

Test 2 was an energetic rupture test on the General Dynamics COPV, with det cord being the energetic rupture mechanism placed at the dome/cylinder transition, the second most likely location this tank would rupture, based on tank design and geometry

The fill process for test 2 began on 8/13/24 at 0936 CDT and took approximately 48mins to fill to the desired pressure. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,285 psi. The head boss temperature ended at 99.4°F.

The energetic rupture test event occurred at 1042 CDT under partly cloudy skies, 84.7°F, 52% relative humidity, and a wind-speed of 0.3 mph W. The det cord successfully ruptured and separated the tank, as desired. See Figure 31 below for images of the tank during and after test.

Figure 31: Test 2 General Dynamics Tank Post-Test (L) and During Separation (R)

Upon post-test evaluation, the head boss fragmented into three fragments that were propelled upwards, while the remaining tank and valve components were driven down into the sand. These three propelled fragments were successfully recovered in the area after the test so a full analysis of mass, size, and velocity can be derived. See Table 6 below for a chart of the test's frag velocity summary.

Table 6: Test 2 Fragment Velocity Summary

Test 2					
Cutter:	*50 gr/ft Det Cord*		**Pressure:**	*4285 psi*	
Location:	*At Dome/Cylinder Transition*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Boss Frag*	*56*	*3.5x2x.25*	*650.2*	*5.8*
2	*Top Boss Frag*	*32*	*3.75x3.25x13*	*551.9*	*6.9*
3	*Top Boss*	*720*	*Ø7x3.75*	*613.9*	*8.6*

See below in Figure 32 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frags.

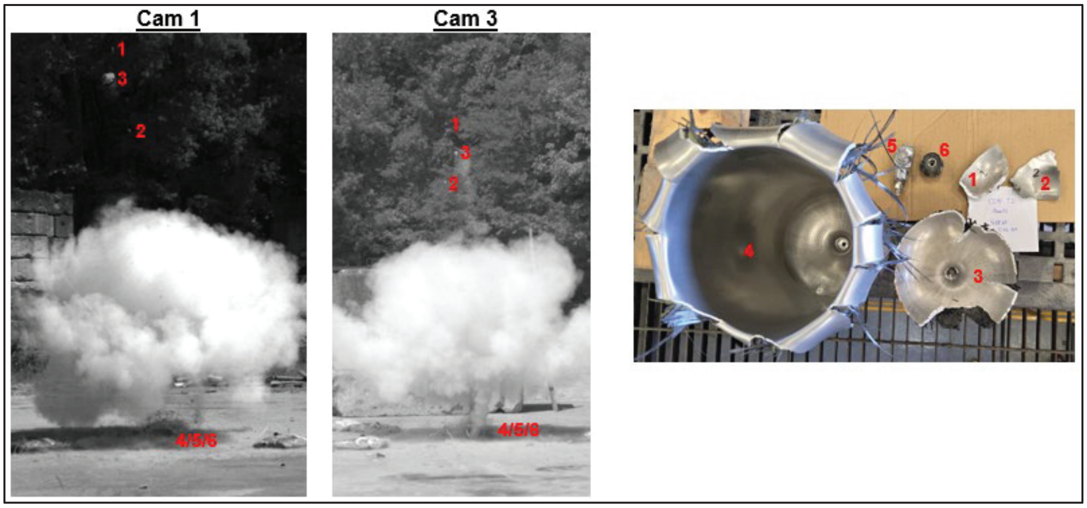


Figure 32: Test 2 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

All but one of the BOP sensors recorded successful pressure curves for this test. Based on the length and strength of the det cord, the net explosive weight of the energetics was 6.9 grams of PETN and the COPV tank contained 8.2L of gaseous nitrogen at 4,285 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 33 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	7.22	5ft
H1	8.09	
H2	N/A	
I2	4.42	7.5ft
J1	5.44	
J2	4.35	
I3	4.13	10ft
K1	3.52	
K2	4.13	

Figure 33: Test 2 Blast Overpressure Results

6.3 Test 3 – Det Cord Rupture @ Dome Transition

Test 3 was an energetic rupture test on the General Dynamics COPV, with det cord being the energetic rupture mechanism placed at the dome/cylinder transition, the second most likely location this tank would rupture, based on tank design and geometry.

The fill process for test 3 began on 8/13/24 at 1104 CDT and took approximately 44mins to fill to the desired pressure. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,309 psi. The head boss temperature ended at 107.5°F.

The energetic rupture test event occurred at 1204 CDT under mostly cloudy skies, 87.8°F, 47% relative humidity, and a wind-speed of 2 mph NW. The det cord successfully ruptured and separated the tank, as desired. See Figure 34 below for images of the tank during and after test.

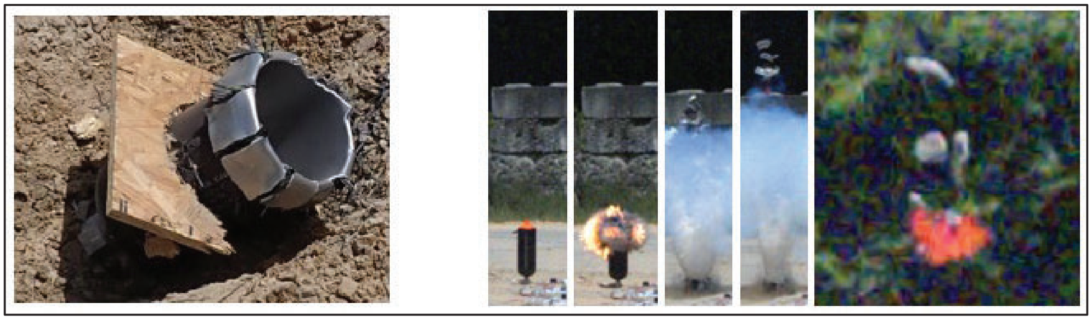


Figure 34: Test 3 General Dynamics Tank Post-Test (L) and During Separation (R)

Upon post-test evaluation, the head boss fragmented into four separate fragments that were propelled upwards, while the remaining tank and valve components were driven into the sand. These four propelled fragments were not recovered after the test, as they had been likely thrown outside the immediate test area. Therefore, no mass or size can be deduced from the fragments. See Table 7 below for a chart of the test's frag velocity summary.

Table 7: Test 3 Fragment Velocity Summary

Test 3					
Cutter:	*50 gr/ft Det Cord*		**Pressure:**	*4309 psi*	
Location:	*At Dome/Cylinder Transition*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Boss Piece*			*529.5*	*6.4*
2	*Boss Piece*			*603.5*	*5.7*
3	*Boss Piece*			*618.9*	*7.5*
4	*Boss Piece*			*593.2*	*3.1*

See below in Figure 35 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frags.

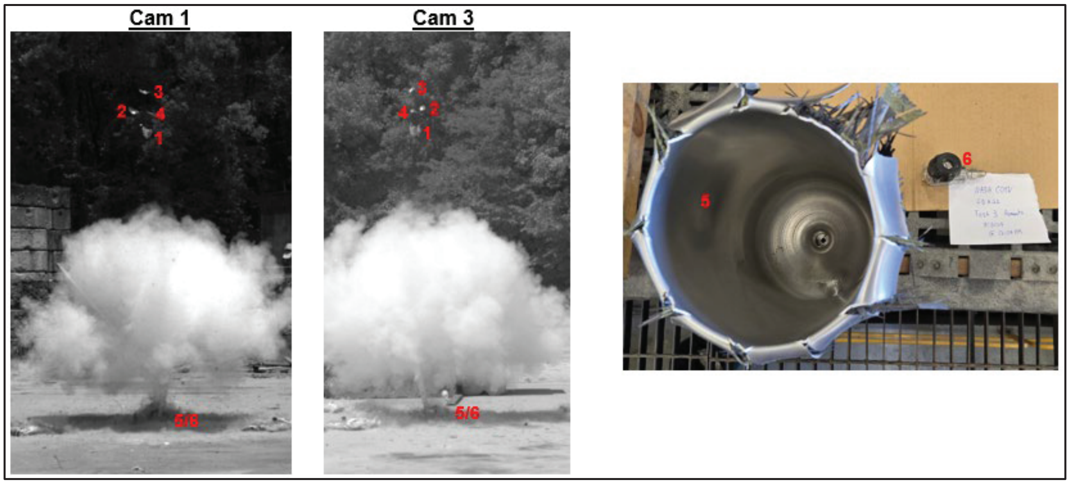


Figure 35: Test 3 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

All but one of the BOP sensors recorded successful pressure curves for this test. Based on the length and strength of the det cord, the net explosive weight of the energetics was 6.9 grams of PETN and the COPV tank contained 8.2L of gaseous nitrogen at 4,309 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 36 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	6.42	5ft
H1	6.78	
H2	N/A	
I2	3.81	7.5ft
J1	4.17	
J2	5.00	
I3	3.95	10ft
K1	3.84	
K2	4.02	

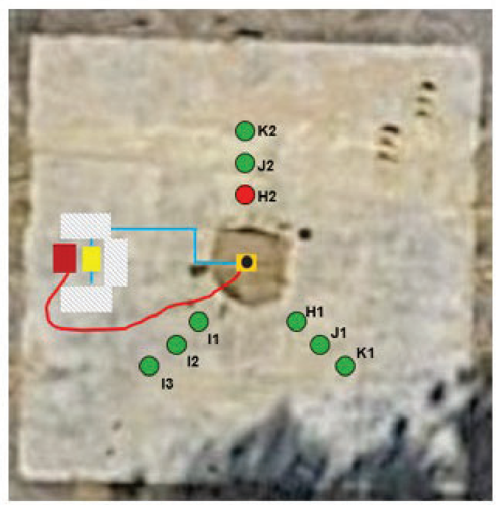


Figure 36: Test 3 Blast Overpressure Results

6.4 Test 4 – Det Cord Rupture @ Dome Transition

Test 4 was an energetic rupture test on the General Dynamics COPV, with det cord being the energetic rupture mechanism placed at the dome/cylinder transition, the second most likely location this tank would rupture, based on tank design and geometry.

The fill process for test 4 began on 8/13/24 at 1225 CDT and took approximately 39mins to fill to the desired pressure. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,315 psi. The head boss temperature ended at 110.6°F.

The energetic rupture test event occurred at 1320 CDT under mostly cloudy skies, 86°F, 53% relative humidity, and a wind-speed of 0.5 mph S. The det cord successfully ruptured and separated the tank, as desired. See Figure 37 below for images of the tank during and after test.

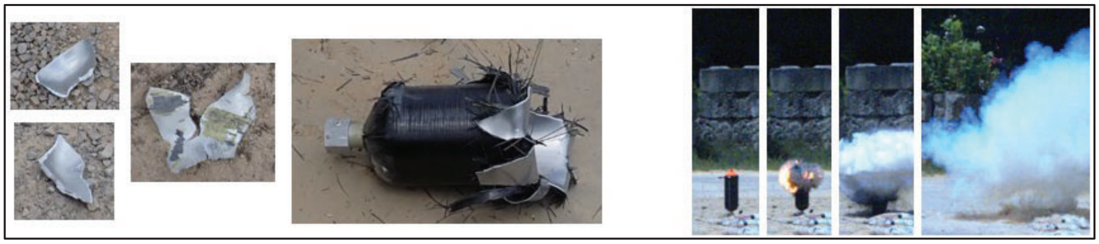


Figure 37: Test 4 General Dynamics Tank Post-Test (L) and During Separation (R)

Upon post-test evaluation, the head boss fragmented into four fragments that were propelled upwards, while the remaining tank and valve components were driven down into the sand. Three of the four fragments were recovered post-test so a full analysis of mass, size, and velocity can be derived for those. The one frag that was not recovered was assumed to be the remaining weight left over from the total initial weight minus the recovered frags and size dimensions were assumed for it as well. See Table 8 below for a chart of the test's frag velocity summary.

Table 8: Test 4 Fragment Velocity Summary

Test 4					
Cutter:	*50 gr/ft Det Cord*		**Pressure:**	*4315 psi*	
Location:	*At Dome/Cylinder Transition*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Boss Piece*	*78*	*5.5x3x.25*	*397.4*	*37*
2	*Boss Piece*	*90*	*5x2.75x.25*	*623*	*39.1*
3	*Boss Piece*	*62*	*5.25x4x.13*	*585.6*	*31.5*
4	*Remnant Head Boss*	*814*	*Ø4x3.75*	*428.4*	*27.2*

See below in Figure 38 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frags.

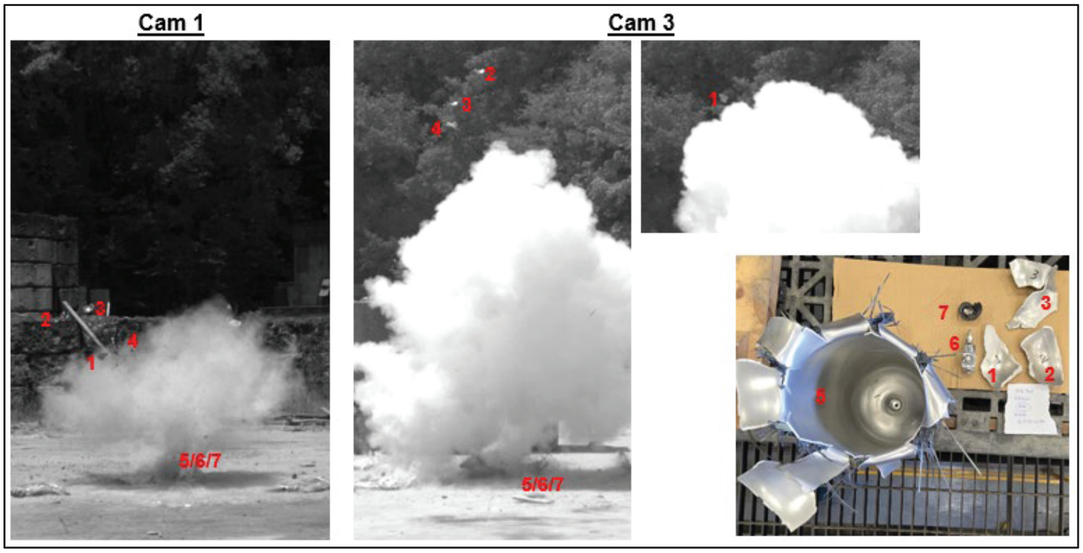


Figure 38: Test 4 High-Speed Frag Footage (L) and Recovered Frags (R)

All but one of the BOP sensors recorded successful pressure curves for this test. Based on the length and strength of the det cord, the net explosive weight of the energetics was 6.9 grams of PETN and the COPV tank contained 8.2L of gaseous nitrogen at 4,315 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 39 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	4.35	5ft
H1	6.93	
H2	N/A	
I2	3.73	7.5ft
J1	5.44	
J2	5.58	
I3	3.26	10ft
K1	3.92	
K2	4.10	

Figure 39: Test 4 Blast Overpressure Results

6.5 Test 5 – Det Cord Rupture @ Boss

Test 5 was an energetic rupture test on the General Dynamics COPV, with det cord being the energetic rupture mechanism placed right around the boss. While this is not the most likely failure mechanism for this tank, it is the most massive, small fragment that could reasonably be expected to be liberated in a rupture event.

The fill process for test 5 began on 8/13/24 at 1342 CDT and took approximately 1hr and 32mins to fill to the desired pressure. The team filling the tank did not fully close the ball valve before the fill lines were purged, which resulted in a depressurization of the tank. The fill process was then restarted and the ultimate pressure being reached and sealed properly. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,314 psi. The head boss temperature ended at 105.3°F.

The energetic rupture test event occurred at 1531 CDT under mostly cloudy skies, 86.5°F, 51% relative humidity, and a wind-speed of 1 mph S. Upon initiation, the det cord failed to cut through the tank wall, resulting in a hazardous situation where the COPV was damaged and still contained pressure. See Figure 40 below for images of the tank before and during the detonation event.

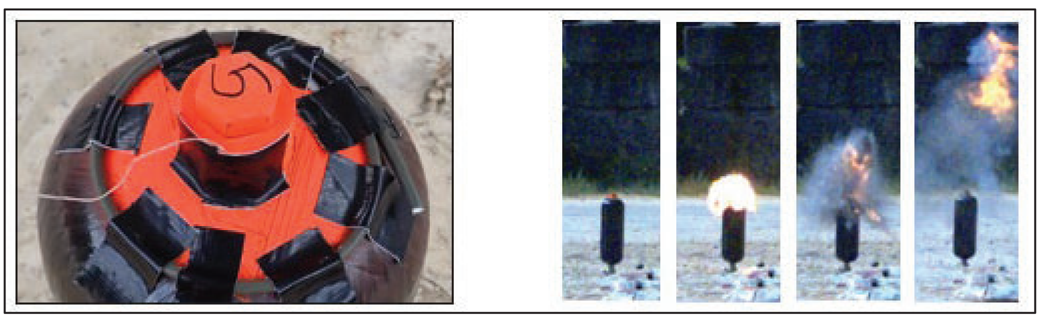


Figure 40: Test 5 General Dynamics Tank Pre-Test (L) and During Detonation Event (R)

To mitigate the dangerous situation that was presented, AvMC's risk assessment solution to the situation was to setup their remote-fired 7.62mm rifle system to remotely shoot a bullet at the tank from a safe distance. The intention was that the bullet would easily penetrate the case and allow it to vent the stored pressure appropriately. This method was successfully employed and the tank was shot and successfully vented at 1627 CDT. Based on recovered tank frags, it was derived that the bullet likely struck the tank close to the bottom boss. No video data of this bullet impact was recorded due to the differing control system so no frag velocities could be obtained from the event. Ten (10) fragments were recovered from this shot in the area post-test. See Figure 41 below for images of the remote-controlled rifle used, as well as the resulting fragments collected.

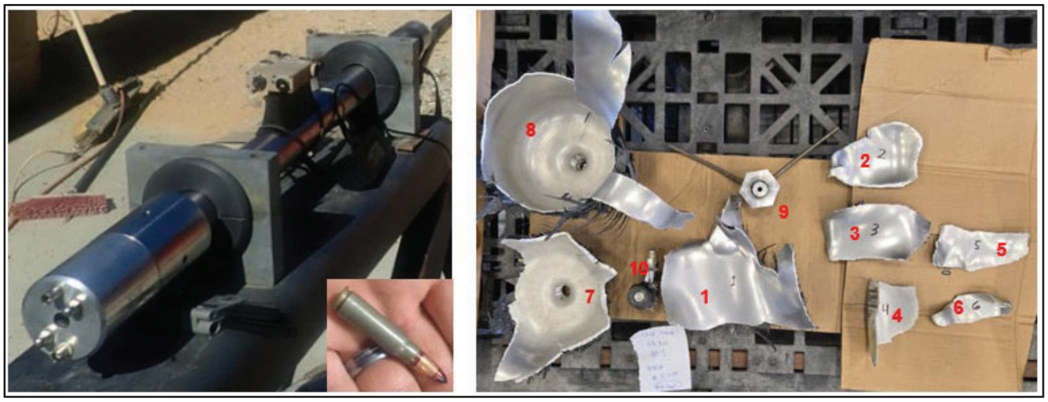


Figure 41: Test 5 Remote-Controlled Rifle System (L) and Resulting Post-Impact Fragments (R)

Though the detonation event did not result in a tank rupture, some of the BOP sensors recorded pressure curves from the detonation wave. Based on the length and strength of the det cord, the net explosive weight of the energetics was 4.8 grams of PETN. See Figure 42 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	5ft
H1	2.18	
H2	N/A	
I2	N/A	7.5ft
J1	2.39	
J2	N/A	
I3	1.34	10ft
K1	1.52	
K2	N/A	

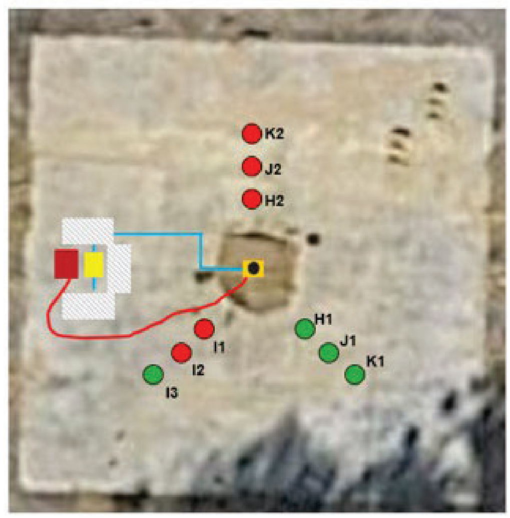


Figure 42: Test 5 Blast Overpressure Results

One of the fragments collected after the bullet impact was the top dome area. The line that the det cord sat on is still visible and clearly did not make much of a dent in penetrating the aluminum liner underneath. As the liner approaches the top boss end, the aluminum material gets progressively thicker. In all of the prior tests, the det cord was placed at locations where the liner was much thinner and resulted in successful rupture events. See Figure 43 below for an image of the det cord impression made on the COPV dome.

Figure 43: Test 5 Det Cord Impression on COPV Dome

6.6 Test 6 – Conical Shaped Charge Jet Rupture @ Boss

Since, in the prior test, the det cord was not successful in penetrating that thicker aluminum area, the AvMC and NASA teams collectively agreed upon a new plan to change the cutting charge for the successive test. The team chose to utilize a more traditional conical shaped charge to guarantee a hole punched through the tank. The AvMC team chose the smallest conical shaped charge in their inventory, a small precursor munition from an Army missile system. A conical shaped charge is similar to the mechanism in flex linear, except that the penetrating charge starts off as an inverted cone of malleable metal (typically copper), with explosive material packed behind it. Upon detonation of the explosive material, the cone is rapidly deformed into a linear jet and is propelled forwards at high speed. This style of shaped charge is commonly used in military applications as armor penetrating warheads for punching deep holes in heavy armor.

Test 6 was, therefore, an energetic rupture test on the General Dynamics COPV, with a conical shaped charge being the energetic rupture mechanism aimed right at the boss layer. See Figure 44 below for images of this conical shaped charge and how it was oriented for the test.

Figure 44: Test 6 Conical Shaped Charge Setup (L) and Standalone Picture (R)

The fill process for Test 6 began on 8/14/24 at 1007 CDT and took approximately 44mins to fill to the desired pressure. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,315 psi. The head boss temperature ended at 102°F.

The energetic rupture test event occurred at 1116 CDT under cloudy skies, 79.1°F, 77% relative humidity, and a wind-speed of 0.1 mph NNW. The shaped charge jet successfully penetrated the tank, leaving entry and exit holes, but did not cause a rupture. See Figure 45 below for images of the tank during and after test.

Figure 45: Test 6 General Dynamics Tank During Penetration (L) and Post-Test (R)

As seen in the above Figure, the jet was successful in penetrating straight through the entire tank at the desired rupture location. However, since it was more of a straight hole-punch mechanism, the COPV now had two holes (jet entry and exit) from which to quickly purge the nitrogen gas inside. The purging of nitrogen through these two holes caused a diverging nozzle effect, which propelled the tank away from the rupture location. Effectively, the tank was first propelled downward into the sand but, upon impact with the ground, spun around and was propelled out of the immediate test area. The tank was found about 80 feet away in tall grass near the perimeter of the test area. The velocity of this secondary propulsion event was indeed captured and documented below in Table 9.

Table 9: Test 6 Fragment Velocity Summary

Test 6					
Cutter:	*73 gram Conical Shaped Charge*		**Pressure:**	*4315 psi*	
Location:	*At Boss*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Whole Tank*	*3122*	*Ø6.5x22.2*	*69.6*	*66.7*

See below in Figure 46 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frag.

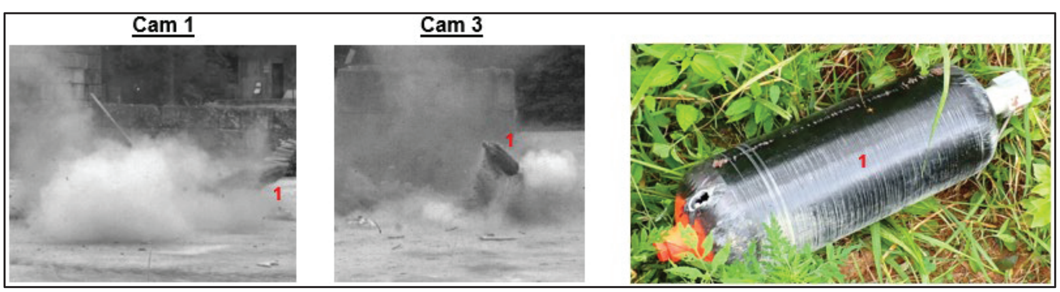


Figure 46: Test 6 High-Speed Frag Footage (L) (C) and Recovered Frag (R)

All but one of the BOP sensors recorded successful pressure curves for this test. Based on the energetic mass inside the conical shaped charge, the net explosive weight of the energetics was 73.3 grams of PBXN-5 and the COPV tank contained 8.2L of gaseous nitrogen at 4,315 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. It should be worth noting that the blast overpressure readings for this test are not uniform around the tank, since the shaped charge detonation was not centrally located. See Figure 47 below for a list of the resulting peak pressures and a schematic map of where each sensor was located and how the conical shaped charge was aimed, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	9.5	5ft
H1	13.27	
H2	20.49	
I2	4.64	7.5ft
J1	5.58	
J2	6.24	
I3	4.02	10ft
K1	4.39	
K2	N/A	

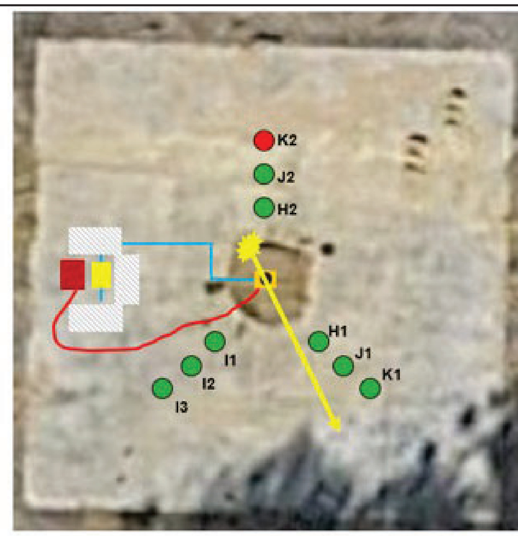


Figure 47: Test 6 Blast Overpressure Results

6.7 Test 7 – Flex Linear Rupture @ Boss

Though the hole cutting mechanism utilized in the prior test was effective, it did not yield the “seam-ripping” effect that was desired in the test series. Therefore, the AvMC and NASA teams decided collectively to make the cutting mechanism flex linear shaped charge for these shots that required a thicker material to penetrate.

Test 7 was an energetic rupture test on the General Dynamics COPV, with flex linear shaped charge being the energetic rupture mechanism placed right around the boss. While this is not the most likely failure mechanism for this tank, it is the most massive, small fragment that could reasonably be expected to be liberated in a rupture event.

The fill process for test 7 began on 8/14/24 at 1218 CDT and took approximately 43mins to fill to the desired pressure. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,325 psi. The head boss temperature ended at 103°F.

The energetic rupture test event occurred at 1320 CDT under cloudy skies, 81.1°F, 73% relative humidity, and a wind-speed of 1 mph SSE. The flex linear shaped charge successfully ruptured and separated the tank, as desired. See Figure 48 below for images of the tank before, during, and after test.

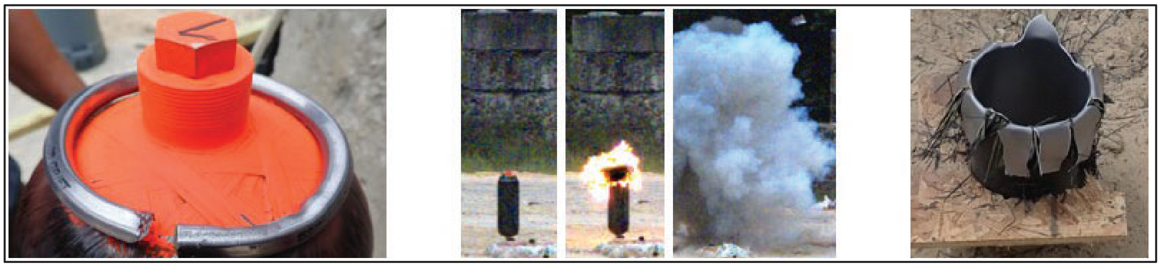


Figure 48: Test 7 General Dynamics Tank Pre-Test (L), During Test (C), and Post-Test (R)

Upon post-test evaluation, the tank fractured into many pieces, throwing frags both upward and outward. One of these fragments was recovered in the area after the test. For this frag, a full analysis of mass, size, and velocity was performed. Velocity was obtained on a few of the non-recovered frags, so size and mass were not obtained. The size and mass of the head boss was assumed to be similar to the one recovered in test 5, so those measurements were used in the below table. See Table 10 below for a chart of the test's frag velocity summary.

Table 10: Test 7 Fragment Velocity Summary

Test 7					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*4325 psi*	
Location:	*At Boss*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Bottom Boss Frag*	*152*	*6.5x4x.25*	*942.3*	*103.7*
7	*Head Boss*	*814*	*Ø3.5x3.5*	*486.6*	*33.4*
8	*Bottom Boss Frag*			*955.2*	*113.1*
9	*Bottom Boss Frag*			*865*	*112.6*

See below in Figure 49 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frags.

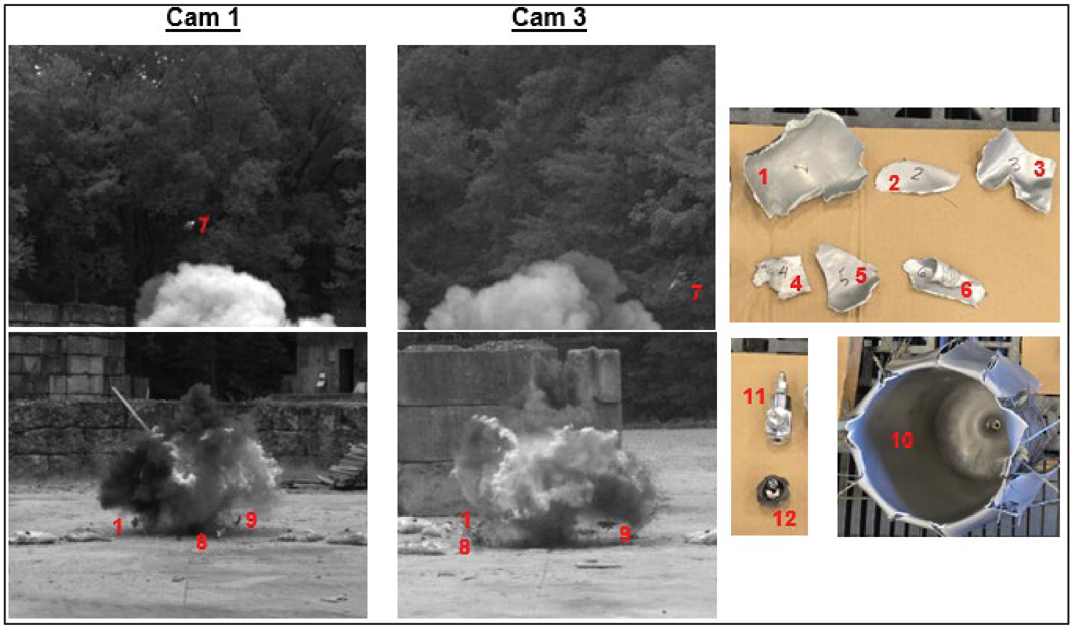


Figure 49: Test 7 High-Speed Frag Footage (L) and Recovered Frags (R)

About half of the BOP sensors recorded successful pressure curves for this test. Based on the length and strength of the flex linear, the net explosive weight of the energetics was 8.5 grams of RDX and the COPV tank contained 8.2L of gaseous nitrogen at 4,325 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 50 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	5ft
H1	N/A	
H2	10.77	
I2	3.84	7.5ft
J1	6.56	
J2	N/A	
I3	3.77	10ft
K1	3.70	
K2	N/A	

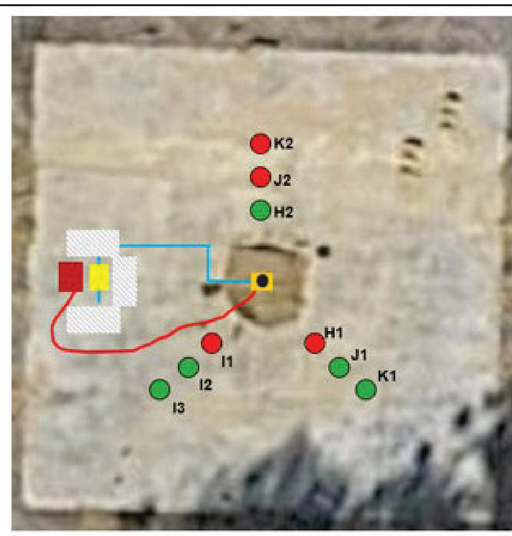


Figure 50: Test 7 Blast Overpressure Results

6.8 Test 17 – Det Cord Rupture @ Dome Taper

Test 17 was an energetic rupture test on the General Dynamics COPV, with det cord being the energetic rupture mechanism placed at the dome/cylinder taper, the most likely location this tank would rupture, based on tank design and geometry.

This test differed greatly from the previous tests because it was requested by NASA to physically capture the propelled fragments in standard fragment capture bundles. Therefore, the COPV was oriented horizontally, such that the central axis of the tank was parallel with the ground. Fragment capture bundles were placed at a known distance towards the front and back bosses, as well as directly 90 degrees. To ensure that the tank fragments actually struck the bundles, the tank was also placed on a table approximately 4ft off the ground. Based on the location of the rupture seam and previous tests, it was assumed that the COPV would split into two separate pieces and each would be propelled in opposite directions. A stack of frag collection bundles was also placed at 90 degrees to catch any frags that may have been thrown radially. High-speed camera views were adjusted to be able to see and track the fragments in flight before they impact the bundles. See Figure 51 below for images of the COPV setup and top-down schematic of the area.

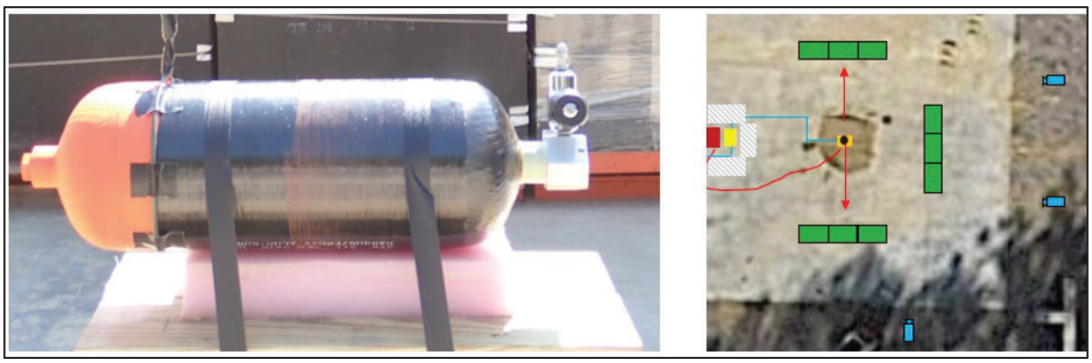


Figure 51: Test 17 COPV Orientation and Overhead Schematic

The fill process for test 17 began on 8/20/24 at 0936 CDT and took approximately 32mins to fill to the desired pressure. The goal pressure for the tank was 4,300 psi and the final reading before the pressure was sealed was 4,335 psi. The head boss temperature ended at 102.4°F.

The energetic rupture test event occurred at 1025 CDT under fair skies, 80°F, 56% relative humidity, and a wind-speed of 0.5 mph ESE. The det cord successfully ruptured and separated the tank, as desired. As expected, the top and bottom bosses were thrown in opposite directions, directly into the frag capture bundles. The top boss penetrated the bundle and then bounced out on to the ground, while the bottom boss penetrated and got stuck in the bundle. See Figure 52 below for images of the tank before, and after test.

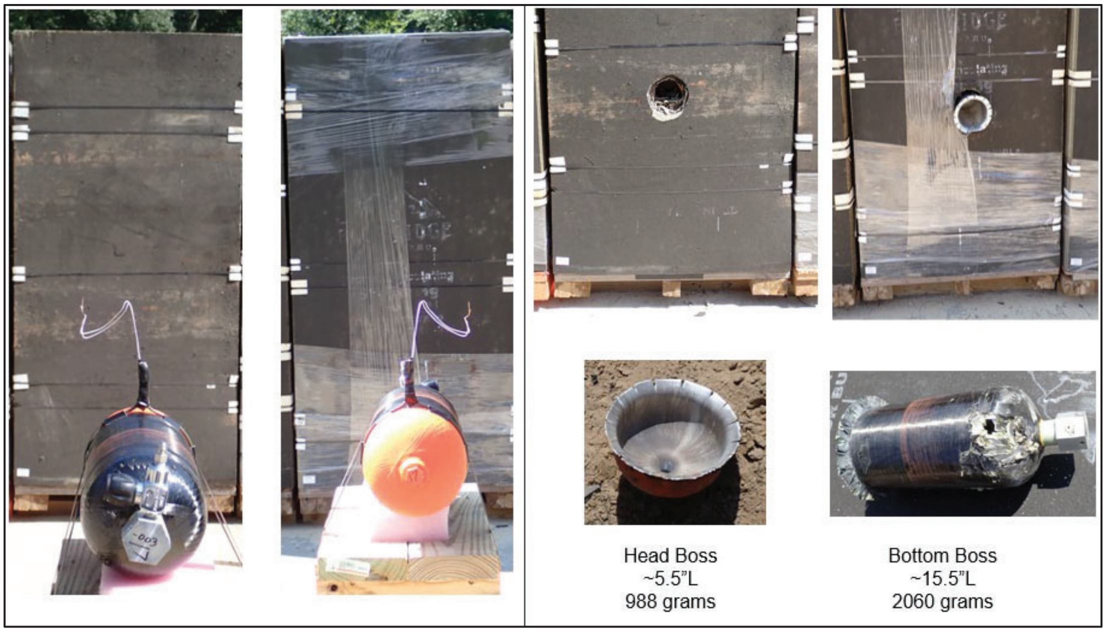


Figure 52: Test 17 General Dynamics Tank Pre-Test (L) and Post-Test (R)

Upon post-test evaluation, indeed the head and bottom bosses were captured physically and in-flight on the high-speed video, yielding a full velocity profile for each fragment. Additionally, as seen in other tests, the valve and knob were sheared off and thrown separately but they both missed the bundle and thus weren't collected post test. However, since these valve components were the same ones used in all of the other testing, the sizes and masses were assumed to be the same. See Table 11 below for a chart of this test's frag velocity summary.

Table 11: Test 17 Fragment Velocity Summary

Test 17					
Cutter:	*50 gr/ft Det Cord*		**Pressure:**	*4335 psi*	
Location:	*At Dome/Cylinder Taper*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Bottom Tank w/ Fitting*	*2060*	*Ø6.5x16*	*716.2*	*180*
2	*Top Boss*	*988*	*Ø6.5x5.25*	*609.3*	*0.7*
3	*Broken Valve*	*430*	*2.5x2.25x1*	*488.6*	*156.6*
4	*Valve Knob*	*46*	*Ø1.6x1.5*	*451.1*	*158.7*

See below in Figure 53 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frags.

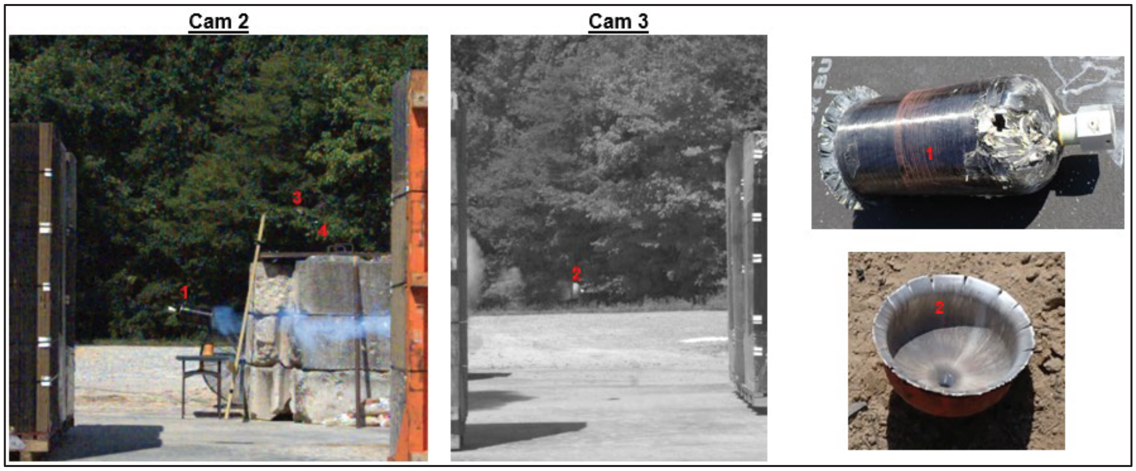


Figure 53: Test 17 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

Due to the test setup complexity added by utilizing frag capture bundles, no blast overpressure sensors were utilized during this test.

7.0 Xperion Type IV Test Results

The next set of test results that will be discussed are from the Xperion COPV tests. (6) of these tests were intentional energetic rupture tests and (3) of them were pressurize-until-burst tests. See Table 12 below for a breakdown of the test matrix executed on this style of COPV.

Table 12: Xperion COPV Test Matrix

Test #	Date/Time	Desired Fill Pressure	Energetic Used	Rupture Location
8	8/14/24 @ 1504	2900 psi	125gr/ft Flex Linear Shape Charge	To Liberate Top Boss
9	8/14/24 @ 1618			To Liberate Bottom Boss
10	8/15/24 @ 0947			To Liberate Bottom Boss
11	8/15/24 @ 1110			To Liberate Bottom Boss
12	8/15/24 @ 1221			At Midline of Cylinder
13	8/15/24 @ 1354			At Midline of Cylinder

Test #	Date/Time	Proof Pressure	Design Burst Pressure	Recorded Burst Pressure
24	8/22/24 @ 1222	4350 psi	6525 psi	7178 psi
25	8/22/24 @ 1346	4350 psi	6525 psi	7614 psi
26	8/22/24 @ 1514	4350 psi	6525 psi	7385 psi

Due to the tank wall thickness of these Xperion tanks, the team utilized the 125gr/ft flex linear shaped charges as the cutting mechanism for the rupture tests.

Test 8 was executed as a rupture test where the cutting seam was around the boss opposite from the pressure manifold, also called the top boss. The tank was vertically oriented such that the pressure manifold side was towards the ground and the top boss was towards the sky. Upon detonation event, very few frags were thrown, so it was decided that the tanks would be flipped for the subsequent shots, in the hopes that more mass, larger fragments would be liberated.

Tests 9 through 11 were executed as rupture tests where the cutting seam was around the boss with the pressure manifold, sometimes called the bottom boss. The tank was vertically oriented such that the pressure manifold side was aimed towards the sky and the "top boss" was aimed towards the ground. For each of these shots, the majority of the tank was thrown straight down into the ground and the majority of the flyaway frags were from the pressure manifold and materials immediately surrounding it, as intended.

Tests 12 and 13 were executed as rupture tests where the cutting seam was around the midplane of the cylinder. For each of these shots, the tank separated into two distinct halves. The bottom half was thrown straight into the ground and the top half was propelled straight up into the sky. The top halves for each test had at least a 10+ second flight time before they impacted the ground nearby.

Finally, tests 24 through 26 were each successfully fired in the pressurize-until-burst test method. Due to the higher burst pressure required, a pressure intensifier was installed to boost the fill pressure beyond the nitrogen supply truck's limits, hence why these were shot last in the overall test series. Fragments from these burst events were numerous and varied greatly in size/shape between shots. The burst pressures for each test were 7,178 psi, 7,614 psi, and 7,385 psi respectively.

7.1 Test 8 – Flex Linear Rupture @ Top Boss

Test 8 was an energetic rupture test on the Xperion COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the top boss of the tank. The tank was oriented such that the pressure manifold was towards the ground and the boss to be cut was pointed towards the sky. For Type IV pressure vessels, liberation of the metallic boss is the primary projectile of concern. The boss being liberated in this test is the blind boss, which has a lower mass than the threaded boss.

The fill process for test 8 began on 8/14/24 at 1349 CDT and took approximately 1 hour and 3 minutes to fill to the desired pressure. The AvMC team failed to open the COPV ball valve before attempting to fill the tank, so the first time the tank was filled, it just filled the feed lines and not the tank. Therefore, the fill time was longer than it should have been. Once this was realized, the team properly opened the ball valve and filled the tank appropriately. The goal pressure for the tank was 2,900 psi and the final reading before the pressure was sealed was 2,933 psi. The head boss temperature ended at 114°F.

The energetic rupture test event occurred at 1504 CDT under mostly cloudy skies, 83.1°F, 60% relative humidity, and a wind-speed of 0.2 mph WNW. The flex linear was successful in cutting open the tank, as desired. See Figure 54 below for images of the tank before, during, and after the test.

Figure 54: Test 8 Xperion Tank Pre-Test (L), Mid-Test (C), and Post-Test (R)

Upon post-test evaluation, the head boss fragmented into a few very small fragments propelled upwards but most of the tank was driven straight down into the sand. The fragments that were seen flying upwards were not positively recovered so no size or mass measurements can be derived. See Table 13 below for a chart of the test's frag velocity summary.

Table 13: Test 8 Fragment Velocity Summary

Test 8					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*2933 psi*	
Location:	*At Top Boss*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Fibrous Panel*			*1058.3*	*92.8*
2	*Fibrous Panel*			*1069.7*	*14.3*
3	*Head Boss*			*800.1*	*15.9*

See Figure 55 below for freeze-frame images of the high-speed video.

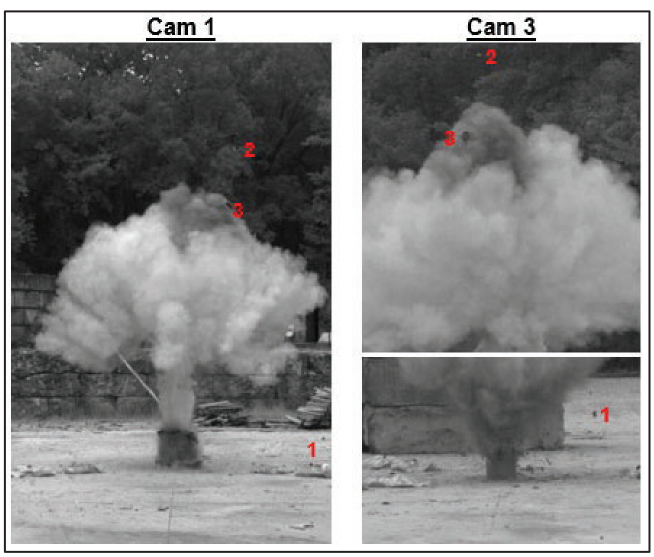


Figure 55: Test 8 High-Speed Frag Footage

Unfortunately, due to the BOP sensors being improperly configured, only two of them recorded successful pressure curves for the test. Based on the length and strength of flex linear, the net explosive weight of the energetics was 8.5 grams of RDX and the COPV tank contained 46L of gaseous nitrogen at 2,933 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 56 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	
H1	N/A	5ft
H2	N/A	
I2	N/A	
J1	5.11	7.5ft
J2	N/A	
I3	N/A	
K1	4.39	10ft
K2	N/A	

Figure 56: Test 8 Blast Overpressure Results

7.2 Test 9 – Flex Linear Rupture @ Bottom Boss

Test 9 was an energetic rupture test on the Xperion COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the bottom boss of the tank. The tank was oriented such that the pressure manifold (the boss to be cut) was towards the sky and the head boss was pointed towards the ground. For Type IV pressure vessels, liberation of the metallic boss is the primary projectile of concern. The boss being liberated in this test is the threaded boss, which has a higher mass than the bling boss.

The fill process for test 9 began on 8/14/24 at 1539 CDT and took approximately 24 minutes to fill to the desired pressure. The goal pressure for the tank was 2,900 psi and the final reading before the pressure was sealed was 2,920 psi. The head boss temperature ended at 109°F.

The energetic rupture test event occurred at 1618 CDT under mostly cloudy skies, 83.1°F, 63% relative humidity, and a wind-speed of 0.5 mph S. The flex linear was successful in cutting open the tank, as desired. See Figure 57 below for images of the tank before, during, and after the test.

Figure 57: Test 9 Xperion Tank Pre-Test (L), Mid-Test (C), and Post-Test (R)

Upon post-test evaluation, the manifold boss fragmented into a few small fragments propelled upwards but most of the tank was driven straight down into the sand. Some of the fragments seen flying upwards were not positively recovered but they appeared to be the broken ball valve and knob, as captured in previous tests. Therefore, assumed sizes and masses were applied to their respective velocities. Additionally, the main boss/manifold was not positively identified in either camera 1 or 3 because the nitrogen cloud occluded the view. However, it was positively identified in camera 4 because the view was zoomed out enough to see the whole cloud. Therefore, 2-dimensional velocity and angle were derived from that view. See Table 14 below for a chart of the test's frag velocity summary.

Table 14: Test 9 Fragment Velocity Summary

Test 9					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*2920 psi*	
Location:	*At Bottom Boss*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Valve Knob*	*46*	*Ø1.5x1.25*	*678.9*	*20.2*
2	*Broken Valve*	*430*	*3.5x2.25x1*	*245.9*	*17.6*
3	*Fibrous Panel*			*604.5*	*101.3*
4	*Head Boss*			*445*	*4.3*

See below in Figure 58 for freeze-frame images of the high-speed video.

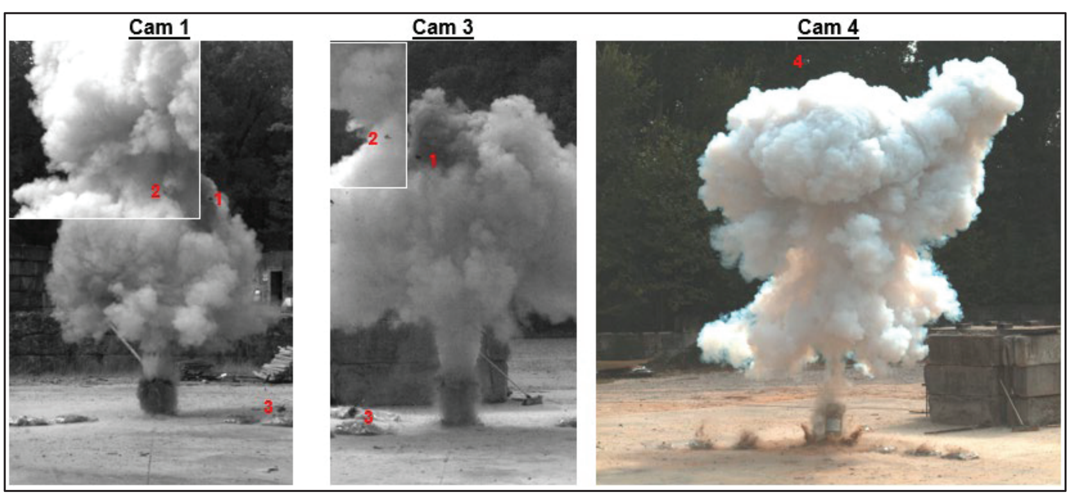


Figure 58: Test 9 High-Speed Frag Footage

Unfortunately, due to the BOP sensors being improperly configured, only one of them recorded a successful pressure curve for the test. Based on the length and strength of flex linear, the net explosive weight of the energetics was 8.5 grams of RDX and the COPV tank contained 46L of gaseous nitrogen at 2,920 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 59 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	5ft
H1	N/A	
H2	5.69	
I2	N/A	7.5ft
J1	N/A	
J2	N/A	
I3	N/A	10ft
K1	N/A	
K2	N/A	

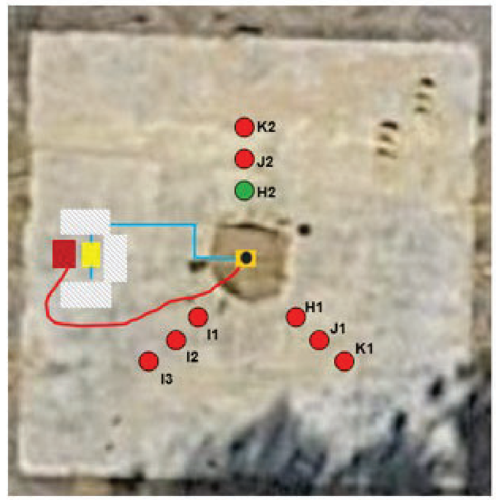


Figure 59: Test 9 Blast Overpressure Results

7.3 Test 10 – Flex Linear Rupture @ Bottom Boss

Test 10 was an energetic rupture test on the Xperion COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the bottom boss of the tank. The tank was oriented such that the pressure manifold (the boss to be cut) was towards the sky and the head boss was pointed towards the ground. For Type IV pressure vessels, liberation of the metallic boss is the primary projectile of concern. The boss being liberated in this test is the threaded boss, which has a higher mass than the blind boss.

The fill process for test 10 began on 8/15/24 at 0900 CDT and took approximately 28 minutes to fill to the desired pressure. The goal pressure for the tank was 2,900 psi and the final reading before the pressure was sealed was 2,891 psi. The head boss temperature ended at 121°F.

The energetic rupture test event occurred at 0947 CDT under partly cloudy skies, 82.6°F, 72% relative humidity, and a wind-speed of 2.3 mph NW. The flex linear was successful in cutting open the tank, as desired. See Figure 60 below for images of the tank before, during, and after the test.

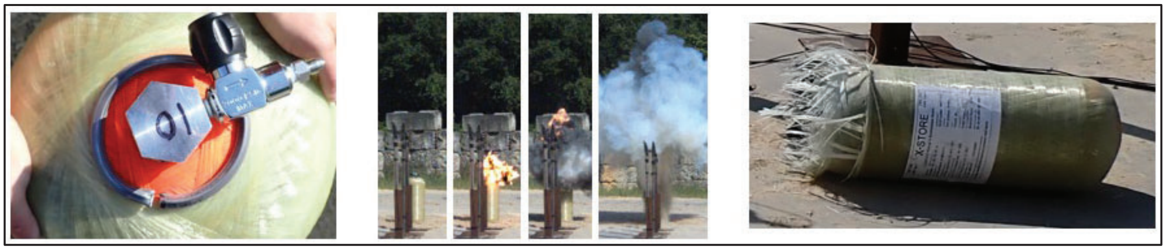


Figure 60: Test 10 Xperion Tank Pre-Test (L), Mid-Test (C), Post-Test (R)

Upon post-test evaluation, the manifold boss fragmented into a few small fragments propelled upwards but most of the tank was driven straight down into the sand. Some of the fragments seen flying upwards were not positively recovered but they appeared to be the broken ball valve and knob, as captured in previous tests. Therefore, assumed sizes and masses were applied to their respective velocities. Additionally, some other boss frags were not positively identified in either camera 1 or 3 because the nitrogen cloud occluded the view. However, they were positively identified in camera 4 because the view was zoomed out enough to see the whole cloud. Therefore, 2-dimensional velocity and angle were derived from that view. See Table 15 below for a chart of the test's frag velocity summary.

Table 15: Test 10 Fragment Velocity Summary

Test 10					
Cutter:	125 gr/ft LSC		**Pressure:**	2891 psi	
Location:	At Bottom Boss				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	Broken Valve	484	2.5x2.25x1	511.3	5.7
2	Fiberglass Boss Ring	40	Ø5x.25	500	12.6
3	Fibrous Panel			871.6	62.3
4	Bottom Boss w/ Fitting			480.8	13.3

See below in Figure 61 for freeze-frame images of the high-speed video.

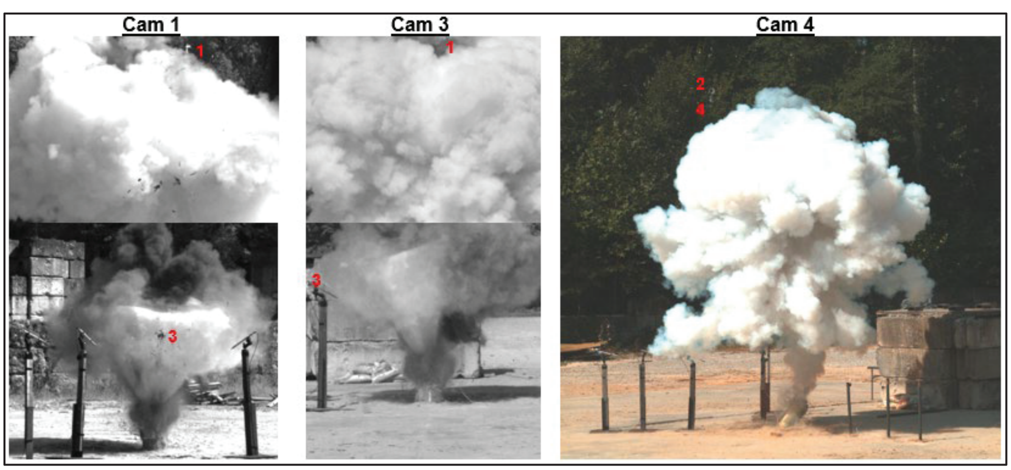


Figure 61: Test 10 High-Speed Frag Footage

All but one of the BOP sensors recorded successful pressure curves for this test. Additionally, AvMC installed pencil gauge sensors starting with this test so that concurrent measurements can be made. All (6) of the fielded pencil gauges successfully recorded pressure curves. The pencil gauge peak pressures were noticeably less than the collected BOP peak pressures. This is most likely due to the side-on vs. front-on style of pressure measurement, explained in Section 4.6. Based on the length and strength of the flex linear, the net explosive weight of the energetics was 8.5 grams of RDX and the COPV tank contained 46L of gaseous nitrogen at 2,891 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. The pressure curves from the pencil gauges can be found in Appendix C. See Figure 62 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	10.3	~ 5 ft
H1	11.17	
H2	N/A	
I2	7.14	~ 7.5 ft
J1	8.01	
J2	5.77	
I3	4.39	~ 10 ft
K1	5.84	
K2	5.11	

Pencil ID	Peak P (psi)	Distance from Center
11829	8.61	5 ft
11811	6.70	
11809	3.94	7.5 ft
9859	5.07	
7418	2.96	10 ft
11813	3.25	

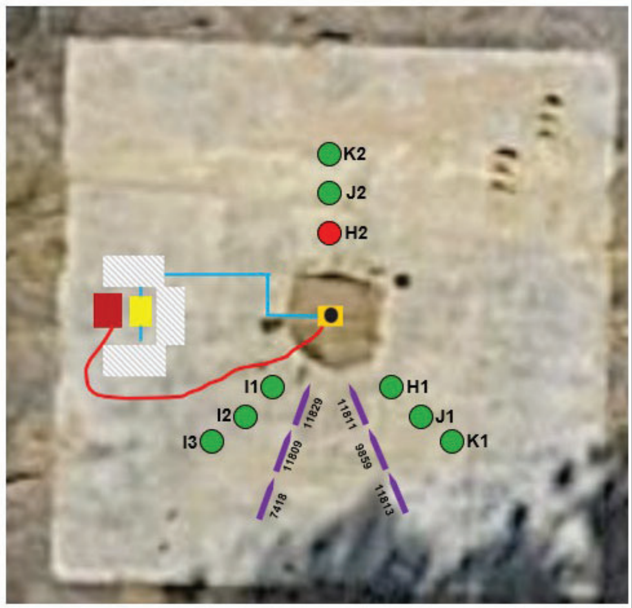


Figure 62: Test 10 Blast Overpressure Results

7.4 Test 11 – Flex Linear Rupture @ Bottom Boss

Test 11 was an energetic rupture test on the Xperion COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the bottom boss of the tank. The tank was oriented such that the pressure manifold (the boss to be cut) was towards the sky and the head boss was pointed towards the ground. For Type IV pressure vessels, liberation of the metallic boss is the primary projectile of concern. The boss being liberated in this test is the threaded boss, which has a higher mass than the blind boss.

The fill process for test 11 began on 8/15/24 at 1025 CDT and took approximately 28 minutes to fill to the desired pressure. The goal pressure for the tank was 2,900 psi and the final reading before the pressure was sealed was 2,918 psi. The head boss temperature ended at 133.8°F.

The energetic rupture test event occurred at 1110 CDT under partly cloudy skies, 87.9°F, 62% relative humidity, and a wind-speed of 2.2 mph W. The flex linear was successful in cutting open the tank, as desired. See Figure 63 below for images of the tank before, during, and after the test.

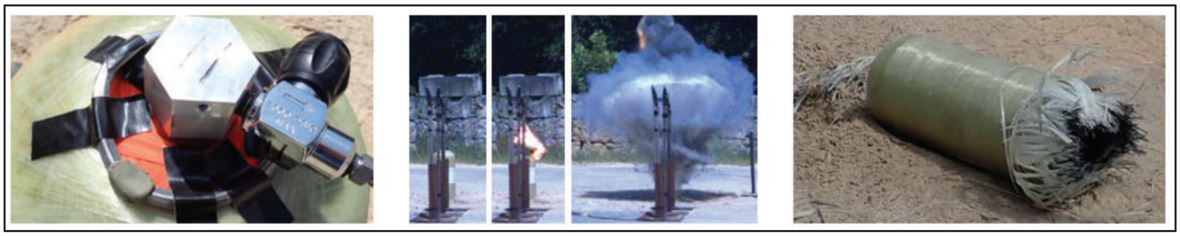


Figure 63: Test 11 Xperion Tank Pre-Test (L), Mid-Test (C), and Post-Test (R)

Upon post-test evaluation, the manifold boss fragmented into a few small fragments propelled upwards but most of the tank was driven straight down into the sand. None of the fragments from this test were positively recovered. Additionally, some of the frags were not positively identified in either camera 1 or 3 because the nitrogen cloud occluded the view. However, they were positively identified in camera 4 because the view was zoomed out enough to see the whole cloud. Therefore, 2-dimensional velocity and angle were derived from that view. See Table 16 below for a chart of the test's frag velocity summary.

Table 16: Test 11 Fragment Velocity Summary

Test 11					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*2918 psi*	
Location:	*At Bottom Boss*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Fibrous Panel*			*427.8*	*114.7*
2	*Fibrous Panel*			*467.6*	*106*
3	*Bottom Boss w/ Fitting*			*487.9*	*5.3*
4	*Half of Fiberglass Ring*			*467.9*	*6.6*
5	*Half of Fiberglass Ring*			*474.9*	*4.4*

See below in Figure 64 for freeze-frame images of the high-speed video.

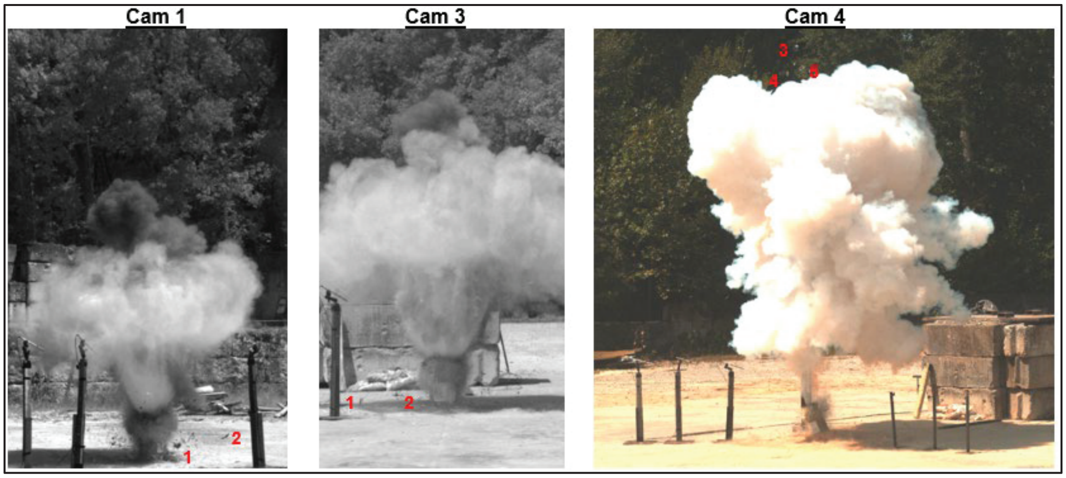


Figure 64: Test 11 High-Speed Footage

Due to the BOP sensors being configured improperly, none of them recorded pressure curves of this test event. However, with the pencil gauges now in place, all (6) of them successfully recorded waveforms. Based on the length and strength of the flex linear, the net explosive weight of the energetics was 8.5 grams of RDX and the COPV tank contained 46L of gaseous nitrogen at 2,918 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. The pressure curves from the pencil gauges can be found in Appendix C. See Figure 65 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	~ 5 ft
H1	N/A	
H2	N/A	
I2	N/A	~ 7.5 ft
J1	N/A	
J2	N/A	
I3	N/A	~ 10 ft
K1	N/A	
K2	N/A	

Pencil ID	Peak P (psi)	Distance from Center
11829	9.69	5 ft
11811	5.31	
11809	4.79	7.5 ft
9859	4.36	
7418	3.63	10 ft
11813	2.63	

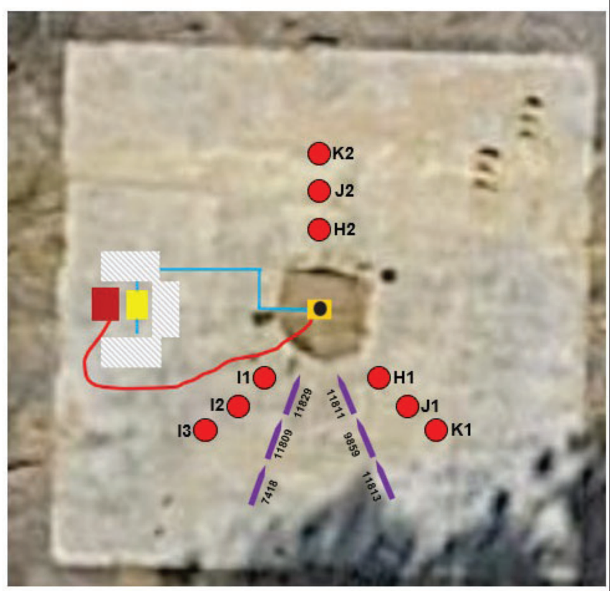


Figure 65: Test 11 Blast Overpressure Results

7.5 Test 12 – Flex Linear Rupture @ Midline

Test 12 was an energetic rupture test on the Xperion COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the midline of the tank. Liner geometry is consistent throughout the cylindrical portion, so rupture at the midline was chosen to hield a large, recoverable piece. The tank was oriented such that the pressure manifold (the boss to be cut) was towards the sky and the head boss was pointed towards the ground.

The fill process for test 12 began on 8/15/24 at 1141 CDT and took approximately 24 minutes to fill to the desired pressure. The goal pressure for the tank was 2,900 psi and the final reading before the pressure was sealed was 2,915 psi. The head boss temperature ended at 120°F.

The energetic rupture test event occurred at 1221 CDT under partly cloudy skies, 86.6°F, 64% relative humidity, and a wind-speed of 0.4 mph SSE. The flex linear was successful in cutting open the tank, as desired. See Figure 66 below for images of the tank before, during, and after the test.

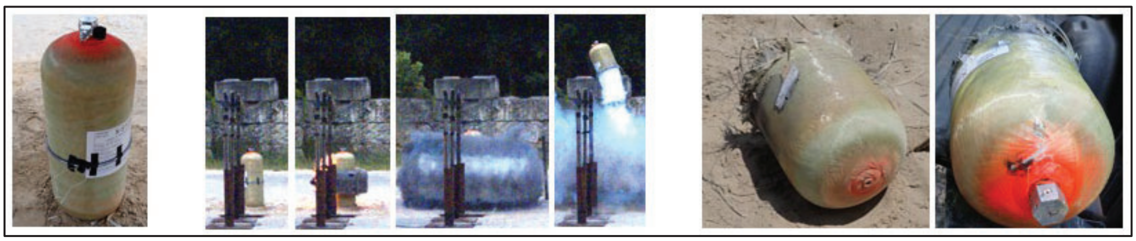


Figure 66: Test 12 Xperion Tank Pre-Test (L), Mid-Test, (C), and Post-Test (R)

Upon post-test evaluation, the tank split into two equal halves, with the top half being thrown upwards into the sky and the bottom pushed into the sand. Both fragments were recovered post-test. Apart from the velocity calculation from the high-speed videos, the entire flight time of the top half was captured via the overwatch cameras. The flight time of this top half of the tank was approximately 17 seconds. The team expected the asset to fly nearly straight up (0 degrees polar), but it was calculated to be slightly off (~6 degrees). Since the cameras were indeed level for the shot, it's theorized that the tank could have been leaning a slight bit, which yielded a launch trajectory that was slightly off angle from vertical. See Table 17 below for a chart of the test's frag velocity summary.

Table 17: Test 12 Fragment Velocity Summary

Test 12					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*2915 psi*	
Location:	*At Cylinder Midline*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Half w/ Fitting*	*7332*	*Ø12x17*	*605.3*	*6.1*

See below in Figure 67 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frag.

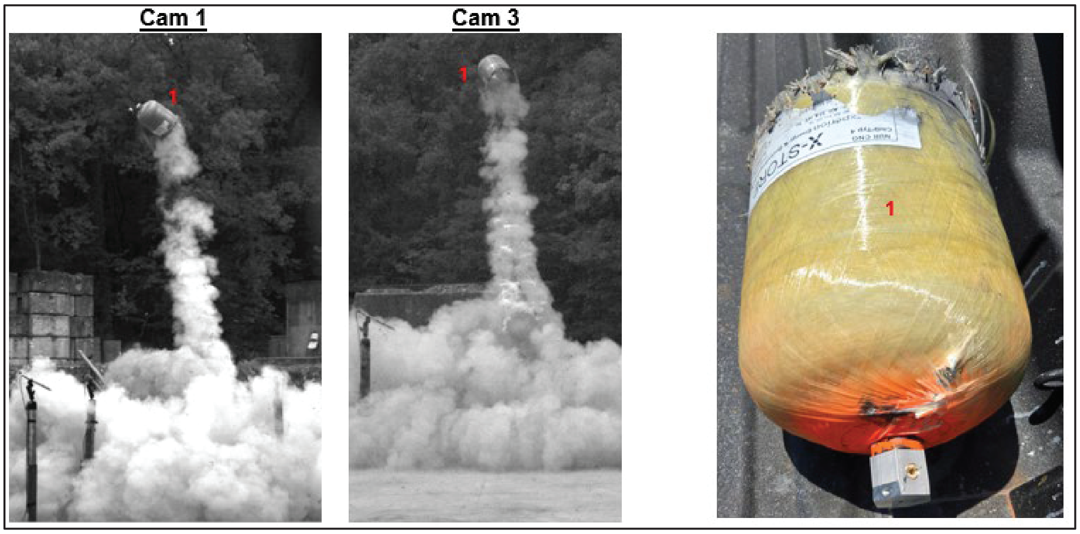


Figure 67: Test 12 High-Speed Frag Footage (L) (C) and Recovered Frag (R)

All pencil gauges and all but two of the BOP sensors successfully recorded pressure curves for this test. Based on the length and strength of the det cord, the net explosive weight of the energetics was 22.7 grams of RDX and the COPV tank contained 46L of gaseous nitrogen at 2,915 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. The pressure curves from the pencil gauges can be found in Appendix C. See Figure 68 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	12.65	~ 5 ft
H1	13.27	
H2	16.17	
I2	10.66	~ 7.5 ft
J1	10.95	
J2	N/A	
I3	9.39	~ 10 ft
K1	10.95	
K2	N/A	

Pencil ID	Peak P (psi)	Distance from Center
11829	8.61	5 ft
11811	7.13	
11809	5.69	7.5 ft
9859	5.94	
7418	5.46	10 ft
11813	5.07	

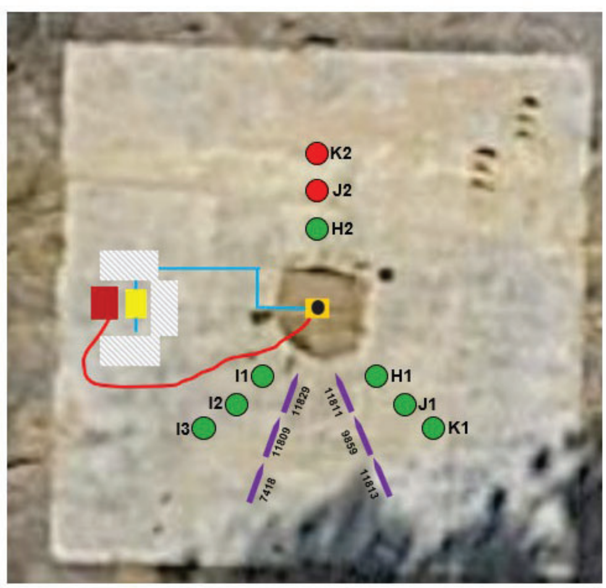


Figure 68: Test 12 Blast Overpressure Results

7.6 Test 13 – Flex Linear Rupture @ Midline

Test 13 was an energetic rupture test on the Xperion COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the midline of the tank. Liner geometry is consistent throughout the cylindrical portion, so rupture at the midline was chosen to yield a large, recoverable piece. The tank was oriented such that the pressure manifold was towards the ground and the head boss was pointed towards the sky, opposite from the orientation in test 12.

The fill process for test 13 began on 8/15/24 at 1253 CDT and took approximately 24 minutes to fill to the desired pressure. The goal pressure for the tank was 2,900 psi and the final reading before the pressure was sealed was 2,953 psi. The head boss temperature ended at 137°F.

The energetic rupture test event occurred at 1354 CDT under partly cloudy skies, 89.9°F, 50% relative humidity, and a wind-speed of 1 mph SE. The flex linear was successful in cutting open the tank, as desired. See Figure 69 below for images of the tank before, during, and after the test.

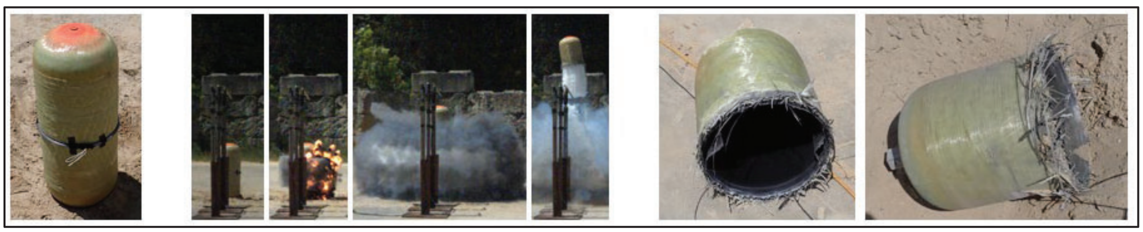


Figure 69: Test 13 Xperion Tank Pre-Test (L), Mid-Test (C), and Post-Test (R)

Upon post-test evaluation, the tank split into two equal halves, with the top half being thrown upwards into the sky and the bottom pushed into the sand. Both fragments were recovered post-test. Apart from the velocity calculation from the high-speed videos, the entire flight time of the top half was captured via the overwatch cameras. The flight time of this top half of the tank was approximately 18 seconds. The team expected the asset to fly nearly straight up (0 degrees polar), but it was calculated to be slightly off (~3.4 degrees). Since the cameras were indeed level for the shot, it's theorized that the tank could have been leaning a slight bit, which yielded a launch trajectory that was slightly off angle from vertical. See Table 18 below for a chart of the test's frag velocity summary.

Table 18: Test 13 Fragment Velocity Summary

Test 13					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*2953 psi*	
Location:	*At Cylinder Midline*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Half*	*7918*	*Ø12x17*	*635.1*	*3.4*

See below in Figure 70 for freeze-frame images of the high-speed video, as well as a photograph of the recovered frag.

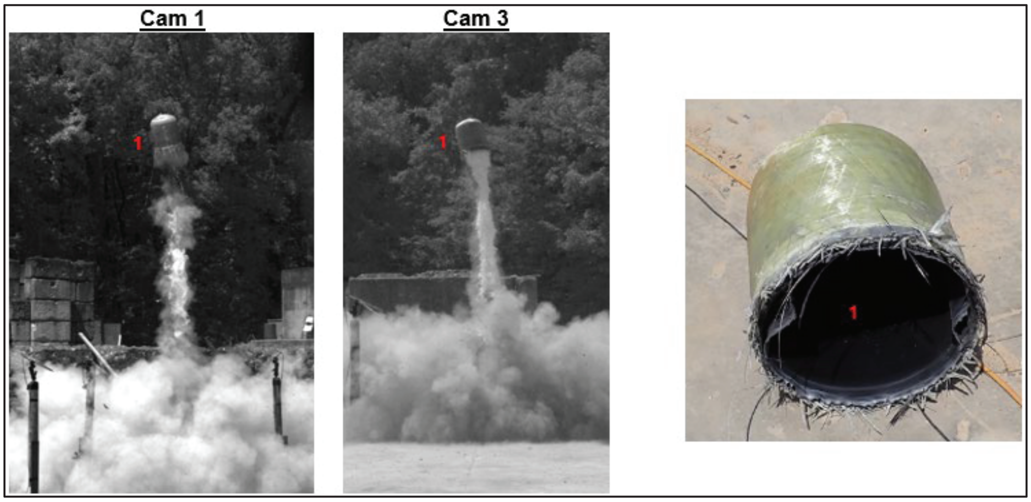


Figure 70: Test 13 High-Speed Frag Footage (L) (C) and Recovered Frag (R)

Due to the BOP sensors being configured improperly, none of them recorded pressure curves of this test event. However, with the pencil gauges now in place, all (6) of them successfully recorded waveforms. Based on the length and strength of the flex linear, the net explosive weight of the energetics was 22.7 grams of RDX and the COPV tank contained 46L of gaseous nitrogen at 2,953 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. The pressure curves from the pencil gauges can be found in Appendix C. See Figure 71 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	~ 5 ft
H1	N/A	
H2	N/A	
I2	N/A	~ 7.5 ft
J1	N/A	
J2	N/A	
I3	N/A	~ 10 ft
K1	N/A	
K2	N/A	

Pencil ID	Peak P (psi)	Distance from Center
11829	8.03	5 ft
11811	6.50	
11809	5.78	7.5 ft
9859	5.67	
7418	5.28	10 ft
11813	5.33	

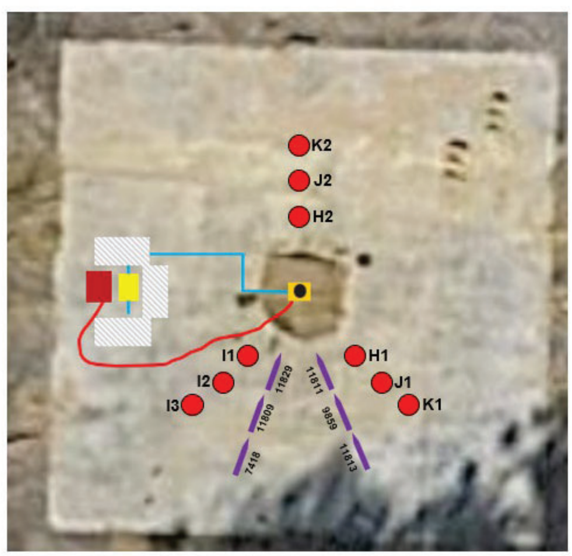


Figure 71: Test 13 Blast Overpressure Results

7.7 Test 24 – Pressurize Until Burst

Test 24 was a pressurize-until-burst style test, therefore no energetics were utilized in the event. The nitrogen gas supply truck only could output about 4,500 psi and the estimated burst level for these tanks was 6,500+ psi. Due to the high designed-burst-pressure, the NASA team provided the AvMC team with a pressure intensifier that takes a lower supplied pressure level on the input side and compresses it further to provide higher pressure on the output side. This pressure intensifier was installed near the gas supply truck and the flow-rate control needle valve was installed on the output side of the intensifier. See Figure 72 below for a picture of this supply truck with pressure intensifier configuration.

Figure 72: N_2 Supply Truck with Pressure Intensifier

The fill process was started on 8/22/24 at 1145 CDT and took 37 minutes to build pressure and ultimately violently burst. At the time of burst (approximately 1222 CDT), the weather conditions were partly cloudy skies, 83.3°F, 59% relative humidity, and a wind speed of 0.4 mph W. The maximum pressure recorded inside the tank at the time of burst was 7178 psi. See Figure 73 below for the pressurization curve, as recorded by the AvMC DAQ system.

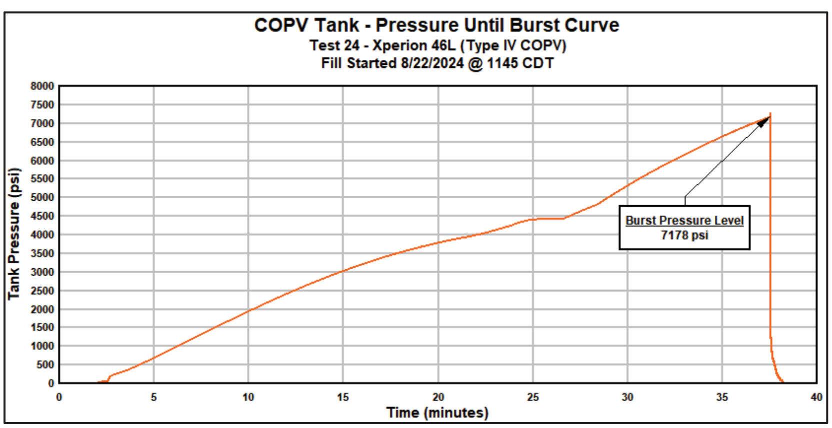


Figure 73: Test 24 Pressurization-Until-Burst Fill Curve

See below in Figure 74 for images of the tank before, during, and after test.

Figure 74: Test 24 Xperion Tank Pre-Test (L), Mid-Test (C), and Post-Test (R)

The burst event was significantly more violent than the energetic rupture tests. The head boss, plastic liner and composite layers were positively identified in the video and recovered post-test. However, many other smaller fragments of liner and composites were thrown in all directions and were significantly harder to analyze or recover. Three fragments were positively identified in the high-speed video views and Table 19 below shows a chart of the resulting frag velocity summary.

Table 19: Test 24 Fragment Velocity Summary

Test 24					
Test Type:	*Intensified Burst*	**Burst Pressure:**			*7178 psi*
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Head Boss w/ Composite*	*458*	*Ø13x4*	*667.5*	*46*
2	*Fibrous Panel*			*888.7*	*63.7*
3	*Plastic Liner Frag*			*1229.1*	*76.7*

See below in Figure 75 for freeze-frame images of the high-speed video, as well as a photograph of the recovered fragments.

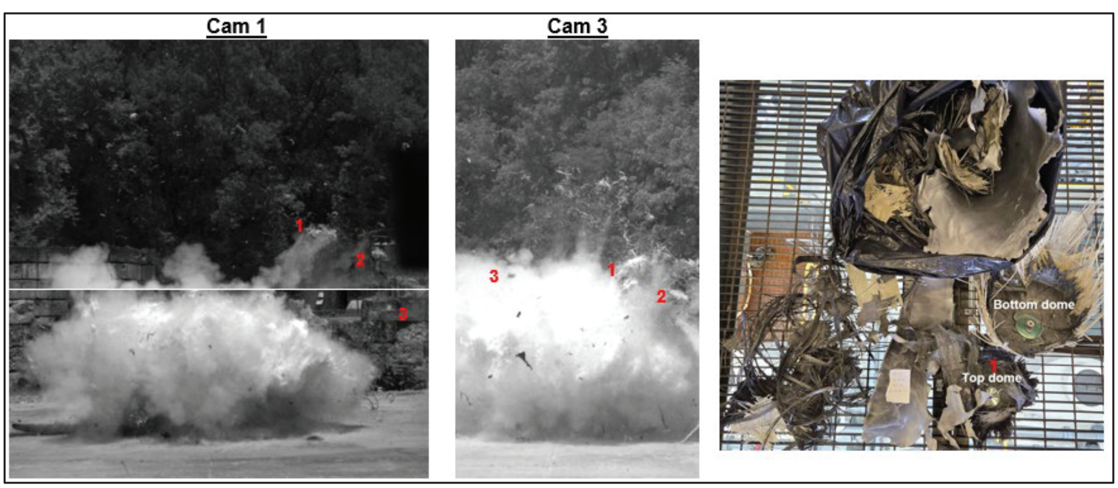


Figure 75: Test 24 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

As the burst event was to rupture at an unknown time, no blast overpressure sensors were placed in the test area for test 24.

7.8 Test 25 – Pressurize Until Burst

Test 25 was a pressurize-until-burst style test, therefore no energetics were utilized in the event. As with the prior test, the pressure intensifier was utilized to boost tank pressures up to the magnitudes required.

The fill process was started on 8/22/24 at 1307 CDT and took 40 minutes to build pressure and ultimately violently burst. At the time of burst (approximately 1346 CDT), the weather conditions were partly cloudy skies, 82.9°F, 58% relative humidity, and a wind speed of 0.6 mph S. The maximum pressure recorded inside the tank at the time of burst was 7614 psi. See Figure 76 below for the pressurization curve, as recorded by the AvMC DAQ system.

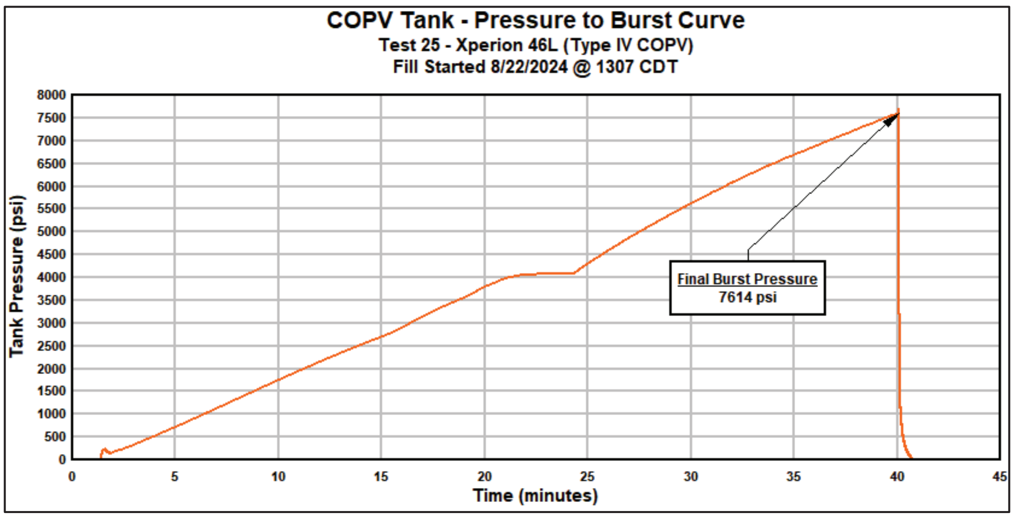


Figure 76: Test 25 Pressurization-Until-Burst Fill Curve

See below in Figure 77 for images of the tank before and after test.

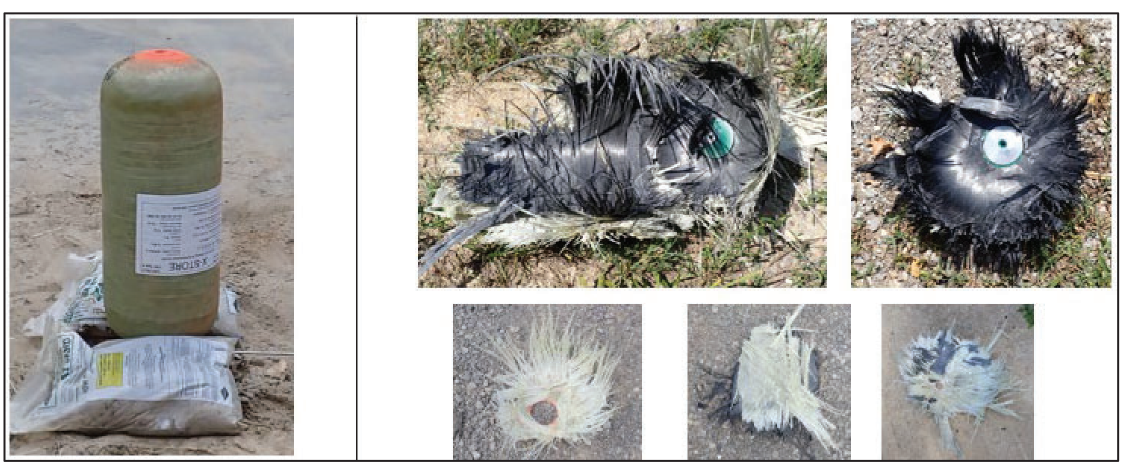


Figure 77: Test 25 Xperion Tank Pre-Test (L) and Post-Test (R)

The burst event was significantly more violent than the energetic rupture tests. The head boss, plastic liner and composite layers were positively identified in the video and recovered post-test. However, many other smaller fragments of liner and composites were thrown in all directions and were significantly harder to analyze or recover. Three fragments were positively identified in the high-speed video views and Table 20 below shows a chart of the resulting frag velocity summary.

Table 20: Test 25 Fragment Velocity Summary

Test 25					
Test Type: *Intensified Burst*		**Burst Pressure:**			*7614 psi*
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Head Boss w/ Composite*	*392*	*Ø13x4*	*720*	*38.2*
2	*Fiberglass Ring*	*336*	*Ø13x4*	*686*	*37.4*
3	*Plastic Liner Frag*			*607.5*	*37.8*

See below in Figure 78 for freeze-frame images of the high-speed video, as well as a photograph of the recovered fragments.

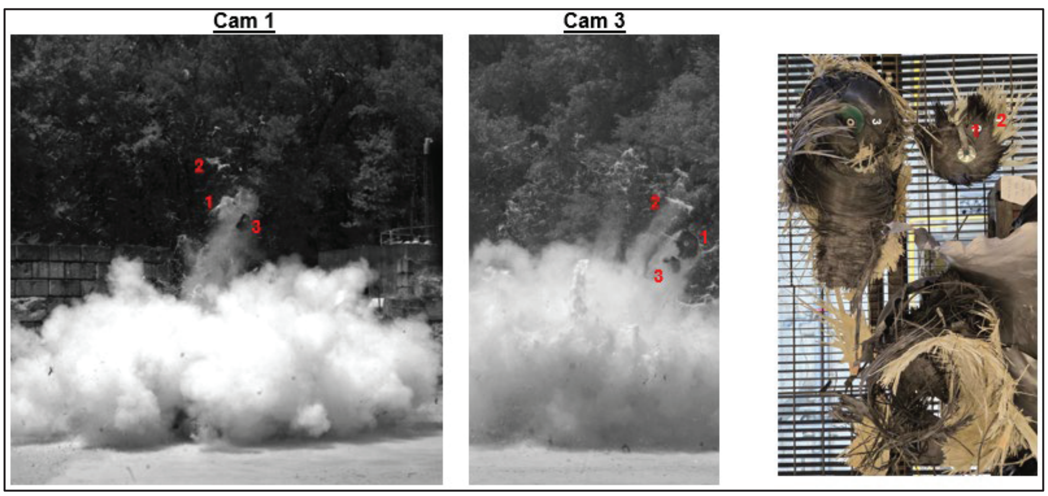


Figure 78: Test 25 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

As the burst event was to rupture at an unknown time, no blast overpressure sensors were placed in the test area for test 25.

7.9 Test 26 – Pressurize Until Burst

Test 26 was a pressurize-until-burst style test, therefore no energetics were utilized in the event. As with the prior test, the pressure intensifier was utilized to boost tank pressures up to the magnitudes required.

The fill process was started on 8/22/24 at 1434 CDT and took 39 minutes to build pressure and ultimately violently burst. At the time of burst (approximately 1514 CDT), the weather conditions were partly cloudy skies, 83.4°F, 61% relative humidity, and a wind speed of 1.1 mph S. The maximum pressure recorded inside the tank at the time of burst was 7385 psi. See Figure 79 below for the pressurization curve, as recorded by the AvMC DAQ system.

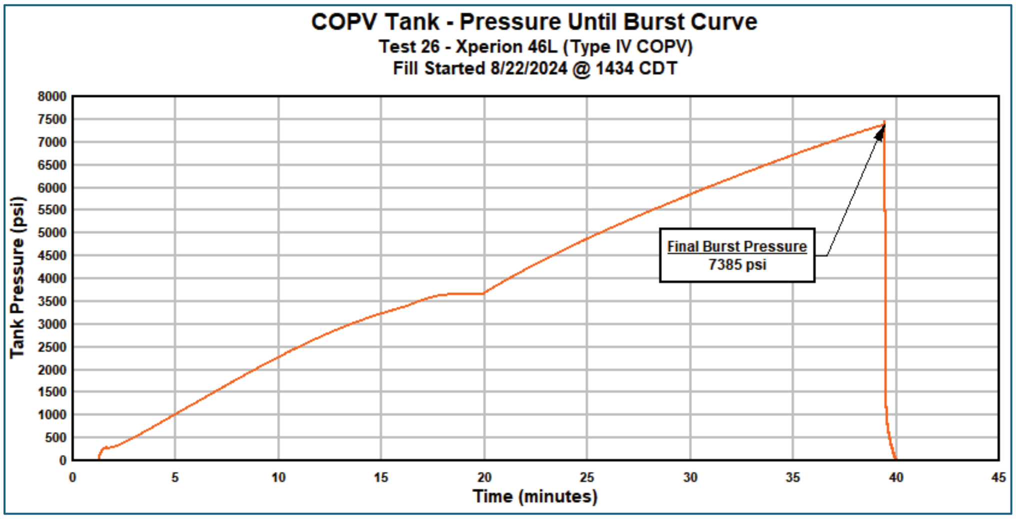


Figure 79: Test 26 Pressurization-Until-Burst Fill Curve

See below in Figure 80 for images of the tank before and after test.


Figure 80: Test 26 Xperion Tank Pre-Test (L) and Post-Test (R)

The burst event was significantly more violent than the energetic rupture tests. The head boss, plastic liner and composite layers were positively identified in the video and recovered post-test. However, many other smaller fragments of liner and composites were thrown in all directions and were significantly harder to analyze or recover. Three fragments were positively identified in the high-speed video views and Table 21 below shows a chart of the resulting frag velocity summary.

Table 21: Test 26 Fragment Velocity Summary

Test 26					
Test Type: *Intensified Burst*		**Burst Pressure:**		*7385 psi*	
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Head Boss w/ Composite*	*360*	*Ø12x5*	*788.3*	*44.2*
2	*Head Boss Plastic Liner*	*254*	*Ø16x.09*	*671*	*38.5*
3	*Fibrous Panel*	*5812*	*Ø13x13*	*800.2*	*79.8*

See below in Figure 81 for freeze-frame images of the high-speed video, as well as a photograph of the recovered fragments.

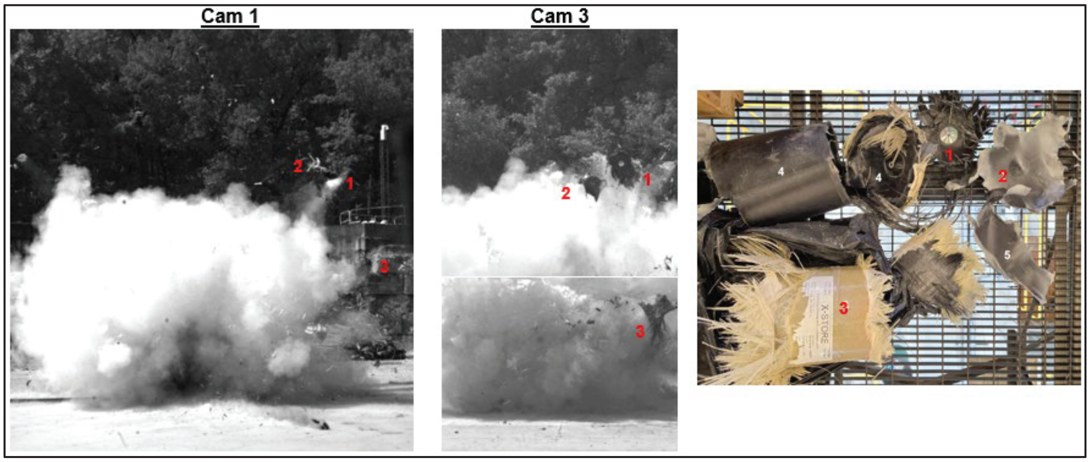


Figure 81: Test 26 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

As the burst event was to rupture at an unknown time, no blast overpressure sensors were placed in the test area for test 26.

8.0 Infinite Composites Small Type IV Test Results

The next set of test results that will be discussed are from the Infinite Composites Small COPV tests. Only three (3) of these tests were conducted and they were all intentional energetic rupture tests. See Table 22 below for a breakdown of the test matrix executed on this style of COPV.

Table 22: Infinite Composites Small Test Matrix

Test #	Date/Time	Desired Fill Pressure	Energetic Used	Rupture Location
14	8/15/24 @ 1520	4500 psi	125gr/ft Flex Linear Shape Charge	To Liberate Boss
15	8/15/24 @ 1013			To Liberate Boss
16	8/15/24 @ 1142			At Cylinder Midline

Due to the tank wall thickness of these Infinite Composites Small tanks, the team utilized the 125gr/ft flex linear shaped charges as the cutting mechanism for the rupture tests.

Tests 14 and 15 were executed as rupture tests where the cutting seam was around the boss opposite from the pressure manifold, also called the top boss. The tank was vertically oriented such that the pressure manifold side was towards the ground and the top boss was towards the sky. Frags that came off were mostly small boss components that separated during the rupture cut.

Test 16 was executed as a rupture test where the cutting seam was around the midline of the cylindrical portion of the tank. The tank was oriented the same as the previous test, with pressure manifold side towards the ground. After the seam rupture, the top half of the tank broke up into a few smaller fragments, sending them mostly in the vertical direction.

8.1 Test 14 – Flex Linear Rupture @ Top Boss

Test 14 was an energetic rupture test on the Infinite Composites Small COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the top boss of the tank. The tank was oriented such that the pressure manifold was towards the ground and the boss to be cut was pointed towards the sky. For Type IV pressure vessels, liberation of the metallic boss is the primary projectile of concern.

The fill process for test 14 began on 8/15/24 at 1424 CDT and took approximately 41 minutes to fill to the desired pressure. The goal pressure for the tank was 4,500 psi and the final reading before the pressure was sealed was 4,530 psi. The head boss temperature ended at 107.6°F.

The energetic rupture test event occurred at 1520 CDT under mostly cloudy skies, 88.9°F, 51% relative humidity, and a wind-speed of 1 mph SSE. The flex linear was successful in cutting open the tank, as desired. See Figure 82 below for images of the tank before and after the test.

Figure 82: Test 14 Infinite Composites Small Tank Pre-Test (L) and Post-Test (R)

Upon post-test evaluation, the head boss fragmented into three fragments propelled up and outwards, while the remaining tank and valve components were driven down into the sand. The two composite fragments were not positively recovered, therefore, only velocity magnitudes and directions were calculated for them. The top boss was recovered on a latter test so the mass and size for it are substituted into this data set. See Table 23 below for a chart of the test's frag velocity summary.

Table 23: Test 14 Fragment Velocity Summary

Test 14					
Cutter:	*125 gr/ft LSC*		**Pressure:**		*4530 psi*
Location:	*At Top Boss*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Boss, Metallic*	*148*	*Ø2.5x1.5*	221	5.1
2	*Top Boss Composite*			881.7	47.7
3	*Top Boss Composite*			923.6	31.4

See Figure 83 below for freeze-frame images of the high-speed video.

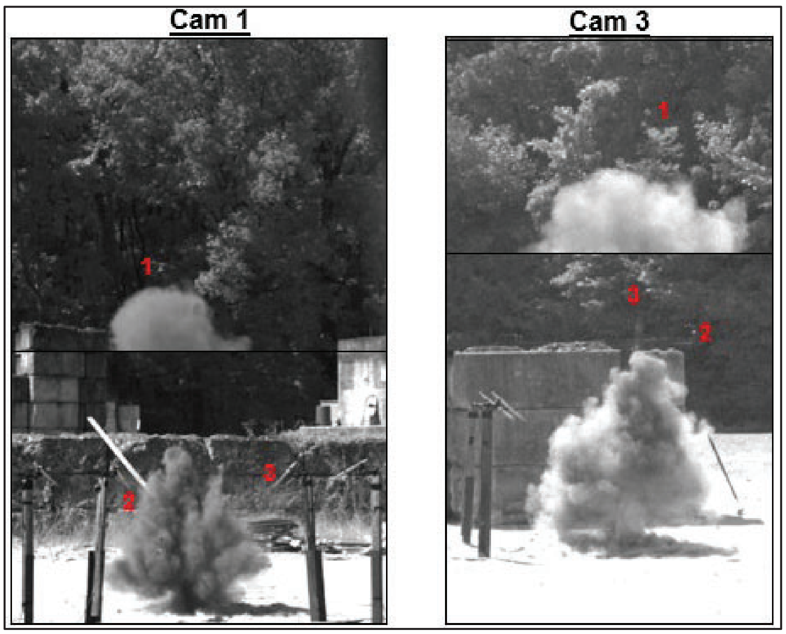


Figure 83: Test 14 High-Speed Frag Footage

All but two of the BOP sensors and all of the pencil gauges recorded successful pressure curves for this test. The raw pencil gauge pressure curves can be seen in Appendix C. Based on the length and strength of the flex linear, the net explosive weight of the energetics was 7.2 grams of RDX and the COPV tank contained 1.9L of gaseous nitrogen at 4,530 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 84 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	5.77	~ 5 ft
H1	5.62	
H2	7.11	
I2	3.84	~ 7.5 ft
J1	4.57	
J2	N/A	
I3	3.52	~ 10 ft
K1	3.37	
K2	N/A	

Pencil ID	Peak P (psi)	Distance from Center
11829	4.04	5 ft
11811	3.21	
11809	2.42	7.5 ft
9859	2.21	
7418	2.04	10 ft
11813	1.83	

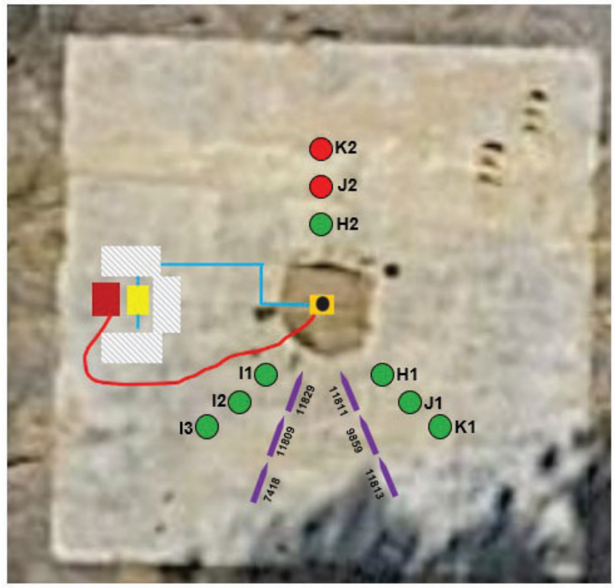


Figure 84: Test 14 Blast Overpressure Results

8.2 Test 15 – Flex Linear Rupture @ Top Boss

Test 15 was an energetic rupture test on the Infinite Composites Small COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the top boss of the tank. For Type IV pressure vessels, liberation of the metallic boss is the primary projectile of concern. The tank was oriented such that the pressure manifold was towards the ground and the boss to be cut was pointed towards the sky.

The fill process for test 15 began on 8/19/24 at 0913 CDT and took approximately 45 minutes to fill to the desired pressure. The goal pressure for the tank was 4,500 psi and the final reading before the pressure was sealed was 4,492 psi. The head boss temperature ended at 95°F.

The energetic rupture test event occurred at 1013 CDT under partly cloudy skies, 78.6°F, 69% relative humidity, and a wind-speed of 2 mph SE. The flex linear was successful in cutting open the tank, as desired. See Figure 85 below for images of the tank before and after the test.

Figure 85: Test 15 Infinite Composites Small Tank Pre-Test (L) and Post-Test (C) (R)

Upon post-test evaluation, the head boss fragmented into five fragments propelled up and outwards, while the remaining tank and valve components were driven down into the sand. The top metallic portion of the boss was indeed recovered, but the composite portions were not. The plug that was installed in the top boss was also separated and seen as a frag in the high-speed video. Though it was not recovered, the pre-test knowledge of the plug allowed the team to assign a realistic mass for it. See Table 24 below for a chart of the test's frag velocity summary.

Table 24: Test 15 Fragment Velocity Summary

Test 15					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*4492 psi*	
Location:	*At Top Boss*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Boss, Metallic*	*104*	*Ø2.5x1.5*	*208.5*	*5.6*
2	*Top Boss Plug*	*44*		*377.8*	*8.6*
3	*Top Boss, Composite*			*869.3*	*24.5*
4	*Top Boss, Composite*			*688.1*	*15.3*
5	*Top Boss, Composite*			*487.7*	*19.9*

See Figure 86 below for freeze-frame images of the high-speed video.

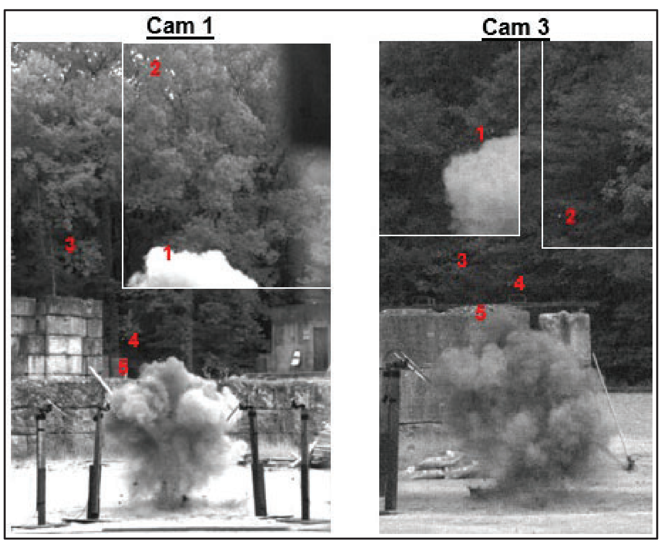


Figure 86: Test 15 High-Speed Frag Footage

All of the BOP sensors and pencil gauges recorded successful pressure curves for this test. The raw pencil gauge pressure curves can be seen in Appendix C. Based on the length and strength of the flex linear, the net explosive weight of the energetics was 7.2 grams of RDX and the COPV tank contained 1.9L of gaseous nitrogen at 4,492 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. See Figure 87 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	5.15	~ 5 ft
H1	6.16	
H2	8.56	
I2	3.81	~ 7.5 ft
J1	3.77	
J2	5.00	
I3	3.63	~ 10 ft
K1	3.59	
K2	3.55	

Pencil ID	Peak P (psi)	Distance from Center
11829	4.71	5 ft
11811	4.19	
11809	2.28	7.5 ft
9859	1.93	
7418	1.93	10 ft
11813	1.77	

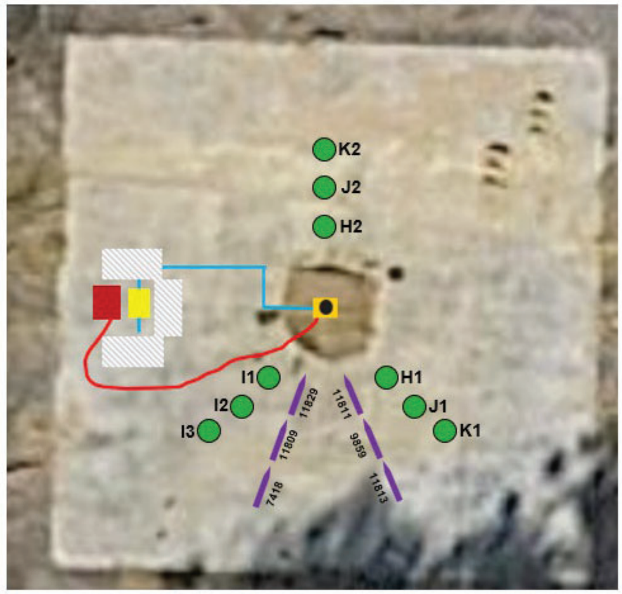


Figure 87: Test 15 Blast Overpressure Results

8.3 Test 16 – Flex Linear Rupture @ Midline

Test 16 was an energetic rupture test on the Infinite Composites Small COPV, with flex linear shaped charge being the energetic rupture mechanism placed around the midline of the tank. Liner geometry is consistent throughout the cylindrical portion, so rupture at the midline was chosen to yield a large, recoverable piece. The tank was oriented such that the pressure manifold was towards the ground and the head boss was pointed towards the sky.

The fill process for test 16 began on 8/19/24 at 1046 CDT and took approximately 42 minutes to fill to the desired pressure. The goal pressure for the tank was 4,500 psi and the final reading before the pressure was sealed was 4,488 psi. The head boss temperature ended at 105°F.

The energetic rupture test event occurred at 1142 CDT under partly cloudy skies, 81°F, 61% relative humidity, and a wind-speed of 0.8 mph SSE. The flex linear was successful in cutting open the tank, as desired. See Figure 88 below for images of the tank before and after the test.

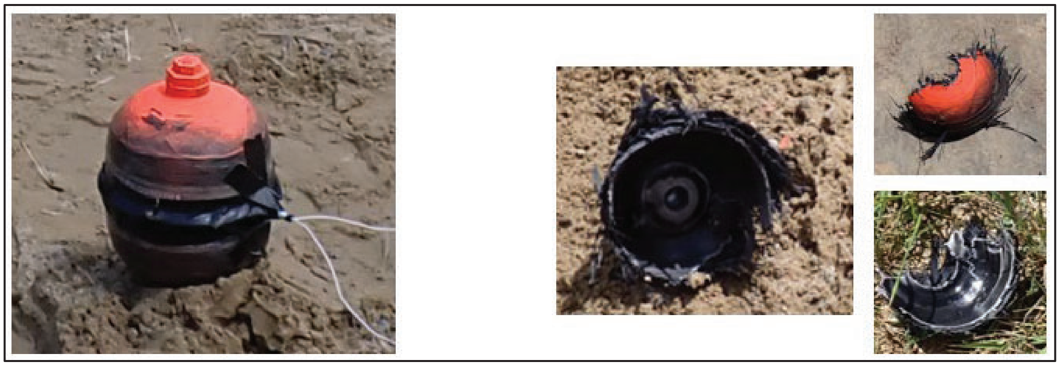


Figure 88: Test 16 Infinite Composites Small Tank Pre-Test (L) and Post-Test (R)

Upon post-test evaluation, the head boss fragmented into four fragments propelled up and outwards, while the remaining tank and valve components were driven down into the sand. The top metallic portion of the boss was not recovered but the size and mass were assumed to be the same as previous test. Various composite portions were recovered but could not be positively identified to any of the frags seen in the high-speed videos. See Table 25 below for a chart of the test's frag velocity summary.

Table 25: Test 16 Fragment Velocity Summary

Test 16					
Cutter:	*125 gr/ft LSC*		**Pressure:**	*4488 psi*	
Location:	*At Cylinder Midline*				
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Boss, Metallic*	*104*	*Ø2.5x1.5*	*335*	*5.4*
2	*Composite Dome Half*			*864.5*	*13.6*
3	*Composite Dome Half*			*866.9*	*12*
4	*Fibrous Material*			*812.6*	*20*

See Figure 89 below for freeze-frame images of the high-speed video.

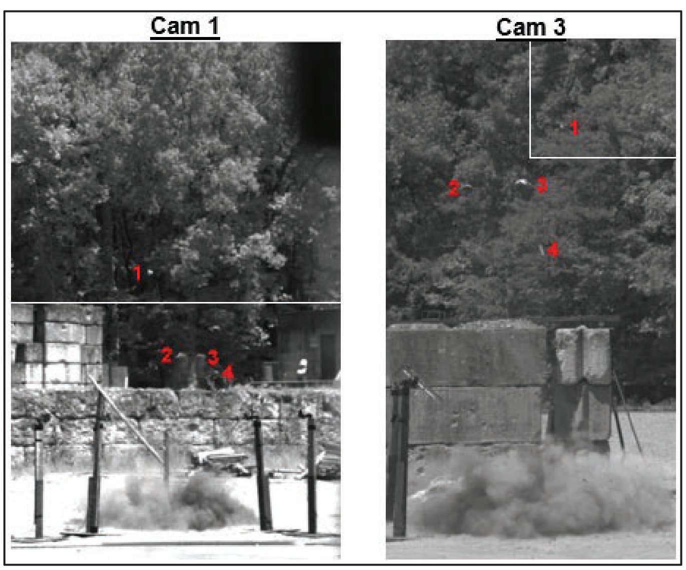


Figure 89: Test 16 High-Speed Frag Footage

Due to the BOP sensors being configured improperly, only one of them recorded a pressure curve of this test event. However, all (6) of the pencil gauges successfully recorded waveforms. Based on the length and strength of the flex linear, the net explosive weight of the energetics was 11.2 grams of RDX and the COPV tank contained 1.9L of gaseous nitrogen at 4,488 psi. Each of these items (energetics and stored inert gas) contributed to the resulting blast overpressure readings. The pressure curves from the pencil gauges can be found in Appendix C. See Figure 90 below for a list of the resulting peak pressures and a schematic map of where each sensor was located, relative to the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	~ 5 ft
H1	N/A	
H2	N/A	
I2	N/A	~ 7.5 ft
J1	N/A	
J2	N/A	
I3	N/A	~ 10 ft
K1	N/A	
K2	4.82	

Pencil ID	Peak P (psi)	Distance from Center
11829	4.3	5 ft
11811	2.93	
11809	2.63	7.5 ft
9859	2.25	
7418	2.18	10 ft
11813	1.96	

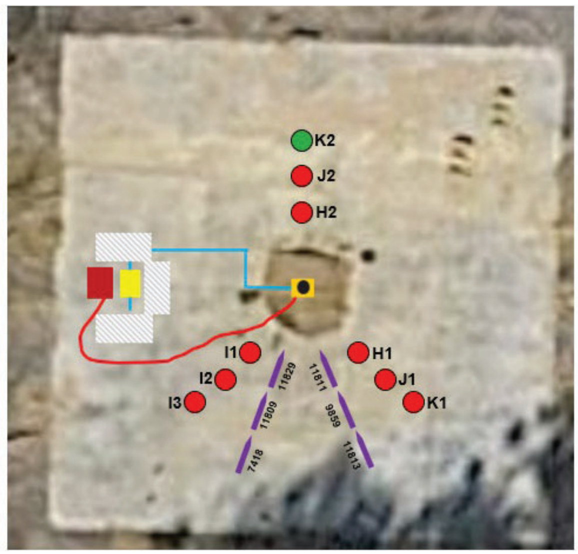


Figure 90: Test 16 Blast Overpressure Results

9.0 Cimarron Type V Test Results

The next set of test results that will be discussed are from the Cimarron COPV tests. Only (2) of these tests were conducted and they were both fired in pressurize until burst configurations. See Table 26 below for a breakdown of the test matrix executed on this style of COPV.

Table 26: Cimarron Type V COPV Test Matrix

Test #	Date/Time	Proof Pressure	Design Burst Pressure	Test Result
18	8/21/24 @ 1052	750 psi	1000 psi	Developed Leak @ 1152psi
21	8/21/24 @ 1514			Developed Leak @ 1433psi

Test 18 failed to violently burst due to minor cracks that formed during pressurization that prevented the tank from fragmenting apart. For this test, the pressurization method was meant to be a straight pressurize-until-burst type, which meant that the tank pressure was to be continually increased until it burst apart. When the team began the pressurization process, the needle valve (used for flow-rate control) was opened too much and yielded a sharp spike in pressure up to about 750psi very quickly. The team quickly responded by choking the pressure flow and bringing it back to a more controlled pressure-rise rate. Once the tank reached about 1,150psi, the pressurization curve flattened out, meaning that, even though more pressure was being added to the system, it was simultaneously leaking out at the same rate. Therefore, the team stopped the filling process and, once it had dropped to a safe level, went out and physically inspected the tank for visual cracks and audible leaking, both of which were confirmed. It is not believed amongst the NASA and AvMC teams that the quick spike of pressure at the beginning of the fill process was the cause of the leaking cracks.

Test 21 also failed to violently burst due to minor cracks formed during pressurization. For this test, the pressurization method was to be a stepped-increase-until-burst type, which meant that the tank pressure was to be increased from 0 to 500psi, then decreased back to 0, then increased to 750psi, then decreased back to 0, then finally increased until burst. The team was successful in attaining the desired peak pressures (500, 750, and 1000+ psi) but failed to bring the tank back down to 0 psi between peaks, instead only dropping to about 300psi. The reason why 0 could not be obtained was due to how long and small in diameter the fill plumbing system was. The increasing pressure events were easy to dial in at a desired rise rate because the pressure on the supply side was considerably higher than the COPV tank side, so it could overcome the pressure losses over long distances. However, as the team was venting the tank down, the high pressure inside the tank was only slightly higher than the ambient air that it was venting to, which caused a pressure choke that made the venting process slow down as it approached 0psi. It could have taken an hour or two to allow the tank to fully vent to 0psi. Therefore, the NASA and AvMC team agreed that letting it vent down to 300 psi was acceptable so that the tests could continue at an attainable pace. Ultimately, after the pressure steps, once the pressure reached about 1,430 psi, stress cracks formed in the tank and caused the same type of leaking seen in the previous test that prevented the tank from bursting as desired.

9.1 Test 18 – Pressurize Until Burst

Test 18 was a pressurize-until-burst style test, therefore no energetics were utilized in the event.

The fill process was started on 8/21/24 at 1034 CDT and took 5 minutes to build pressure to a high enough level that it could no longer increase further, forming stress cracks and leaks in the composite that prevented a violent burst event. At the time of fill (approximately 1039 CDT), the weather conditions were fair skies, 77°F, 56% relative humidity, and a wind speed of 0.3 mph S. The maximum pressure recorded inside the tank at the time that the leaks formed and could no longer contain the pressure was 1,152 psi. See Figure 91 below for the pressurization curve, as recorded by the AvMC DAQ system.

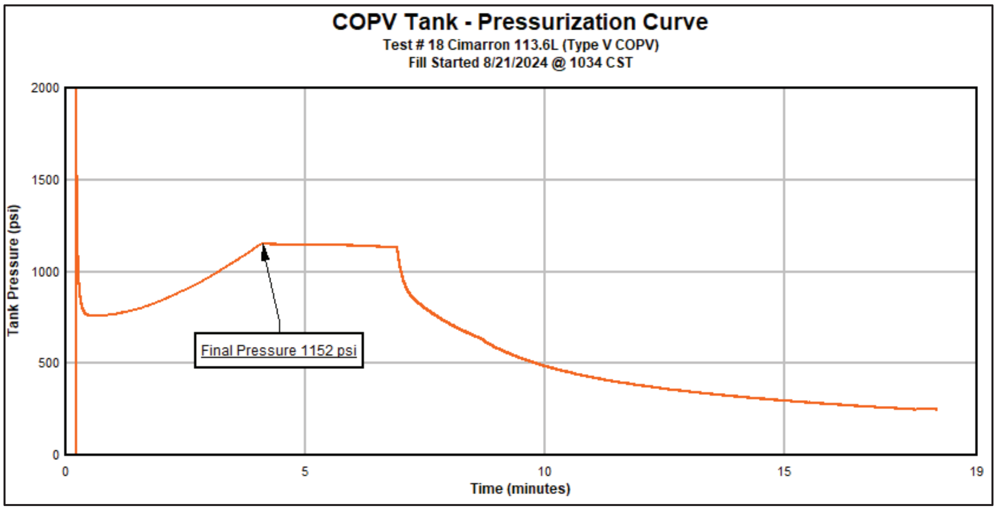


Figure 91: Test 18 Pressurization-Until-Burst Fill Curve

See below in Figure 92 for images of the tank before the test and zoomed-in images of some of the stress cracks formed during test.

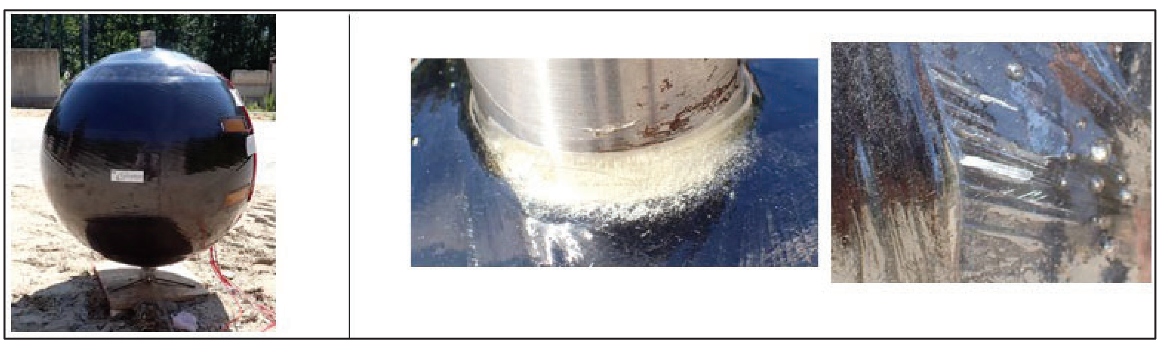


Figure 92: Test 18 Cimarron Tank Pre-Test (L) and Post-Test Stress Cracks (R)

9.2 Test 21 – Stepped Until Burst

Test 21 was a stepped-pressurize-until-burst style test, therefore no energetics were utilized in the event. As described previously, the goal was to incrementally fill and purge the tank to higher and higher pressures, starting at 500psi, then to 750psi, and finally until burst event occurs.

The fill process was started on 8/21/24 at 1420 CDT and took 46 minutes to run through the stepped increase process and then build pressure to a high enough level that it could no longer increase further, forming stress cracks and leaks in the composite that prevented a violent burst event. At the time of leaks forming (approximately 1507 CDT), the weather conditions were fair skies, 80.9°F, 43% relative humidity, and a wind speed of 0.45 mph E. The maximum pressure recorded inside the tank at the time that the leaks formed and could no longer contain the pressure was 1,433 psi. See Figure 93 below for the pressurization curve, as recorded by the AvMC DAQ system.

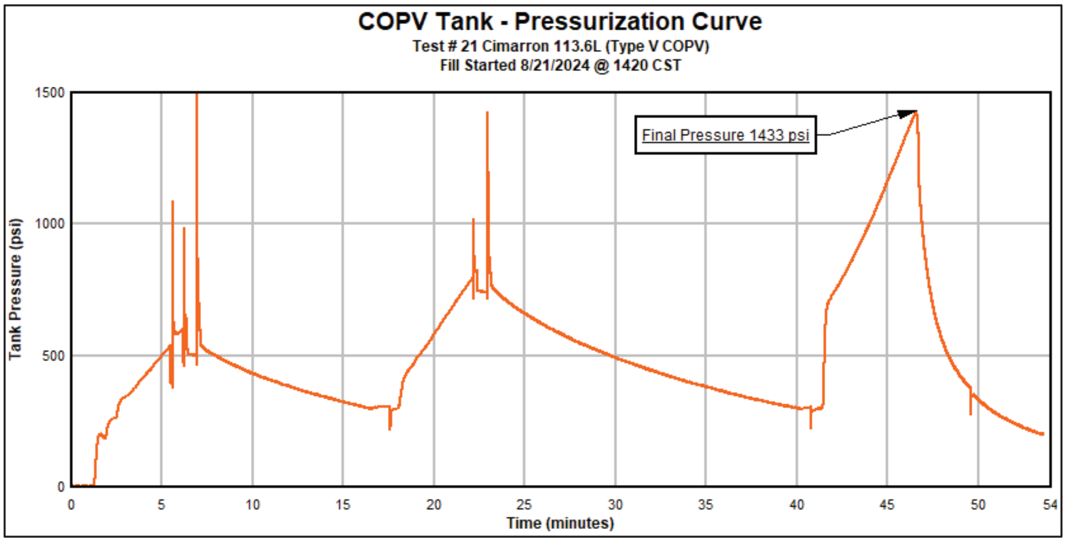


Figure 93: Test 21 Stepped-Pressurization-Until-Burst Fill Curve

See below in Figure 94 for images of the tank before the test and zoomed-in image of some of the stress cracks formed during test.

Figure 94: Test 21 Cimarron Tank Pre-Test (L) and Post-Test Stress Cracks (R)

10.0 HyPerComp Type V Test Results

The next set of test results that will be discussed are from the HyPerComp COPV tests. Only (2) of these tests were conducted and they were both fired in pressurize until burst configurations. See Table 27 below for a breakdown of the test matrix executed on this style of COPV.

Table 27: HyPerComp Type V COPV Test Matrix

Test #	Date/Time	Proof Pressure	Design Burst Pressure	Test Result
19	8/21/24 @ 1125	75 psi	100 psi	Developed Leak @ 745psi
22	8/22/24 @ 1027			Developed Leak @ 376psi

Test 19 failed to violently burst due to minor cracks that formed during pressurization that prevented the tank from fragmenting apart. Pressurization was meant to be the pressurize-until-burst method, which meant that the tank pressure was to be continually increased until it burst apart. Once the tank got to about 745 psi, the pressurization curve flattened out, meaning that, even though more pressure was being added to the system, it was simultaneously leaking out at the same rate. Therefore, the team stopped the filling process and, once it had dropped to a safe level, physically went out and inspected the tank for visual cracks and audible leaking, both of which were confirmed.

Test 22 also failed to burst due to cracks formed during pressurization. For this test, the pressurization method was to be a stepped-increase-until-burst type, which meant that the tank pressure was to be increased from 0 to 500psi, then decreased back to 0, then increased to 750psi, then decreased back to 0, then finally increased until burst. When the first pressurization rise was started, the peak 500psi was not even reached before the tank formed cracks and started leaking. The peak pressure that was reached was around 376 psi. Similarly, the team confirmed visual cracks and audible pressure leaking.

10.1 Test 19 – Pressurize Until Burst

Test 19 was a pressurize-until-burst style test, therefore no energetics were utilized in the event.

The fill process was started on 8/21/24 at 1121 CDT and took only 1 minute to build pressure to a high enough level that it could no longer increase further, forming stress cracks and leaks in the composite that prevented a violent burst event. At the time of fill (approximately 1123 CDT), the weather conditions were fair skies, 77.5°F, 50% relative humidity, and a wind speed of 1 mph W. The maximum pressure recorded inside the tank at the time that the leaks formed and could no longer contain the pressure was 745 psi. See Figure 95 below for the pressurization curve, as recorded by the AvMC DAQ system.

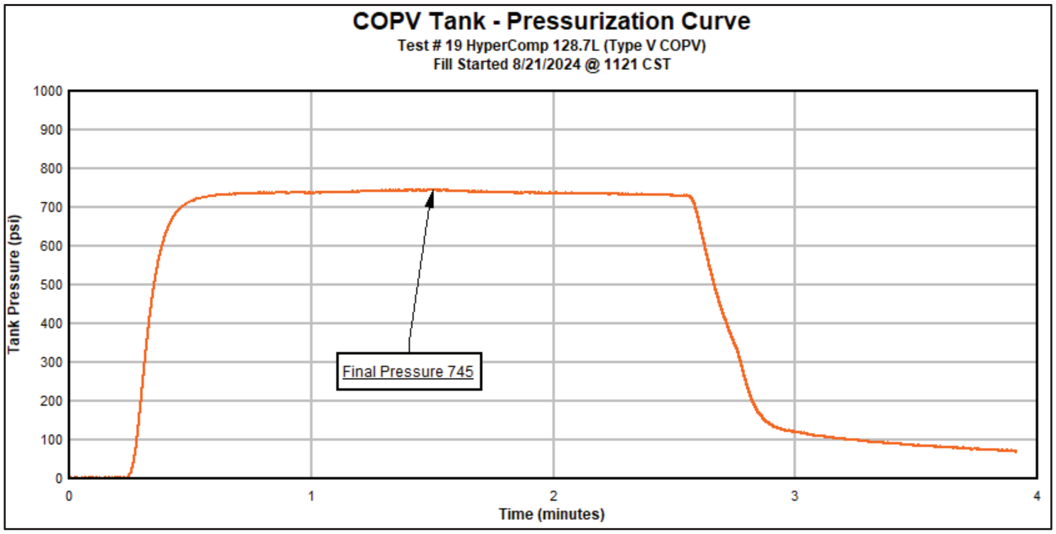


Figure 95: Test 19 Pressurization-Until-Burst Fill Curve

See below in Figure 96 for images of the tank before the test and zoomed-in images of some of the stress cracks formed during test.

Figure 96: Test 19 HyPerComp Tank Pre-Test (L) and Post-Test Stress Cracks (R)

10.2 Test 22 – Stepped Until Burst

Test 22 was a stepped-pressurize-until-burst style test, therefore no energetics were utilized in the event. As described previously, the goal was to incrementally fill and purge the tank to higher and higher pressures, starting at 500psi, then to 750psi, and finally until burst event occurs.

The fill process was started on 8/22/24 at 1017 CDT and took 4 minutes to run through the stepped increase process and then build pressure to a high enough level that it could no longer increase further, forming stress cracks and leaks in the composite that prevented a violent burst event. At the time of leaks forming (approximately 1021 CDT), the weather conditions were fair skies, 80.7°F, 59% relative humidity, and a wind speed of 0.6 mph NE. The maximum pressure recorded inside the tank at the time that the leaks formed and could no longer contain the pressure was 376 psi. See Figure 97 below for the pressurization curve, as recorded by the AvMC DAQ system.

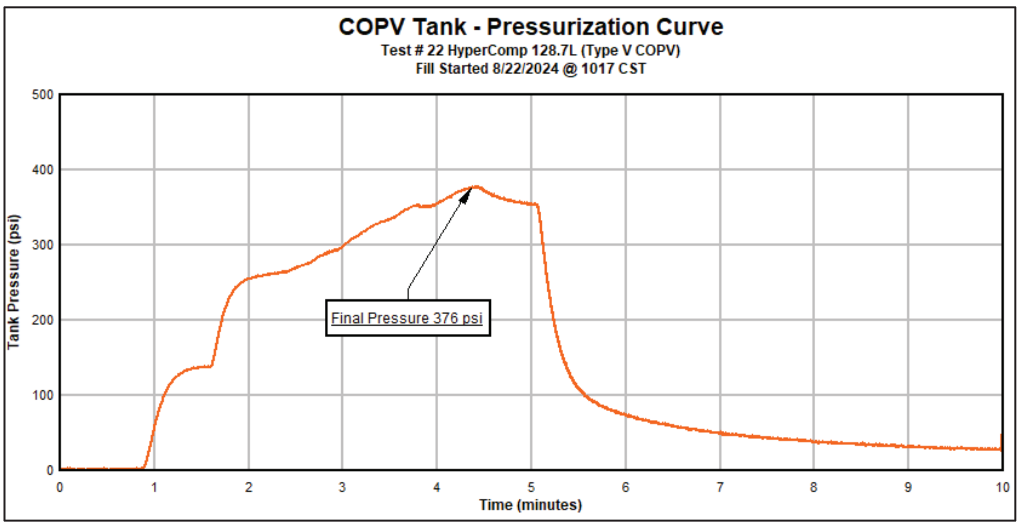


Figure 97: Test 22 Stepped-Pressurization-Until-Burst Fill Curve

See below in Figure 98 for images of the tank before the test and zoomed-in image of some of the stress cracks formed during test.

Figure 98: Test 22 HyPerComp Tank Pre-Test (L) and Post-Test Stress Cracks (C)(R)

11.0 Infinite Composites Large Type IV Test Results

The final set of test results that will be discussed are from the Infinite Composites Large COPV tests. Only (2) of these tests were conducted and they were both fired in pressurize-until-burst configurations. See Table 28 below for a breakdown of the test matrix executed on this style of COPV.

Table 28: Infinite Composites Large COPV Test Matrix

Test #	Date/Time	Proof Pressure	Design Burst Pressure	Recorded Burst Pressure
20	8/21/24 @ 1159	750 psi	1000 psi	2077 psi
23	8/21/24 @ 1332			2209 psi

Test 20 was a successful burst event. The pressurization method was to be a pressurize until burst, which meant that the tank pressure was to be continually increased until it burst apart. When the team began the pressurization process, the needle valve (used for flow-rate control) was opened too much and yielded a sharp spike in pressure very quickly. The team responded quickly by choking it down to get it back into a more controlled pressure-rise rate. The rise rate was held relatively consistent until the tank burst, as intended. The peak pressure recorded at the time of tank burst was about 2,077 psi. As seen by the high-speed video, some slight delamination of the carbon fibers on the outside of the tank was seen in the seconds prior to burst.

Test 23 was also a successful burst event. The pressurization method was to be a stepped-increase-until-burst type, which meant that the tank pressure was to be increased from 0 to 500psi, then decreased back to 0, then increased to 750psi, then decreased back to 0, then finally increased until burst. The team was successful in attaining the desired peak pressures (500, 750, and 1000+ psi) but failed to bring the tank back down to 0 psi in between, instead only getting to about 300 psi. The reason why 0 could not be obtained was due to how long and small in diameter the fill plumbing system was. The increasing pressure events were easy to dial in at a desired rise rate because the pressure on the supply side was considerably higher than the COPV tank side, so it could overcome the pressure losses over long distances. However, as the team was venting the tank down, the high pressure inside the tank was only slightly higher than the ambient air that it was venting to, which caused a pressure choke that made the venting process slow down as it approached 0psi. It could have taken an hour or two to allow the tank to fully vent to 0psi. Therefore, the NASA and AvMC team agreed that letting it vent down to 300 psi was acceptable so that the tests could continue at an attainable pace. Once all of the stepped pressure levels were reached, the pressure was opened up to continue to fill until burst, which occurred around 2,209 psi.

11.1 Test 20 – Pressurize Until Burst

Test 20 was a pressurize-until-burst style test, therefore no energetics were utilized in the event.

The fill process was started on 8/21/24 at 1150 CDT and took 9 minutes to build pressure and ultimately violently burst. At the time of burst (approximately 1159 CDT), the weather conditions were fair skies, 80°F, 48% relative humidity, and a wind speed of 1.4 mph NNW. The maximum pressure recorded inside the tank at the time of burst was 2,077 psi. See Figure 99 below for the pressurization curve, as recorded by the AvMC DAQ system.

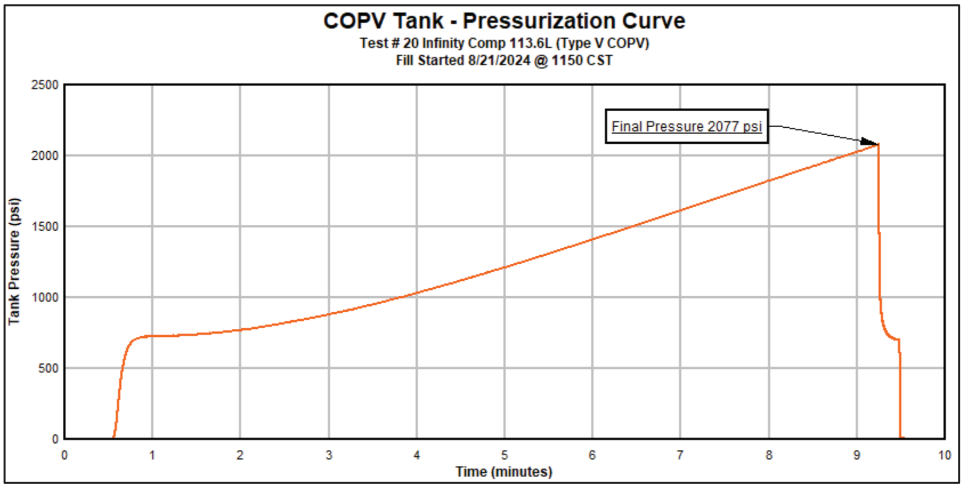


Figure 99: Test 20 Pressurize-Until-Burst Curve

See below in Figure 100 for images of the tank before and after test.

Figure 100: Test 20 Infinite Composites Large Tank Pre-Test (L) and Post-Test (R)

The burst event split the tank into a combination of large and small fragments. The head boss, plastic liner and larger composite pieces were positively identified in the video and all but one were recovered post-test. However, many other smaller fragments of liner and composites were thrown in all directions and were significantly harder to analyze or recover. Table 29 below shows a chart of the resulting frag velocity summary.

Table 29: Test 20 Fragment Velocity Summary

Test 20					
Test Type: *Rise-to-Burst*		**Burst Pressure:**		*2077 psi*	
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Boss, Metallic*	*1150*	*Ø5.8x2*	*198.5*	*2.8*
2	*Fibrous Panel*	*1028*	*27x11x.25*	*1013.9*	*71.8*
3	*Fibrous Panel*	*338*	*20x8x.25*	*1125.8*	*89.7*
4	*Fibrous Panel*	*346*	*17x11x25*	*1016.4*	*66.1*
5	*Fibrous Panel*			*1050*	*63.6*

See below in Figure 101 for freeze-frame images of the high-speed video, as well as a photograph of the recovered fragments.

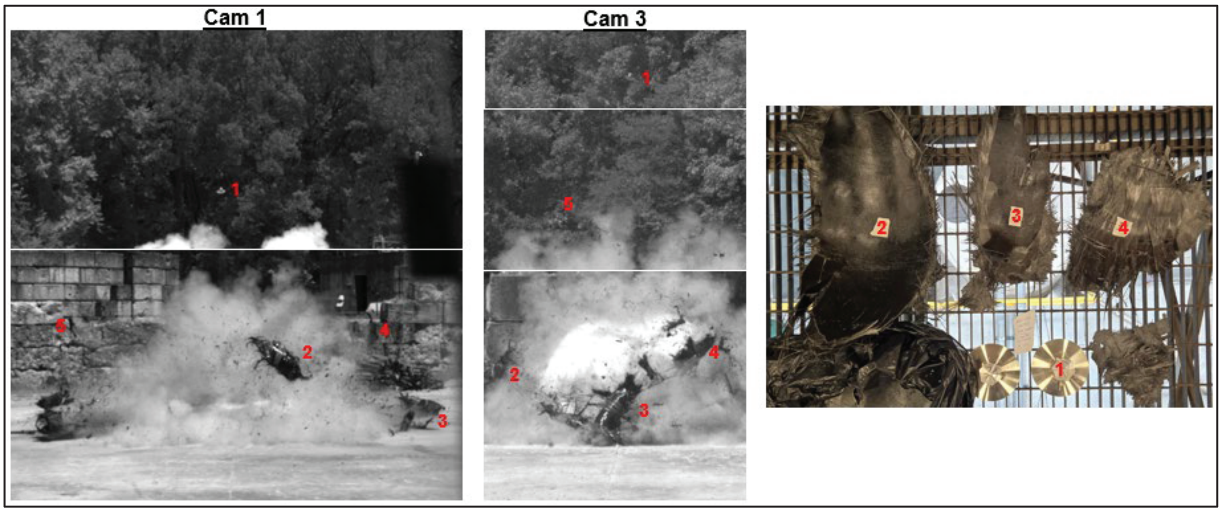


Figure 101: Test 20 High-Speed Footage (L) (C) and Recovered Frags (R)

As the burst event was to rupture at an unknown time, no blast overpressure sensors were placed in the test area for test 20.

11.2 Test 23 – Stepped Until Burst

Test 23 was a stepped-pressurize-until-burst style test, therefore no energetics were utilized in the event. As described previously, the goal was to incrementally fill and purge the tank to higher and higher pressures, starting at 500psi, then to 750psi, and finally until burst event occurs.

The fill process was started on 8/21/24 at 1244 CDT and took 48 minutes to build pressure and ultimately violently burst. At the time of burst (approximately 1332 CDT), the weather conditions were fair skies, 80.9°F, 51% relative humidity, and a wind speed of 0.5 mph SSW. The maximum pressure recorded inside the tank at the time of burst was 2,209 psi. See Figure 102 below for the pressurization curve, as recorded by the AvMC DAQ system.

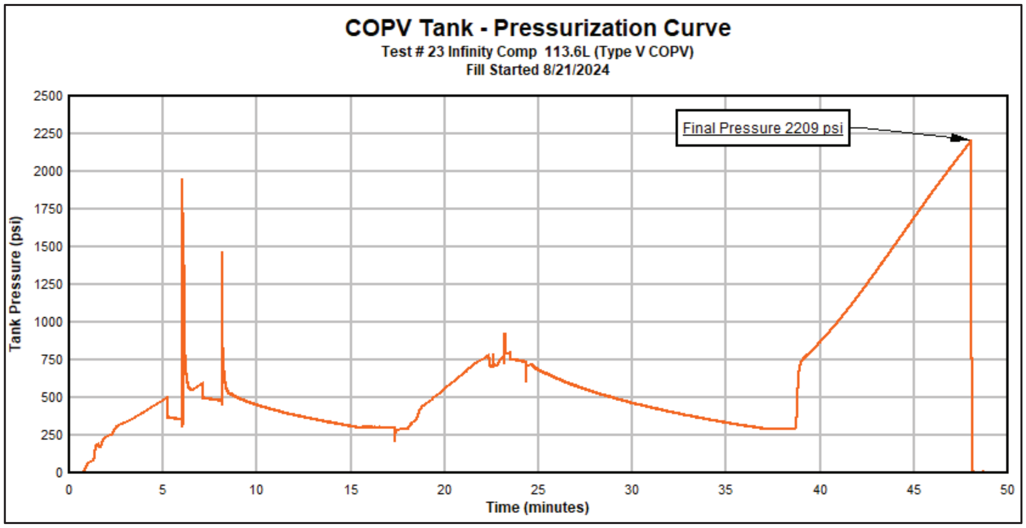


Figure 102: Test 23 Stepped-Increase-Until-Burst Curve

See below in Figure 103 for images of the tank before and after test.

Figure 103: Test 23 Infinite Composites Large Tank Pre-Test (L) and Post-Test (R)

The burst event split the tank into a combination of large and small fragments. The head boss, plastic liner and larger composite pieces were positively identified in the video and all but one were recovered post-test. The metallic top-boss was not recovered, but mass and size estimates were assumed to be the same as recovered in the previous test and were supplemented accordingly. However, many other smaller fragments of liner and composites were thrown in all directions and were significantly harder to analyze or recover. Table 30 below shows a chart of the resulting frag velocity summary.

Table 30: Test 23 Fragment Velocity Summary

Test 23					
Test Type: *Stepped Rise-to-Burst*		**Burst Pressure:**		*2209 psi*	
Frag #	**Description**	**Mass (g)**	**Size (in)**	**Speed (ft/s)**	**Polar Angle (°)**
1	*Top Boss, Metallic*	*1150*	*Ø5.8x2*	*206.9*	*8.9*
2	*Fibrous Panel*	*216*	*15x8.5x.25*	*1085.9*	*61.5*
3	*Fibrous Panel*	*196*	*20x6.5x.25*	*1119.4*	*90*
4	*Fibrous Panel*	*326*	*14x14x.25*	*932.4*	*77.7*
5	*Fibrous Panel*	*174*	*19x6.5x.25*	*697.6*	*69.1*

See below in Figure 104 for freeze-frame images of the high-speed video, as well as a photograph of the recovered fragments.

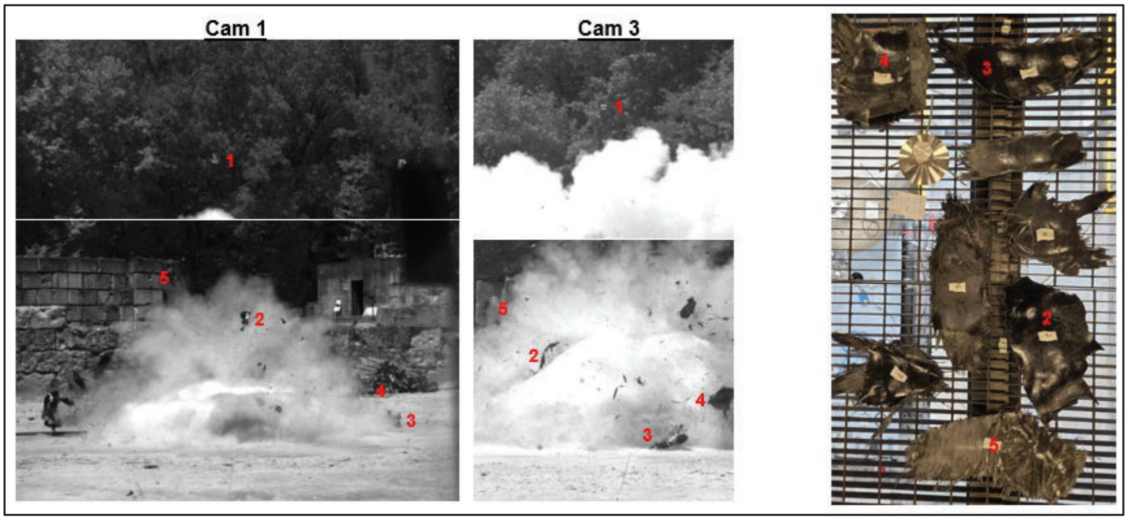


Figure 104: Test 23 High-Speed Frag Footage (L) (C) and Recovered Frags (R)

As the burst event was to rupture at an unknown time, no blast overpressure sensors were placed in the test area for test 23.

12.0 Standalone Energetics Tests

During the energetic rupture tests, blast overpressure was measured but it was unclear how much the inert gas expansion was adding to the resulting blast overpressure measurements. Therefore, a small sub-set of tests was devised to isolate bare energetics and compare the resulting blast overpressure curves to the shots that had COPVs rupturing. The assumption is that the peak overpressure for the tank rupture tests will be higher than just the bare explosives because of the added pressure release of the nitrogen gas expansion.

Three different standalone energetics tests were conducted. Test A was a 4" halo of flex linear, which was comparable to the energetics on tests 7-11 and 14-16. Test B was a 10.5" halo of flex linear, which was comparable to the energetics used on tests 12 and 13. Finally, test C was a 6.5" halo of det cord, comparable to the energetics used in tests 1-5.

12.1 Test A – 4" Halo of Flex Linear

Test A was a standalone energetics test used to compare the blast overpressure curves from the energetic rupture tests. The full suite of (9) BOP sensors and (6) pencil gauges were present for the test. The energetic configuration was a 4" diameter halo of 125gr/ft flex linear shaped charge, which is similar in size and configuration to that used in tests 7-11 and 14-16. The halo of energetics was placed at ground level and initiated on 8/19/24 at 1210 CDT.

The estimated energetics level of this charge was 8.5g of RDX explosive. Due to the improper configuration of the BOP sensors, none of the (9) BOP sensors recorded pressure curves. However, all (6) pencil gauges were successful in recording the blast overpressure event. See Figure 105 below for a list of peak overpressures from this test, as well as a schematic of where each sensor was located around the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	~ 5 ft
H1	N/A	
H2	N/A	
I2	N/A	~ 7.5 ft
J1	N/A	
J2	N/A	
I3	N/A	~ 10 ft
K1	N/A	
K2	N/A	

Pencil ID	Peak P (psi)	Distance from Center
11829	3.73	5 ft
11811	4.27	
11809	1.56	7.5 ft
9859	2.33	
7418	1.19	10 ft
11813	1.57	

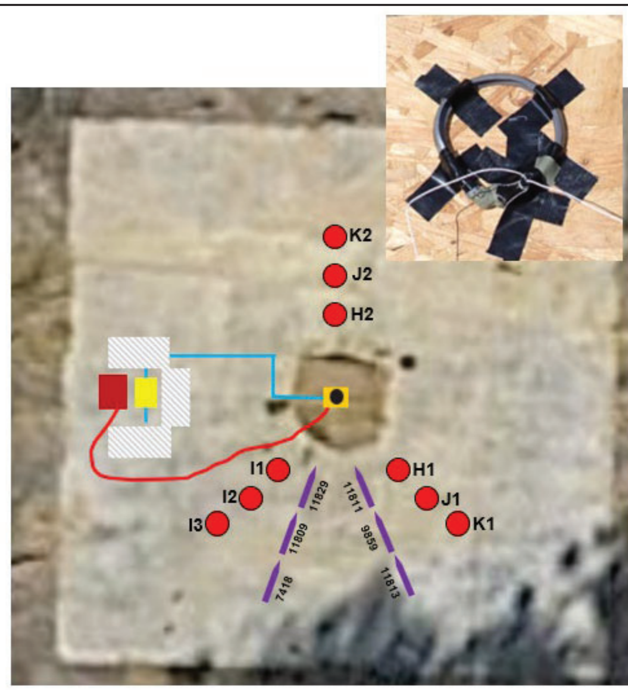


Figure 105: Test A Blast Overpressure Results

The pencil gauge curves can be viewed in Appendix C. The comparison of this test to the COPV rupture test results can be found in the pressure data summary section near the end of this document.

12.2 Test B – 10.5" Halo of Flex Linear

Test B was a standalone energetics test used to compare the blast overpressure curves from the energetic rupture tests. The full suite of (9) BOP sensors and (6) pencil gauges were present for the test. The energetic configuration was a 10.5" diameter halo of 125gr/ft flex linear shaped charge, which is similar in size and configuration to that used in tests 12 and 13. The halo of energetics was placed on a makeshift table approximately 2ft above the ground and initiated on 8/19/24 at 1237 CDT.

The estimated energetics level of this charge was 22.7g of RDX explosive. All (9) BOP sensors and all (6) pencil gauges were successful in recording the blast overpressure event. See Figure 106 below for a list of peak overpressures from this test, as well as a schematic of where each sensor was located around the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	7.14	~ 5 ft
H1	5.37	
H2	5.87	
I2	3.48	~ 7.5 ft
J1	3.26	
J2	3.73	
I3	2.97	~ 10 ft
K1	2.57	
K2	3.12	

Pencil ID	Peak P (psi)	Distance from Center
11829	4.41	5 ft
11811	4.21	
11809	1.85	7.5 ft
9859	1.97	
7418	1.50	10 ft
11813	1.36	

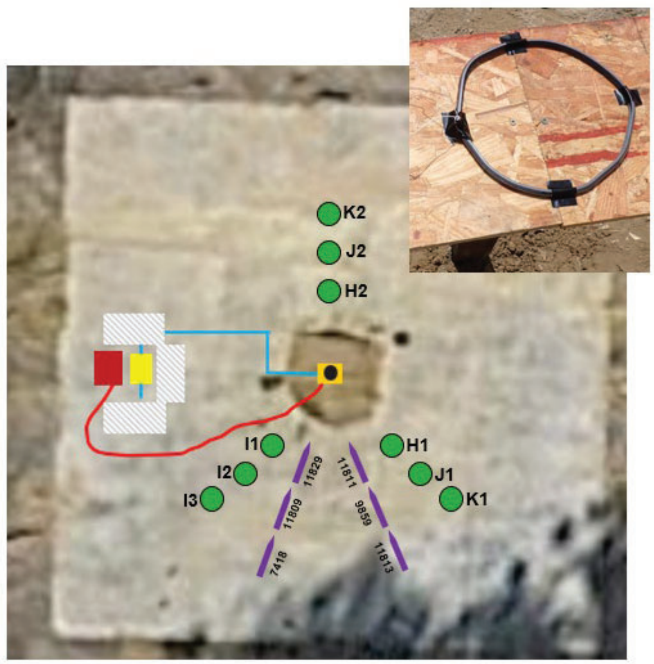


Figure 106: Test B Blast Overpressure Results

The pencil gauge curves can be viewed in Appendix C. The comparison of this test to the COPV rupture test results can be found in the pressure data summary section near the end of this document.

12.3 Test C – 6.5" Halo of Det Cord

Test C was a standalone energetics test used to compare the blast overpressure curves from the energetic rupture tests. The full suite of (9) BOP sensors and (6) pencil gauges were present for the test. The energetic configuration was a 6.5" diameter halo of 50gr/ft detonating cord, which is similar in size and configuration to that used in tests 1-5. The halo of energetics was placed on a makeshift table 2 ft above ground level and initiated on 8/19/24 at 1317 CDT.

The estimated energetics level of this charge was 6.9g of PETN explosive. Due to the improper configuration of the BOP sensors, none of the (9) BOP sensors recorded pressure curves. However, all (6) pencil gauges were successful in recording the blast overpressure event. See Figure 107 below for a list of peak overpressures from this test, as well as a schematic of where each sensor was located around the test area.

BOP ID	Peak P (psi)	Distance from Center
I1	N/A	~ 5 ft
H1	N/A	
H2	N/A	
I2	N/A	~ 7.5 ft
J1	N/A	
J2	N/A	
I3	N/A	~ 10 ft
K1	N/A	
K2	N/A	

Pencil ID	Peak P (psi)	Distance from Center
11829	3.04	5 ft
11811	3.19	
11809	1.24	7.5 ft
9859	1.73	
7418	0.95	10 ft
11813	0.92	

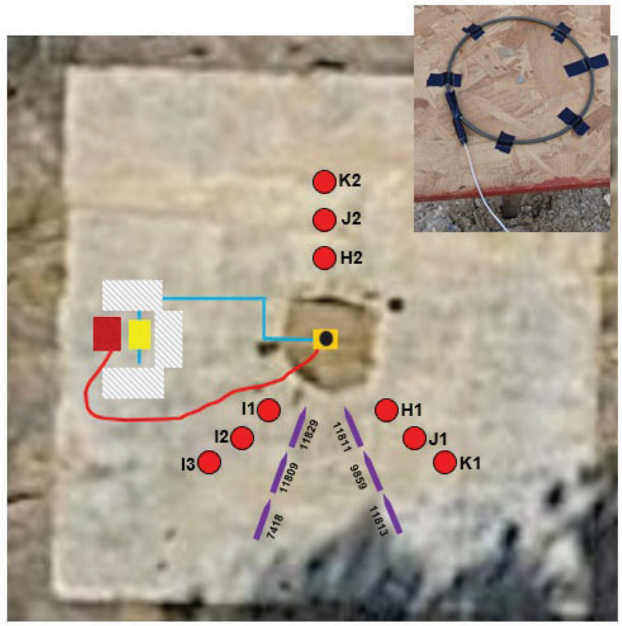


Figure 107: Test C Blast Overpressure Results

The pencil gauge curves can be viewed in Appendix C. The comparison of this test to the COPV rupture test results can be found in the pressure data summary section near the end of this document.

13.0 Full Test Series Data Summary

Due to the wide variety of variables present in this test series, it's difficult to compare all of the results together. Therefore, for the data summary section, tests with similarities will be grouped together to compare results.

13.1 Velocity Data Summary

The first data set that will be summarized is the fragment velocity data. Since each of the different COPV tanks were quite different in composition, the summary will group each of the COPV tanks together for comparison of resulting frag velocities.

See Figure 108 below for the full summary of fragment velocities for the General Dynamics Type III COPV tests.

Test 1

Cutter: *50 gr/ft Det Cord* — Pressure: *4324 psi*
Location: *At Dome/Cylinder Taper*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Boss	1080	Ø6.5x7	560	2.1

Test 2

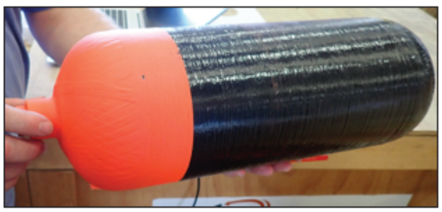
Cutter: *50 gr/ft Det Cord* — Pressure: *4285 psi*
Location: *At Dome/Cylinder Transition*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Boss Frag	56	3.5x2x.25	650.2	5.8
2	Top Boss Frag	32	3.75x3.25x13	551.9	6.9
3	Top Boss	720	Ø7x3.75	613.9	8.6

Test 3

Cutter: *50 gr/ft Det Cord* — Pressure: *4309 psi*
Location: *At Dome/Cylinder Transition*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Boss Piece			529.5	6.4
2	Boss Piece			603.5	5.7
3	Boss Piece			618.9	7.5
4	Boss Piece			593.2	3.1



Test 4

Cutter: *50 gr/ft Det Cord* — Pressure: *4315 psi*
Location: *At Dome/Cylinder Transition*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Boss Piece	78	5.5x3x.25	397.4	37
2	Boss Piece	90	5x2.75x.25	623	39.1
3	Boss Piece	62	5.25x4x.13	585.6	31.5
4	Remnant Head Boss	814	Ø4x3.75	428.4	27.2

Test 6

Cutter: *73 gram Conical Shaped Charge* — Pressure: *4315 psi*
Location: *At Boss*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Whole Tank	3122	Ø6.5x22.2	69.6	66.7

Test 7

Cutter: *125 gr/ft LSC* — Pressure: *4325 psi*
Location: *At Boss*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Bottom Boss Frag	152	6.5x4x.25	942.3	103.7
7	Head Boss	814	Ø3.5x3.5	486.6	33.4
8	Bottom Boss Frag			955.2	113.1
9	Bottom Boss Frag			865	112.6

Test 17

Cutter: *50 gr/ft Det Cord* — Pressure: *4335 psi*
Location: *At Dome/Cylinder Taper*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Bottom Tank w/ Fitting	2060	Ø6.5x16	716.2	180
2	Top Boss	988	Ø6.5x5.25	609.3	0.7
3	Broken Valve	430	2.5x2.25x1	488.6	156.6
4	Valve Knob	46	Ø1.6x1.5	451.1	158.7

Yellow denotes assumed mass   Peach denotes frag not recovered

Figure 108: General Dynamics Type III COPV Fragment Velocity Summary

See Figure 109 below for the full summary of fragment velocities for the Xperion Type IV COPV tests.

Test 8

Cutter: *125 gr/ft LSC* — Pressure: *2933 psi*
Location: *At Top Boss*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Fibrous Panel			1058.3	92.8
2	Fibrous Panel			1069.7	14.3
3	Head Boss			800.1	15.9

Test 9

Cutter: *125 gr/ft LSC* — Pressure: *2920 psi*
Location: *At Bottom Boss*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Valve Knob	46	Ø1.5x1.25	678.9	20.2
2	Broken Valve	430	3.5x2.25x1	245.9	17.6
3	Fibrous Panel			604.5	101.3
4	Head Boss			445	4.3

Test 10

Cutter: *125 gr/ft LSC* — Pressure: *2891 psi*
Location: *At Bottom Boss*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Broken Valve	484	2.5x2.25x1	511.3	5.7
2	Fiberglass Boss Ring	40	Ø5x.25	500	12.6
3	Fibrous Panel			871.6	62.3
4	Bottom Boss w/ Fitting			480.8	13.3

Test 11

Cutter: *125 gr/ft LSC* — Pressure: *2918 psi*
Location: *At Bottom Boss*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Fibrous Panel			427.8	114.7
2	Fibrous Panel			467.6	106
3	Bottom Boss w/ Fitting			487.9	5.3
4	Half of Fiberglass Ring			467.9	6.6
5	Half of Fiberglass Ring			474.9	4.4

Test 12

Cutter: *125 gr/ft LSC* — Pressure: *2915 psi*
Location: *At Cylinder Midline*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Bottom Half w/ Fitting	7332	Ø12x17	605.3	6.1

Test 13

Cutter: *125 gr/ft LSC* — Pressure: *2953 psi*
Location: *At Cylinder Midline*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Half	7918	Ø12x17	635.1	3.4

Test 24

Test Type: *Intensified Burst* — Burst Pressure: *7178 psi*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Head Boss w/ Composite	458	Ø13x4	667.5	46
2	Fibrous Panel			888.7	63.7
3	Plastic Liner Frag			1229.1	76.7

Test 25

Test Type: *Intensified Burst* — Burst Pressure: *7614 psi*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Head Boss w/ Composite	392	Ø13x4	720	38.2
2	Fiberglass Ring	336	Ø13x4	686	37.4
3	Plastic Liner Frag			607.5	37.8

Test 26

Test Type: *Intensified Burst* — Burst Pressure: *7385 psi*

Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Head Boss w/ Composite	360	Ø12x5	788.3	44.2
2	Head Boss Plastic Liner	254	Ø16x.09	671	38.5
3	Fibrous Panel	5812	Ø13x13	800.2	79.8

Yellow denotes assumed mass   Peach denotes frag not recovered

Figure 109: Xperion Type IV COPV Fragment Velocity Summary

See Figure 110 below for the full summary of fragment velocities for the Infinite Composites Small Type IV COPV tests.

Test 14					
Cutter: 125 gr/ft LSC		Pressure: 4530 psi			
Location: At Top Boss					
Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Boss, Metallic	148	Ø2.5x1.5	221	5.1
2	Top Boss Composite			881.7	47.7
3	Top Boss Composite			923.6	31.4

Test 15					
Cutter: 125 gr/ft LSC		Pressure: 4492 psi			
Location: At Top Boss					
Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Boss, Metallic	104	Ø2.5x1.5	208.5	5.6
2	Top Boss Plug	44		377.8	8.6
3	Top Boss, Composite			869.3	24.5
4	Top Boss, Composite			688.1	15.3
5	Top Boss, Composite			487.7	19.9

Test 16					
Cutter: 125 gr/ft LSC		Pressure: 4488 psi			
Location: At Cylinder Midline					
Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Boss, Metallic	104	Ø2.5x1.5	335	5.4
2	Composite Dome Half			864.5	13.6
3	Composite Dome Half			866.9	12
4	Fibrous Material			812.6	20

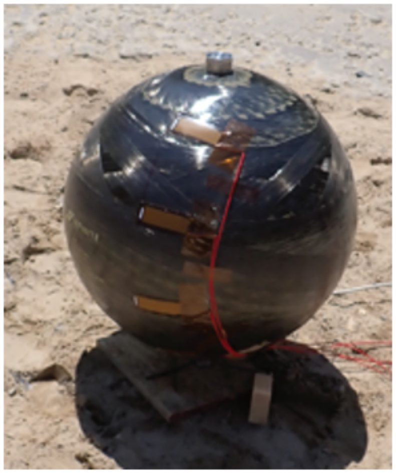
Yellow denotes assumed mass   Peach denotes frag not recovered

Figure 110: Infinite Composites Small Type IV COPV Fragment Velocity Summary

See Figure 111 below for the full summary of fragment velocities for the Infinite Composites Large Type IV COPV tests.

Test 20					
Test Type: Rise-to-Burst		Burst Pressure: 2077 psi			
Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Boss, Metallic	1150	Ø5.8x2	198.5	2.8
2	Fibrous Panel	1028	27x11x.25	1013.9	71.8
3	Fibrous Panel	338	20x8x.25	1125.8	89.7
4	Fibrous Panel	346	17x11x25	1016.4	66.1
5	Fibrous Panel			1050	63.6

Test 23					
Test Type: Stepped Rise-to-Burst		Burst Pressure: 2209 psi			
Frag #	Description	Mass (g)	Size (in)	Speed (ft/s)	Polar Angle (°)
1	Top Boss, Metallic	1150	Ø5.8x2	206.9	8.9
2	Fibrous Panel	216	15x8.5x.25	1085.9	61.5
3	Fibrous Panel	196	20x6.5x.25	1119.4	90
4	Fibrous Panel	326	14x14x.25	932.4	77.7
5	Fibrous Panel	174	19x6.5x.25	697.6	69.1



Yellow denotes assumed mass   Peach denotes frag not recovered

Figure 111: Infinite Composites Large Type IV COPV Fragment Velocity Summary

13.2 Pressure Data Summary

The second data set that will be summarized is the blast overpressure data. Since each of the rupture tests and tanks were quite different in composition, the summary will group each of the similar energetic components together for comparison of resulting blast overpressures. Overall, the BOP sensor readings were 3-6 psi higher than the pencil readings at the same locations. This can be attributed to the difference between front-on and side-on pressure measurement, as described in previous sections.

The first set of blast overpressure comparisons will be on the 4in halo of Flex Linear Shaped Charge. For each of these tests, approximately 8.5g of RDX energetic were detonated. Test A was the bare energetics, test 7 was on a General Dynamics tank, tests 8-11 were on Xperion tanks, and test 14-16 were on Infinite Composites Small tanks. See Figure 112 below for a chart comparing the peak overpressure readings at each location for each test.

All below tests conducted with ~4" Halo of LSC (~8.5g of RDX)

	Test #	A	7	8	9	10	11	14	15	16
	Tank Volume	N/A	8.2 L	46 L				1.9 L		
	Tank Pressure	N/A	4325 psi	2933 psi	2920 psi	2891 psi	2918 psi	4530 psi	4492 psi	4488 psi
5 ft	BOP I1					10.3		5.77	5.15	
	BOP H1					11.17		5.62	6.16	
	BOP H2		10.77		5.69			7.11	8.56	
	Pencil 11829	3.73				8.61	9.69	4.04	4.71	4.3
	Pencil 11811	4.27				6.7	5.31	3.21	4.19	2.93
7.5 ft	BOP I2		3.84			7.14		3.84	3.81	
	BOP J1		6.56	5.11		8.01		4.57	3.77	
	BOP J2					5.77			5	
	Pencil 11809	1.56				3.94	4.79	2.42	2.28	2.63
	Pencil 9859	2.33				5.07	4.36	2.24	1.93	2.25
10 ft	BOP I3		3.77			4.39		3.52	3.63	
	BOP K1		3.7	4.39		5.84		3.37	3.59	
	BOP K2					5.11			3.55	4.82
	Pencil 7418	1.19				2.96	3.63	2.04	1.93	2.18
	Pencil 11813	1.57				3.25	2.63	1.83	1.77	1.96

Peach boxes denote that no data was captured from BOP
Green boxes denote that no Pencil Gauges were used

Figure 112: Blast Overpressure Comparisons of 4" Halo of Flex Linear

As seen in the above chart, when comparing each tank test to the baseline energetics test (Test A), it becomes clear that the rapid expansion of the compressed nitrogen in each tank indeed contributes to increasing the peak blast overpressure. Additionally, the larger volume tanks (Xperion, Tests 8-11) have more pressure and volume to vent and therefore increased the peak pressures more than the smaller volume tanks did.

The second set of blast overpressure comparisons will be on the 10.5in halo of flex linear shaped charge. For each of these tests, approximately 22.7g of RDX energetic were detonated. Test B was the bare energetics and tests 12 and 13 were on Xperion tanks. See Figure 113 below for a chart comparing the peak overpressure readings at each location for each test.

All below tests conducted with ~10.5" Halo of LSC (~22.7g of RDX)

	Test #	B	12	13
	Tank Volume	N/A	46 L	
	Tank Pressure	N/A	2915 psi	2953 psi
5 ft	BOP I1	7.14	12.65	
	BOP H1	5.37	13.27	
	BOP H2	5.87	16.17	
	Pencil 11829	4.41	8.61	8.03
	Pencil 11811	4.21	7.13	6.5
7.5 ft	BOP I2	3.48	10.66	
	BOP J1	3.26	10.95	
	BOP J2	3.73		
	Pencil 11809	1.85	5.69	5.78
	Pencil 9859	1.97	5.94	5.67
10 ft	BOP I3	2.97	9.39	
	BOP K1	2.57	10.95	
	BOP K2	3.12		
	Pencil 7418	1.5	5.46	5.28
	Pencil 11813	1.36	5.07	5.33

Peach boxes denote that no data was captured from BOP

Figure 113: Blast Overpressure Comparisons of 10.5" Halo of Flex Linear

As seen in the above chart, when comparing each tank test to the baseline energetics test (test B), it becomes clear that the rapid expansion of the compressed nitrogen in each tank indeed contributes to increasing the peak blast overpressure.

The final set of blast overpressure comparisons will be on the 6.5in halo of 50gr/ft detonating cord. For each of these tests, approximately 6.9g of PETN energetic were detonated. Test C was the bare energetics and tests 1 through 5 were on General Dynamics tanks. See Figure 114 below for a chart comparing the peak overpressure readings at each location for each test.

All below tests conducted with ~6.5" Halo of Det Cord (~6.9g of PETN)

	Test #	C	1	2	3	4	5
	Tank Volume	N/A	8.2 L				
	Tank Pressure	N/A	4324 psi	4285 psi	4309 psi	4315 psi	4314
5 ft	BOP I1		4.17	7.22	6.42	4.35	
	BOP H1		4.6	8.09	6.78	6.93	2.18
	BOP H2		4.64				
	Pencil 11829	3.04					
	Pencil 11811	3.19					
7.5 ft	BOP I2		3.63	4.42	3.81	3.73	
	BOP J1		3.37	5.44	4.17	5.44	2.39
	BOP J2		3.34	4.35	5	5.58	
	Pencil 11809	1.24					
	Pencil 9859	1.73					
10 ft	BOP I3		2.97	4.13	3.95	3.26	1.34
	BOP K1		2.18	3.52	3.84	3.92	1.52
	BOP K2		2.47	4.13	4.02	4.1	
	Pencil 7418	0.95					
	Pencil 11813	0.92					

Peach boxes denote that no data was captured from BOP
Green boxes denote that no Pencil Gauges were used
Purple boxes denote that distances were 5ft further (10ft / 12.5ft / 15ft)
Blue Boxes denote test that failed to rupture tank

Figure 114: Blast Overpressure Comparisons of 6.5" Halo of Det Cord

The rapid release of the nitrogen gas indeed intensified the overpressure wave, causing higher pressure readings than the test C baseline. Though test C did not have any BOP sensors successfully record, direct comparisons can be made between tests 1-4 and test 5, as test 5 was the one where just the energetics went off and the tank failed to rupture. Though no direct comparison can be made, it is assumed that the BOP sensors would have recorded higher values than the pencil gauges would have.

14.0 Conclusion

In summary, (17) energetic COPV rupture tests, (9) COPV intentional burst tests and (3) standalone energetic tests were conducted at the AvMC Intentional Detonation "Snake Pit" Facility, from August 8-22, 2024. Each of the tank pressurization processes were conducted remotely on-site to minimize the handling of pressurized tanks. High-speed video was captured on each test to collect data on fragment throw angle and resulting velocity. Additionally, a variety of blast overpressure sensors were used to collect information on blast overpressure emanating from the energetic rupture events. See below in Table 31 for the summarized test matrix of the various tests conducted on each of different COPVs.

Table 31: COPV Test Series Matrix (Sorted by Manufacturer)

Designation	COPV Type	Volume	Rated Working Pressure	Designed Burst Pressure	# of Rupture Tests	# of Pressure Until Burst Tests
General Dynamics	III	8.2L (2.16 Gal)	4300 psi	6450 psi	8*	0
Xperion	IV	46L (12.15 Gal)	2900 psi	6525 psi	6	3**
Infinite Comp. Small	IV	1.9 L (0.5 Gal)	4496 psi	8992 psi	3	0
Cimarron	V	113.6L (30 Gal)	500 psi	1000 psi	0	2***
HyPerComp	V	128.7L (34 Gal)	50 psi	100 psi	0	2***
Infinite Comp. Large	IV	113.6L (30 Gal)	500 psi	1000 psi	0	2***
				TOTALS	17	9

* (1) shot will be fired horizontally with frag capture bundles

** Will be shot very last and with a modified Pressure Distribution Panel (due to the high pressures required)

*** Will be utilizing (1) "Stepped Increase to Burst" procedure

15.0 Lessons Learned / Future Work Considerations

Since the techniques utilized in this test series were so novel, numerous lessons were learned that should be considered when planning additional future work.

Regarding the energetic rupture test methodology, the primary focus of this was to effectively rip the COPVs open along a desired cut line. As the test series progressed, two other different rupture mechanisms were utilized due to evolving test requirements. The tank in test 5 was ruptured by a 7.62mm bullet impact and the tank in test 6 was ruptured by a conical shaped charge jet. Each of these unique rupture events caused different fragmentation results. Perhaps future testing could expand on alternate methods of rupture mechanisms, if so desired by the customer.

One of the problems in obtaining fragment velocity was the occlusion of some of the frags due to the white smoke cloud generated by the rapid expansion of pressurized nitrogen gas. Understandably, nitrogen was used due to its wide availability and inert properties. However, if available, perhaps Helium would be a more ideal candidate for future testing, as it is also an inert gas but does not condense into a white cloud during rapid expansion.

Regarding velocity measurement, the 90-degree separation between cameras indeed allowed 3-dimensional velocity vectors to be calculated. However, since only two of the cameras met this criteria, then any fragments that were thrown in the opposite direction from them and or were occluded by the expanding gas smoke cloud were not captured. For future testing, a full set of (4) cameras should be used, each 90 degrees apart, to be able to capture the full picture around each fragmenting tank. This would allow for full 360-degree coverage of each test event to capture velocities of fragments that were otherwise occluded in this test series. See example schematic below in Figure 115 for proposed camera positions for future tests.

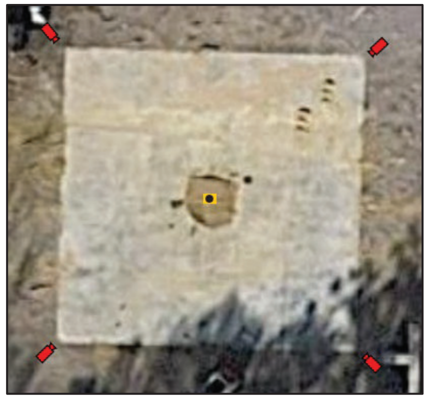


Figure 115: Proposed 360 Degree High-Speed Camera Coverage Schematic

Various important lessons were learned with regards to blast overpressure measurement. For future use of the standalone BOP sensors, the test team must ensure that they are configured in "structure-mode" to ensure that they don't go to "sleep" in between tests. A large number of pressure curves were missed in this test series due to this issue. Additionally, when the pencil gauges were added in this test series, the test team mounted the BOP sensors to the same stand in front-on configuration. As seen in the resulting data, this resulted in the BOP sensors reading higher pressure magnitudes than the nearby pencil gauges. For future testing, the test team should ensure that all of the BOP sensors are mounted to their fixtures in side-on configuration to yield the best comparable results. Finally, the test team should plan to utilize pencil gauges on more tests, since they are the industry standard for free field blast overpressure data collection. Additionally, the height of the mounting poles should be considered in future testing. The pencil gauges were mounted on 4x4 poles about 4ft above ground level. Typically, this is done to minimize ground reflections in a standard detonation event. However, in this test series, as seen in the high-speed camera footage, much of the nitrogen expansion happened lower than the gauges. See below in Figure 116 for an example of this effect on Test 12.

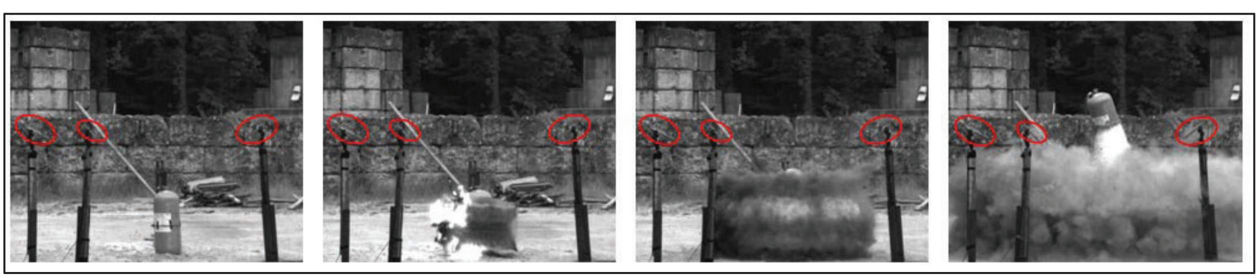


Figure 116: Test 12 Pressure Expansion Relative to Pencil Gauges

For this particular test, the energetic rupture line was at the midline of the Xperion tank which is about 1 ft off the ground. The pencil gauges are circled in red and are about 4ft off the ground. As can be seen in the time lapse, as the nitrogen gas expands, it doesn't quite make it to the height of the pencil gauges, mostly staying about 2-3 feet off the ground. The result of this in the recorded pressure waveforms is that, likely, the peak overpressure effects were not measured from this event. Had the pencil gauges been mounted at the same height above the ground as the rupture event, it is much more likely that the true peak overpressure could have been measured. This concept should be considered further when planning to measure blast overpressure in future test series.

APPENDIX A

3-DIMENSIONAL FRAGMENT VELOCITY DERIVATION METHODOLOGY

Appendix A – 3-Dimensional Fragment Derivation Methodology

Since the traditional DoD methods of deriving fragmentation effects could not be used due to the unique test articles, the AvMC team had to identify procedures for post test data analysis. The following sections detail the velocity derivation process for this unique test series.

Camera Layout Considerations

Initially, the thought process as to where the high-speed cameras were placed was to provide a few differing angles to give different perspectives of the COPV breakup. Each of these views were, as described in previous sections, calibrated at the beginning of each day to provide accurate distance and velocity measurements. However, during post-test analysis, it became clear that it would be best to use only the two most perpendicular views to correlate a final velocity vector for each frag. As shown above in Figure 13, camera 1 and camera 3 were placed exactly 90 degrees apart from each other. Therefore, cameras 1 and 3 were used to determine velocity and polar angle measurements for each fragment and cameras 2 and 4 were used more for qualitative analysis.

Polar Angle Explanation

To start the velocity derivation process, it's important to define the geometric space that will be analyzed. Cameras 1 and 3 were set up to view directly down the relief cracks in the concrete pad, hence why they are exactly 90 degrees apart. At the center of the pad is the COPV, oriented vertically, at ground level. For the sake of geometry, camera 1 only has a view of the fragment travelling in the X-Z planes. Similarly, camera 3 only has a view of the fragment travelling in the Y-Z planes. The final data that is required for performing the verification and validation of the simulation software is a 3-dimensional velocity magnitude and a polar angle (relative to the Z-Axis) for each fragment thrown. See below in Figure 117 for a schematic defining this geometric space.

Figure 117: COPV Frag Velocity Geometric Space

Simple Velocity Measurement Example

An example of a simple velocity measurement would be a circumstance when a fragment was thrown only in the Z-Axis direction (i.e. straight up in the air) with minimal movement in the X or Y axes. In this case, the velocities calculated from each of the camera views should match very closely with each other. See below in Figure 118 for an example of this effect from this test series.

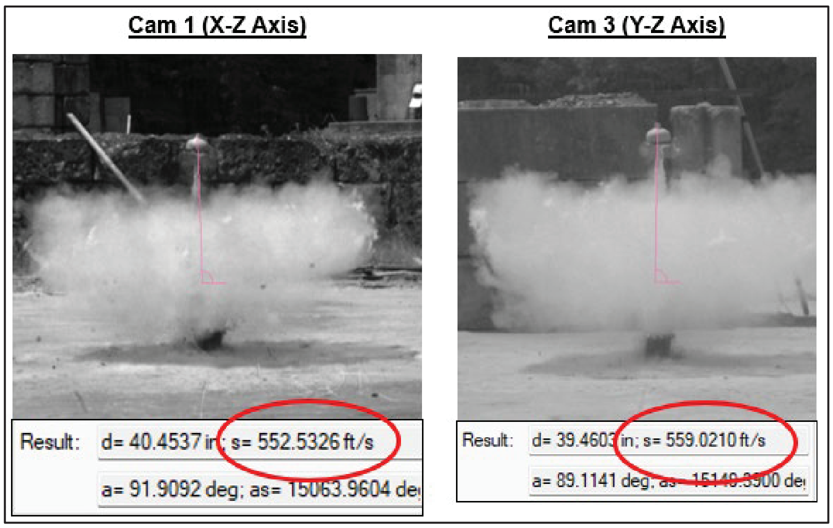


Figure 118: Simple Velocity Derivation - Vertical Frag

As seen in the above figure, the derived velocities from each view are 552.5 ft/s and 559 ft/s respectively, yielding an average velocity of 556 ft/s. Additionally, denoted by the “a=” value, the angles (relative to horizontal) are calculated as 91.9° and 89.1° respectively, meaning that the resultant polar angle relative to the Z-Axis is 1-2 degrees. There is some uncertainty added in exactly which pixels were selected in the videos for each velocity calculation that could explain the slight difference in values. Regardless, this is an ideal case scenario for deriving velocity.

Complex Velocity Measurement Example

An example of a complex method of deriving the velocity vector would be a case where the fragment was thrown at an angle that allows it to travel in all three planes simultaneously. This is achievable if the (X,Y,Z) position of the frag can be determined at a known time relative to time zero (initiation). Using the combination of 90° views, this method is achievable. See below in Figure 119 for a visual representation of this 3-dimensional derivation concept from Test 4-Fragment 1.

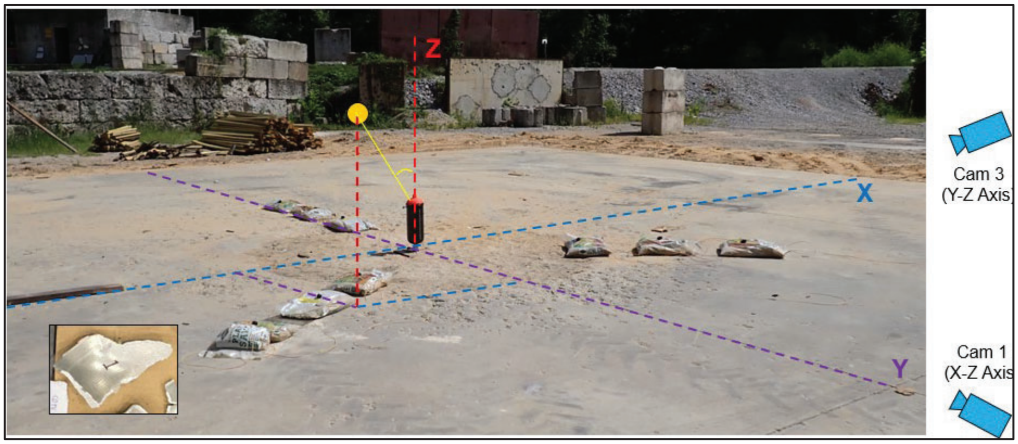


Figure 119: Complex Velocity Derivation - Test 4, Frag 1

Starting with the video captured from camera 1 (viewing the X-Z axis), this fragment can be found 8.74385ms after "time zero". See below in Figure 120 for images of the camera 1 frag track.

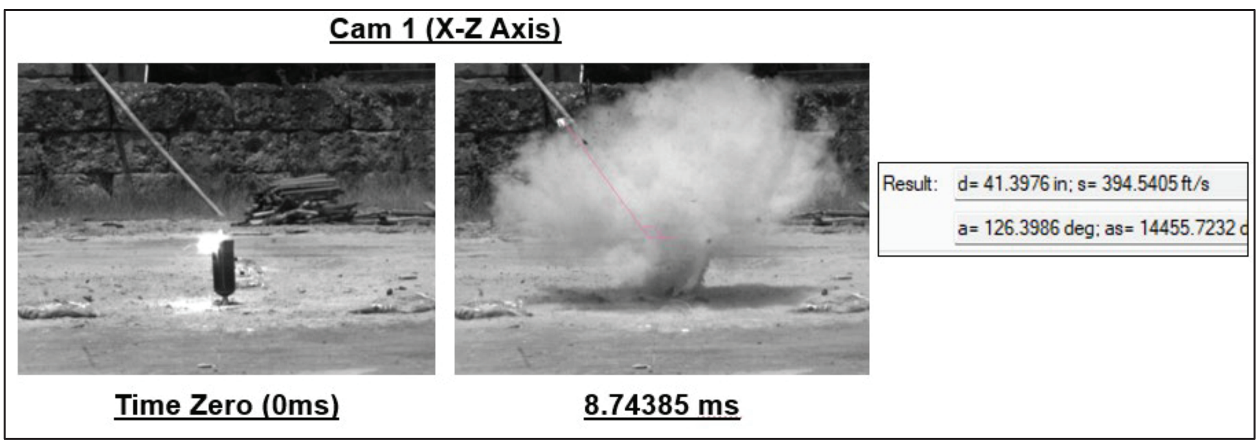


Figure 120: Camera 1 (X-Z Plane) Frag Track

As seen in the above figure, in the 8.74385ms that pass between the two images, the fragment travels 41.3976 inches at an angle of 126.3986° from horizontal, also read as 36.3986° from Vertical (Z-Axis).

Moving to the video captured from camera 3 (viewing the Y-Z axis), due to a large white smoke cloud occluding the view, this fragment can only first be found 37.88235ms after "time zero", which is significantly later in time than the other view. See below in Figure 121 for images of the camera 3 frag track.

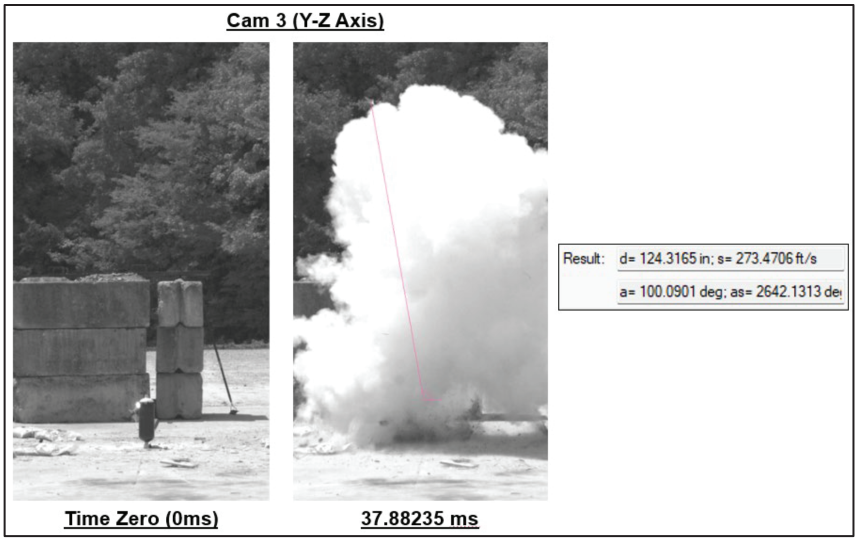


Figure 121: Camera 3 (Y-Z Plane) Frag Track

As seen in the above figure, in the 37.88235ms that pass between the two images, the fragment travels 124.3165 inches at an angle of 100.0901° from horizontal, also read as 10.0901° from the vertical (Z-Axis).

The problem that now exists is that the two positions of that frag are calculated at two very different time stamps. The fragment in camera 3 could not be positively identified until later than in camera 1 because of the white smoke cloud obscuration. Likewise, the fragment tracked in camera 1 completely leaves the field of view by this time. Therefore, in order to calculate the true 3-dimensional velocity and direction, one of these calculations must be extrapolated to the same time.

To accomplish this extrapolation, the assumption must be made that frag velocity is constant over that time period. It is very well understood that this is likely a bad assumption. However, without detailed data about the presented area, drag characteristics, and tumble rate of each frag, it is impossible to calculate the deceleration rate over this distance. That being said, since the distance that this (constant velocity) assumption occurs over is still relatively close to the COPV, it is plausibly true. If this extrapolation was being made when the fragment was 50+ feet away from the COPV source, the error would be considerably more because the fragment has had more time/distance to slow down.

For this example, it was decided to reverse-extrapolate the frag position in camera 3 from 37.9ms back to 8.7ms. Based off of the assumption of constant velocity and the derived distance, duration, and angle from the camera 3 frag at 37.9ms, it can be calculated that the fragment, at 8.74ms, had travelled 28.6942 inches at an angle of 10.09° from vertical. See below in Figure 122 for a pictorial representation of this reverse extrapolation.

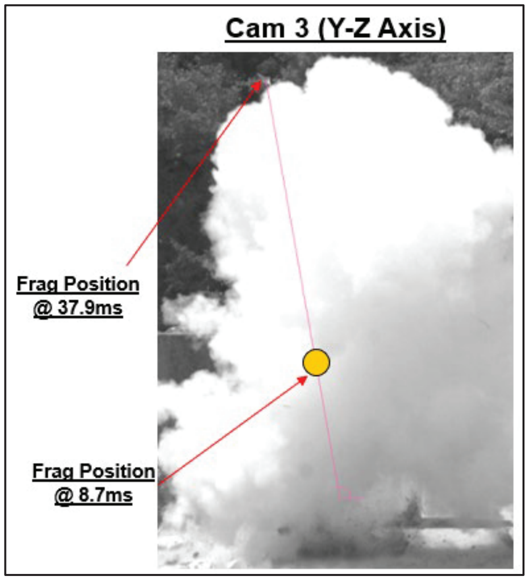


Figure 122: Visual of Reverse Extrapolation

Now that the distances and angles are calculated for each camera image over the same time duration, the individual (X,Y,Z) coordinates can be calculated. For camera 1, the frag had travelled 41.40 inches at 36.4° from vertical in 8.7ms. Since camera 1 is directly viewing the X and Z axes, this can be broken out into an X-component distance of 24.57 inches and a Z-component distance of 33.32 inches. Similarly, for camera 3, the frag had travelled 28.69 inches at 10.7° from vertical in 8.7ms. Since camera 3 is directly viewing the Y and Z axes, this can be broken out into a Y-component distance of 5.03 inches and a Z-component distance of 28.25 inches. See Figure 123 below for a visual of this cartesian coordinate derivation.

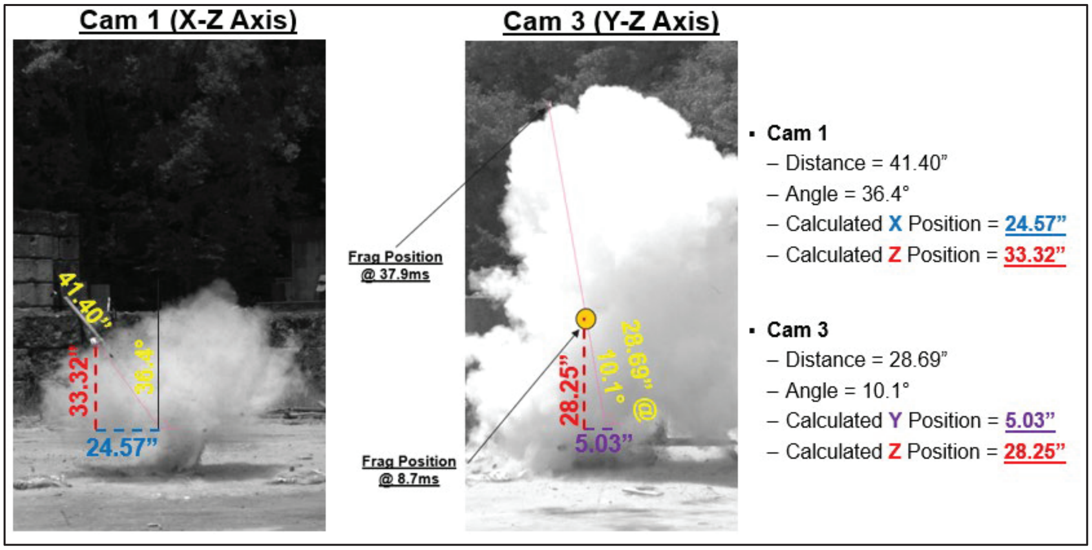


Figure 123: Cartesian Coordinate Derivation of Frag Position

The next issue that's encountered is the fact that there are now two different Z-component values. Though they are near the same magnitude (only 5 inches difference), one of these must be selected to be used for the 3-dimensional position calculation. The question becomes "which of these numbers is more accurate?" See Figure 124 below for a visual that will help answer this question.

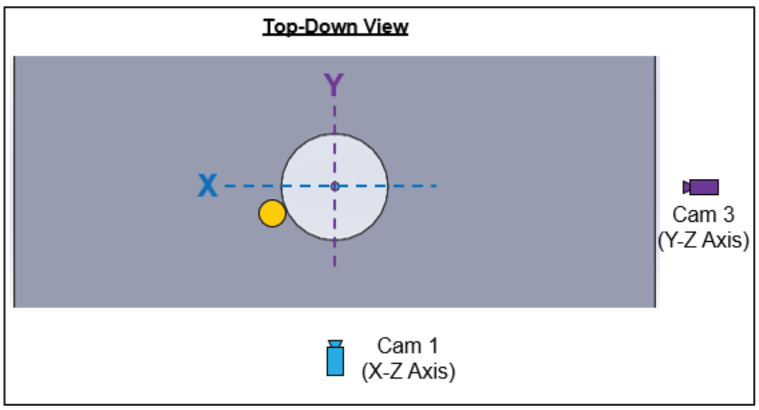


Figure 124: Determination of Z-Component for 3-Dimensional Position

In the above figure, the perspective shown is from a top-down perspective. The orange dot represents the frag position in the current example and the dashed lines represent the calibrated planes for each camera. The thought is that, since the fragment is further away from the Y-Axis than it is the X-Axis, the depth of field in camera 3 would result in a lower-than-actual height (Z-component), which would cause the Z-component error from camera 3 to be higher than the Z-component error from camera 1. Thus, for this example, it was decided that the Z-component derived from camera 1 would be used for the 3-dimensional position calculation, since it's closer to its calibrated plane. There will still be some error from this calculation, but, between the two camera options presented, it will yield a more accurate result.

This will not always be the case for each frag studied. Essentially, whichever of the X- or Y-components is smaller (X- derived from cam 1 and Y- derived from cam 3), the opposite camera will be used to determine the Z-component.

Now that the X-, Y-, and Z-components for 3-dimensional position are calculated at the same time, the 3-dimensional distance formula can be applied to calculate the distance that the frag travelled in that time. Subsequently, this resulting distance can be divided by the time it took to travel there to calculate resultant velocity. Additionally, basic trigonometry rules can be applied to also calculate the polar angle that the frag flew relative to the Z-Axis (vertical). See Figure 125 below for the calculations for this example.

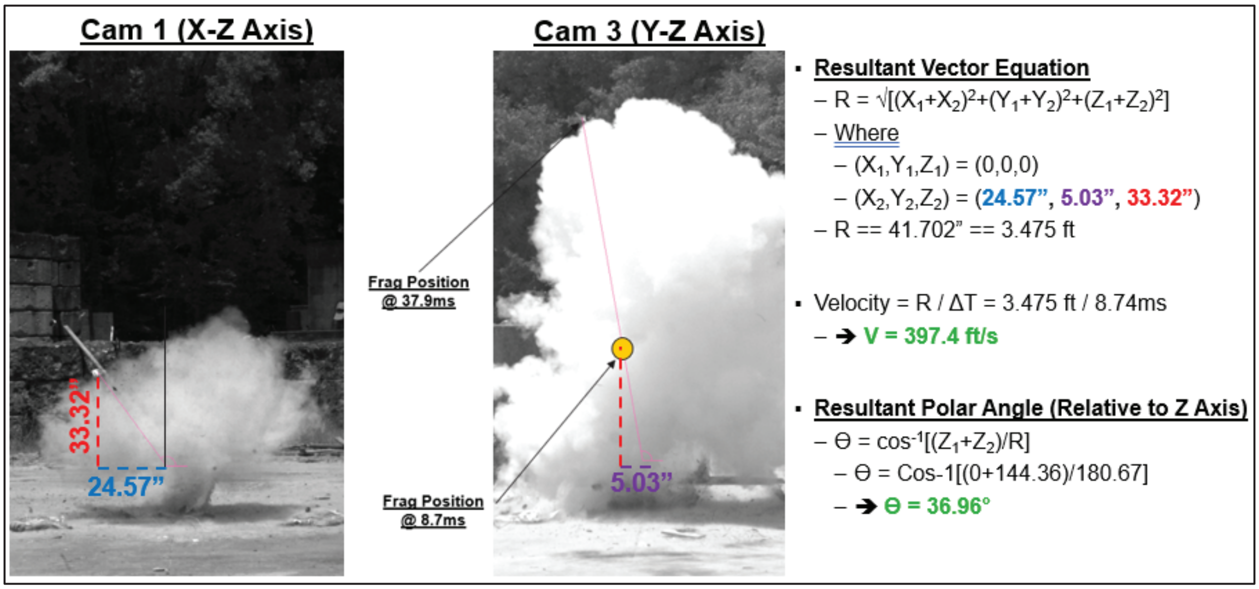


Figure 125: Final Calculation of Velocity and Polar Angle Example

As seen in the above figure, the final calculation for the example fragment (Test 4, Frag 1) is a velocity of 397.4 ft/s at a polar angle of 36.96°. This entire velocity derivation process is utilized in deriving all of the fragment velocity vectors from each test. It is understood that there is some uncertainty/error in this calculation, but given the limited raw data collected and unique test development, it was the best estimation that could be concluded.

The best way to visualize each of the fragments emanating from a test is to study the videos individually, but this is impossible to achieve in the setting of a formal report. Therefore, for each test, a culmination of screenshots from each of the high-speed videos will be displayed, with each fragment labelled. Some of these fragments don't show up until much later in time, relative to the others, so various images were superimposed on the same picture to show each of these fragments in one image. See Figure 126 below for an example of this display technique from Test 20.

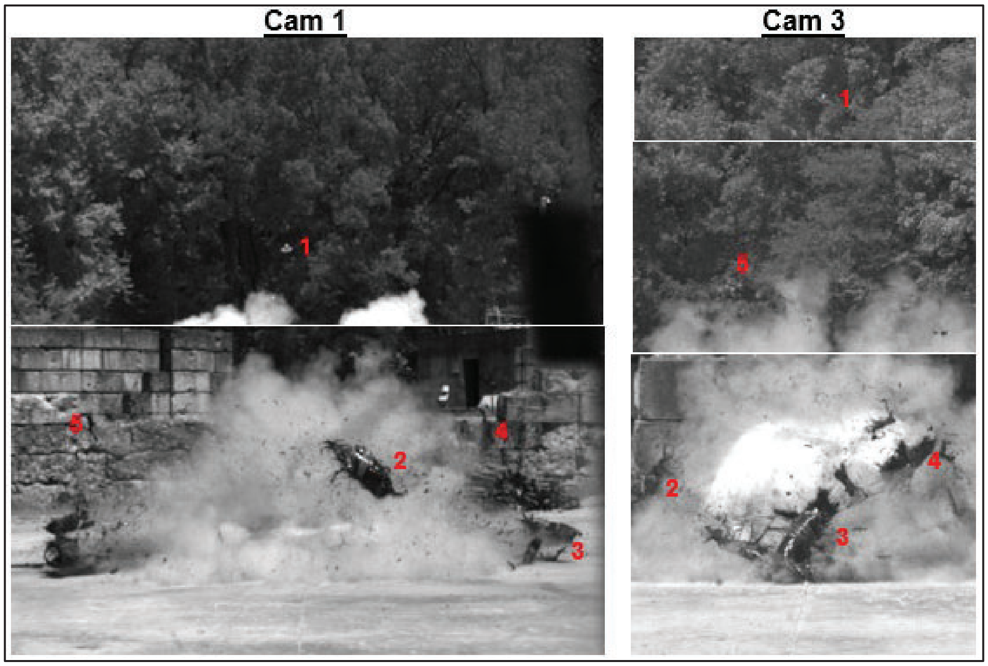


Figure 126: Example of High-Speed Screenshots with Labelled Frags

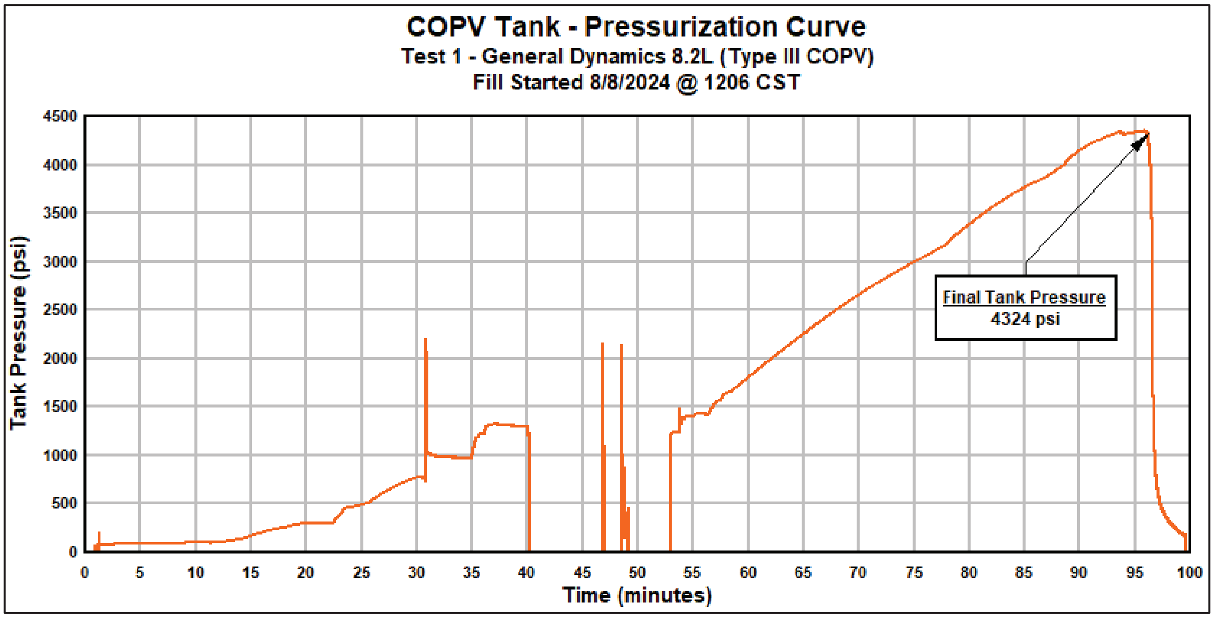
It should also be noted that not all of the frags that came from each tank were tracked and given velocity calculations. Due to the large white cloud that would appear after each rupture event (likely due to rapid expansion of pressurized nitrogen gas), a large number of fragments were occluded from view and could not be positively identified in the post-test videos. For some of the tests, a fragment could be tracked in one view but not the other, which would result in an incomplete 3-dimensional vector. Without having all three distance components calculated, it's impossible to accurately derive velocities for them. This issue could be solved in future tests by placing four (4) cameras around the test area, each at 90° from each other.

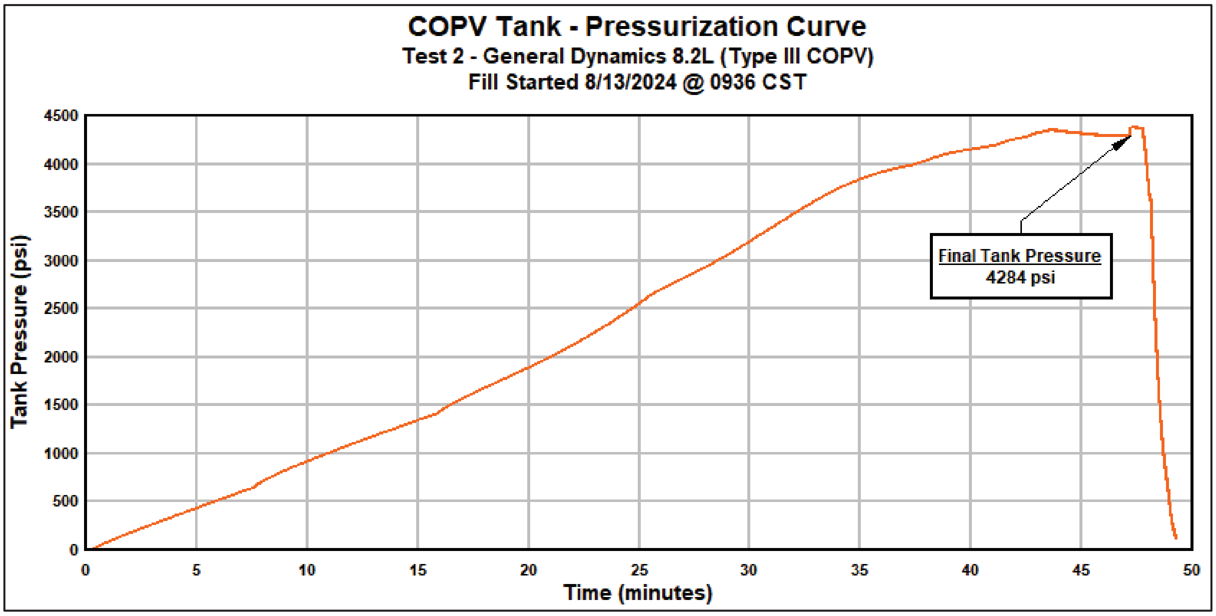
APPENDIX B

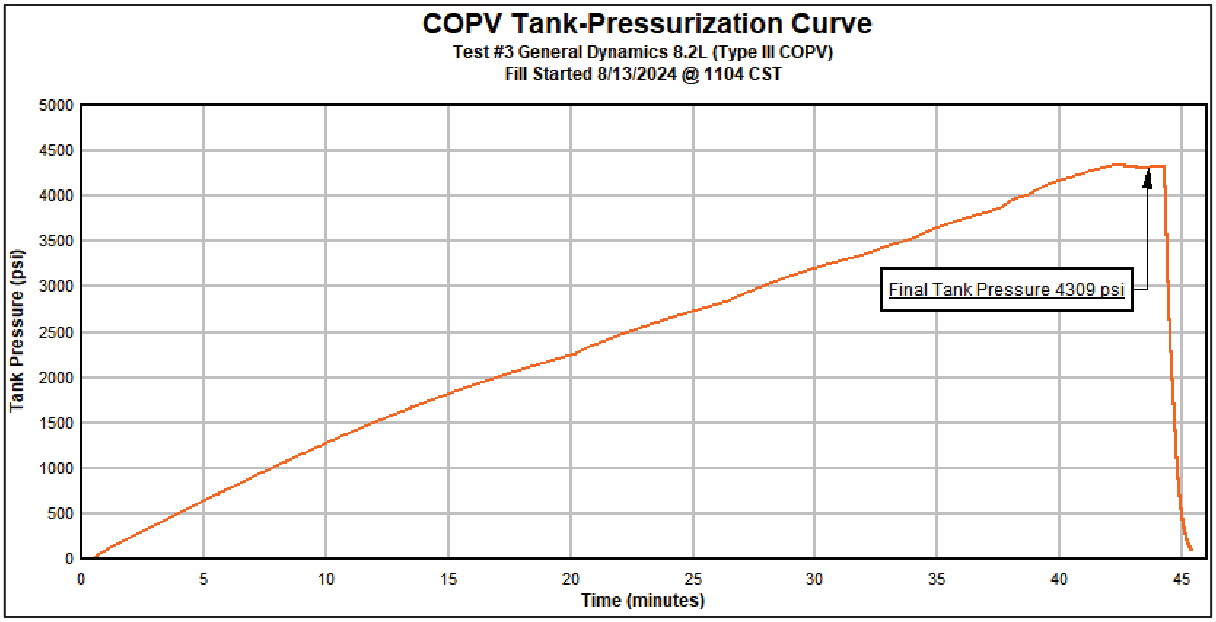
COPV Tank Pressurization Curves

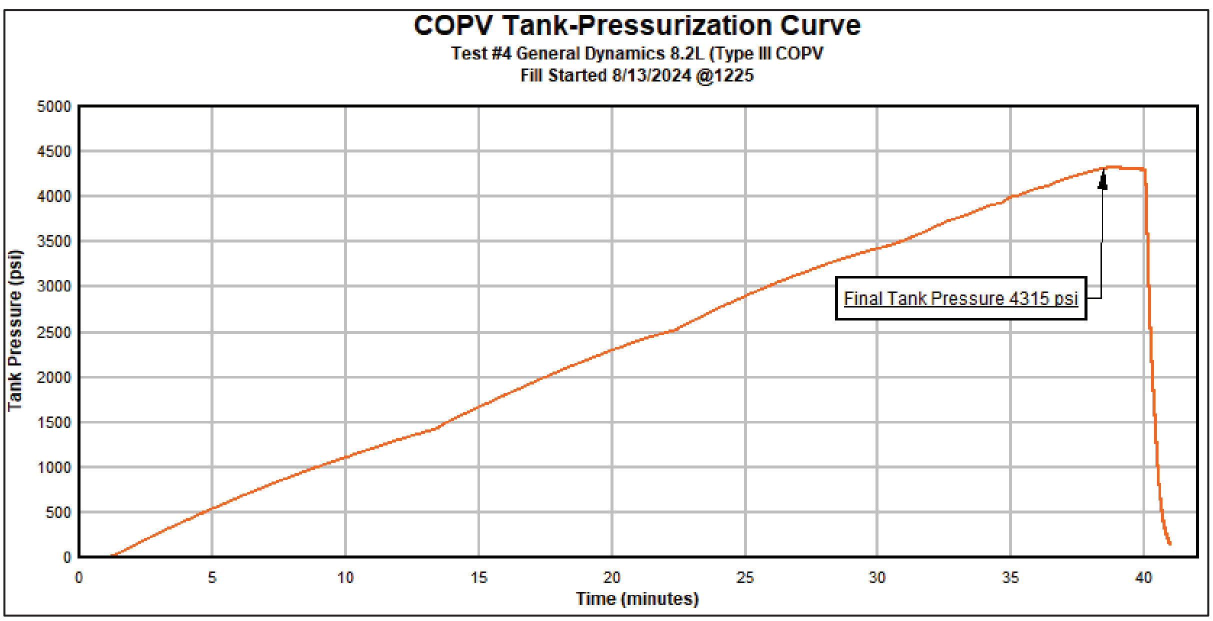
Appendix B – COPV Tank Pressurization Curves

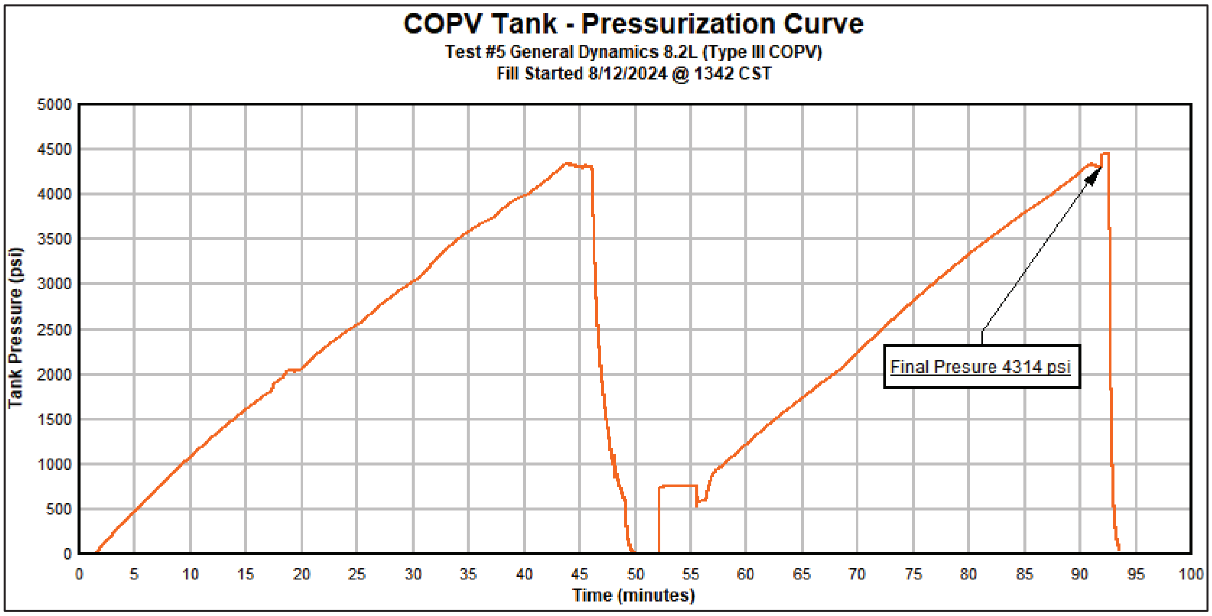
This appendix will include the raw data curves for each of the tank pressurization events that occurred during this test series. They will be displayed in the order that the tests were conducted.

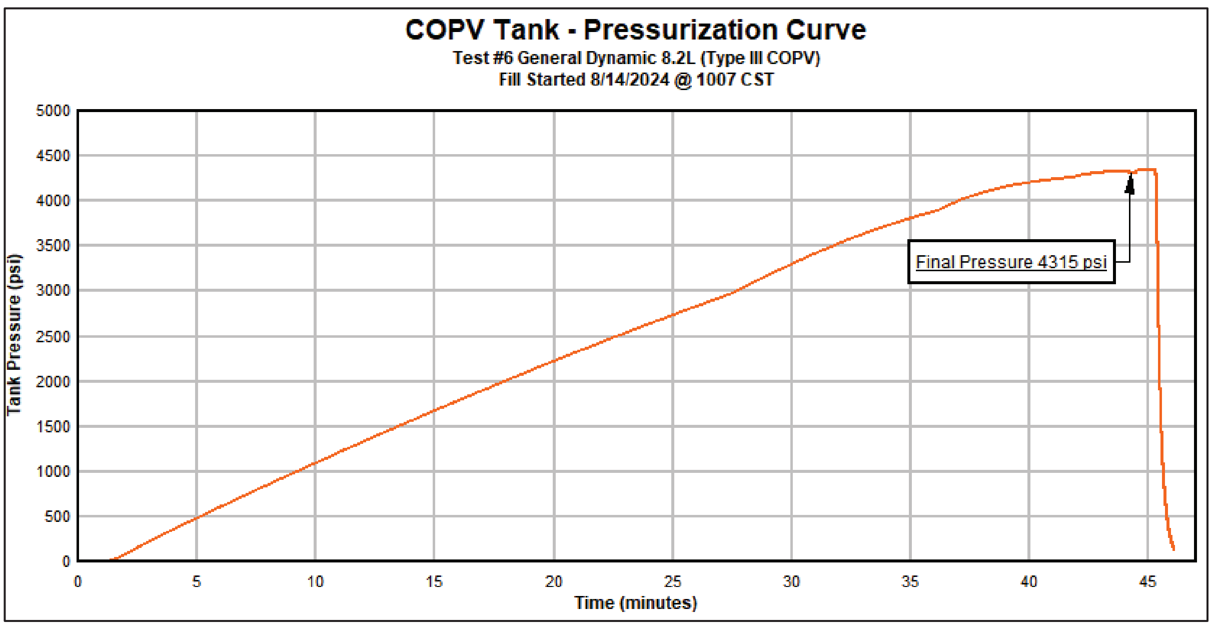


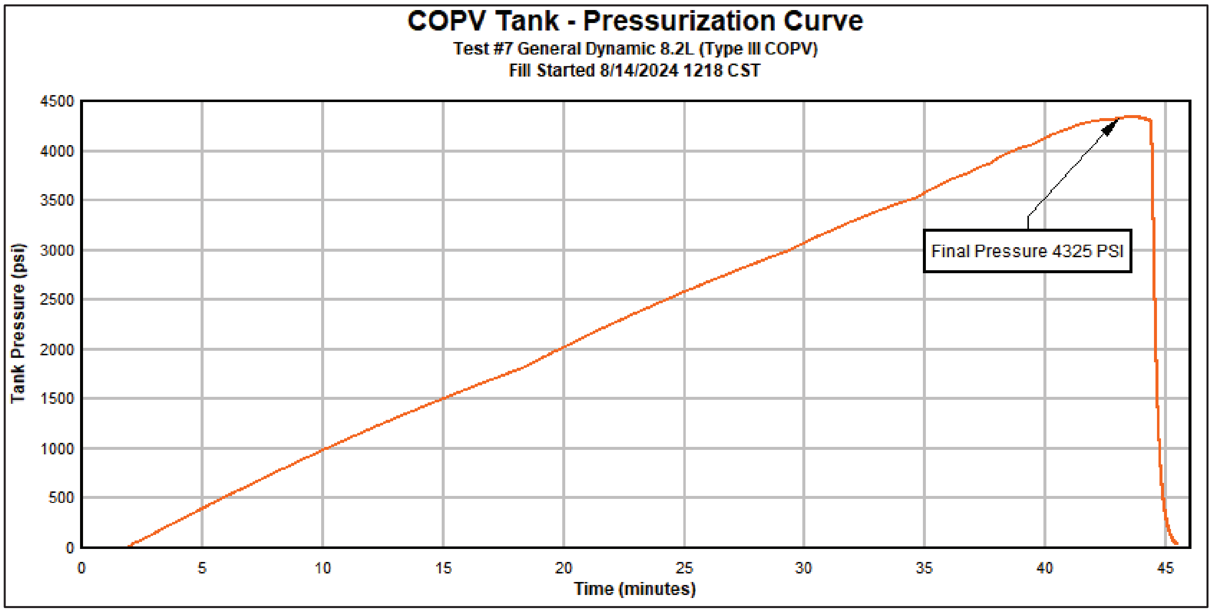


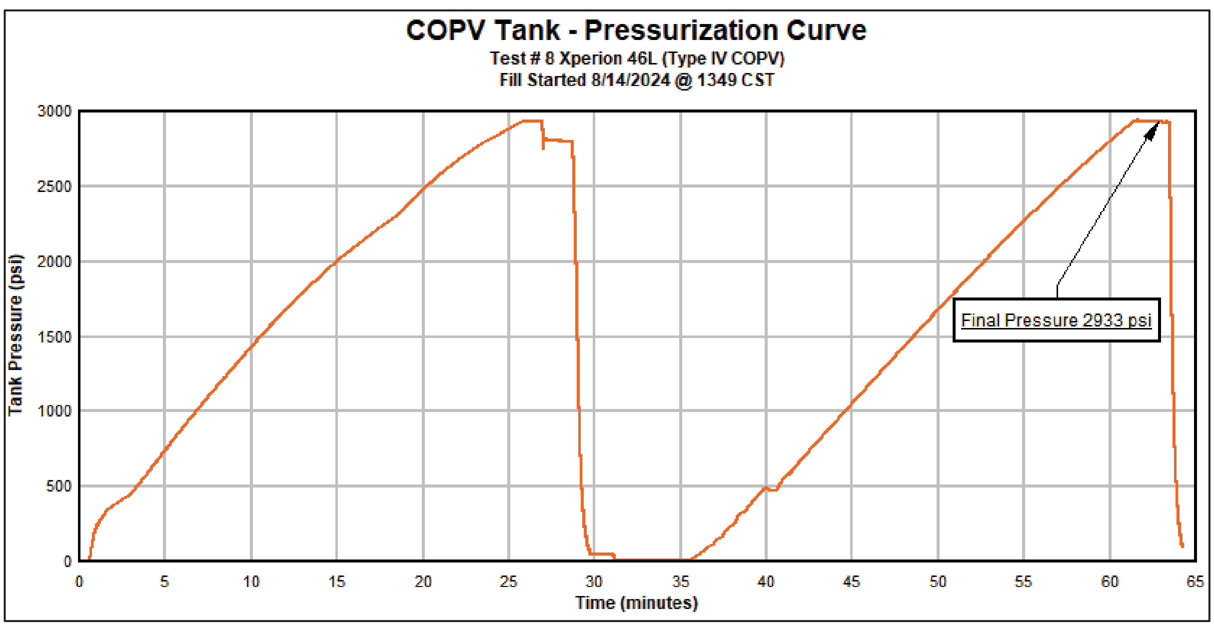

COPV Tank-Pressurization Curve
Test #3 General Dynamics 8.2L (Type III COPV)
Fill Started 8/13/2024 @ 1104 CST
Tank Pressure (psi)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
5
10
15
20
25
30
35
40
45
Time (minutes)
Final Tank Pressure 4309 psi

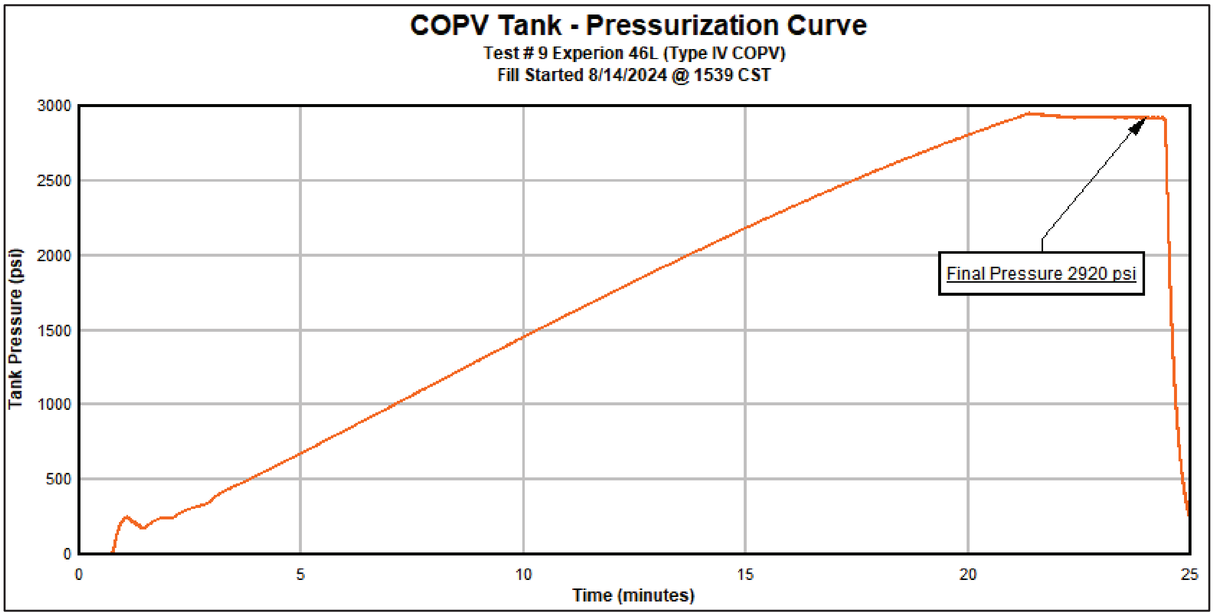

COPV Tank-Pressurization Curve
Test #4 General Dynamics 8.2L (Type III COPV
Fill Started 8/13/2024 @1225
Tank Pressure (psi)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
0
5
10
15
20
25
30
35
40
Time (minutes)
Final Tank Pressure 4315 psi

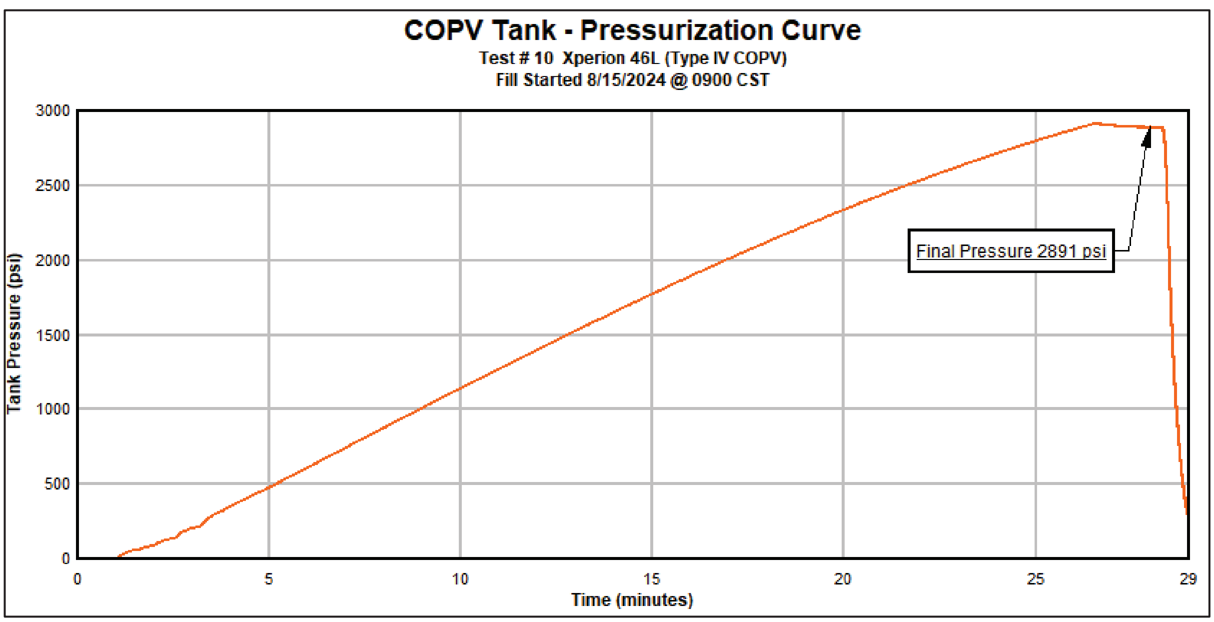

COPV Tank - Pressurization Curve
Test #5 General Dynamics 8.2L (Type III COPV)
Fill Started 8/12/2024 @ 1342 CST
Tank Pressure (psi)
Time (minutes)
Final Presure 4314 psi

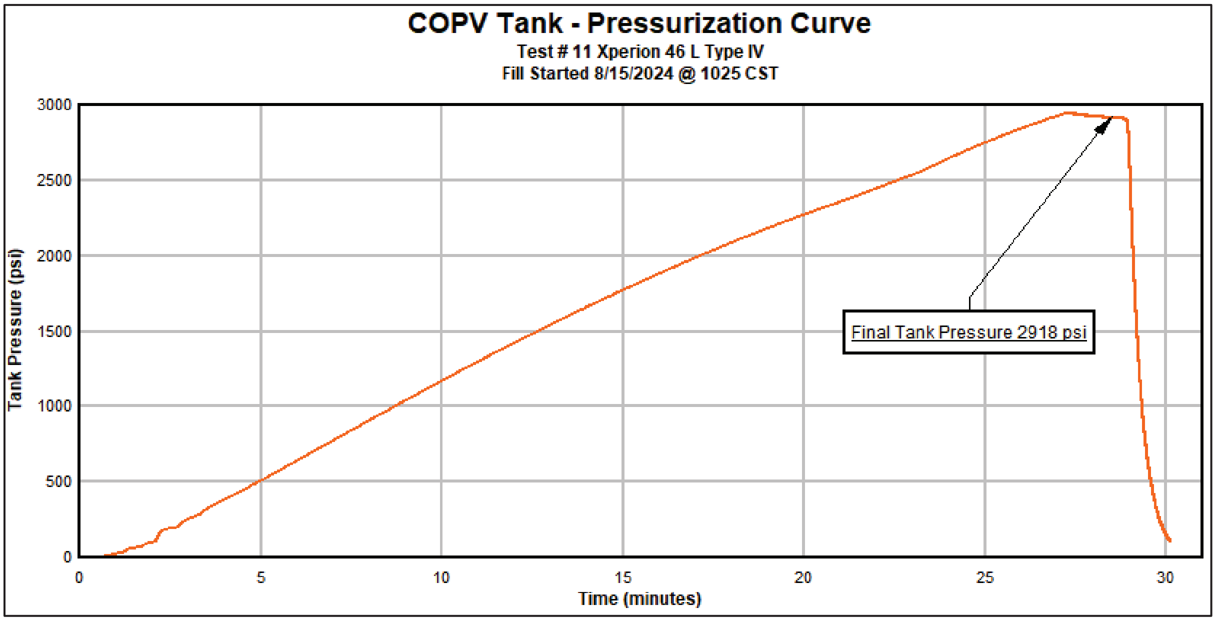

COPV Tank - Pressurization Curve
Test #6 General Dynamic 8.2L (Type III COPV)
Fill Started 8/14/2024 @ 1007 CST
Tank Pressure (psi)
Time (minutes)
Final Pressure 4315 psi

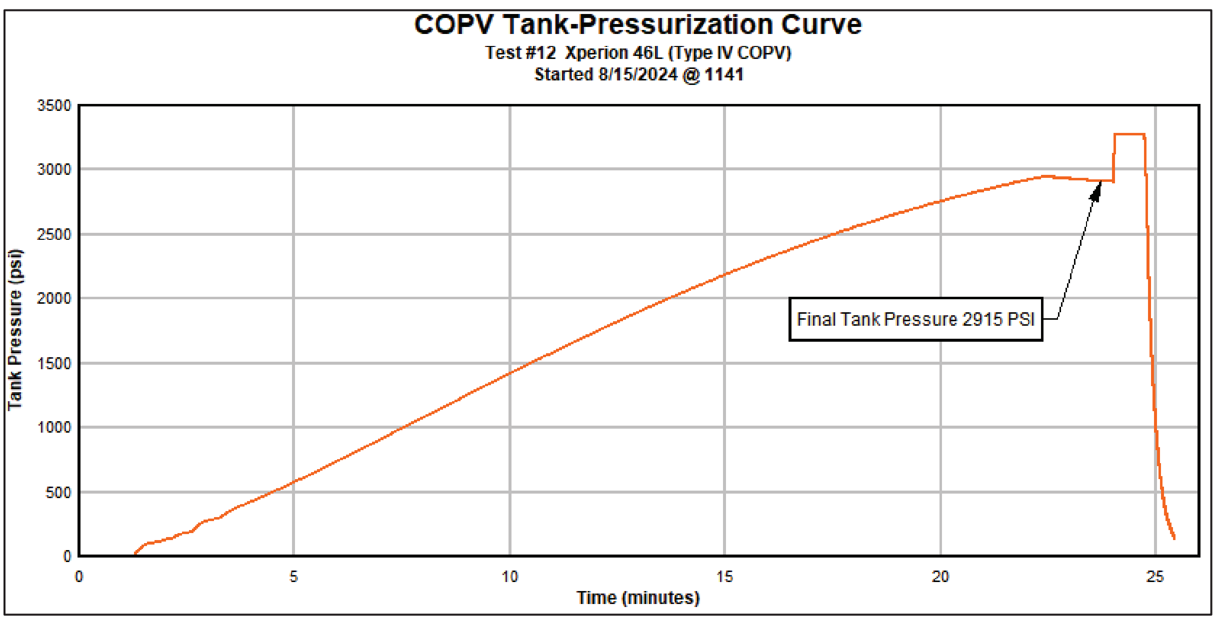

COPV Tank - Pressurization Curve
Test #7 General Dynamic 8.2L (Type III COPV)
Fill Started 8/14/2024 1218 CST
Tank Pressure (psi)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
Time (minutes)
Final Pressure 4325 PSI

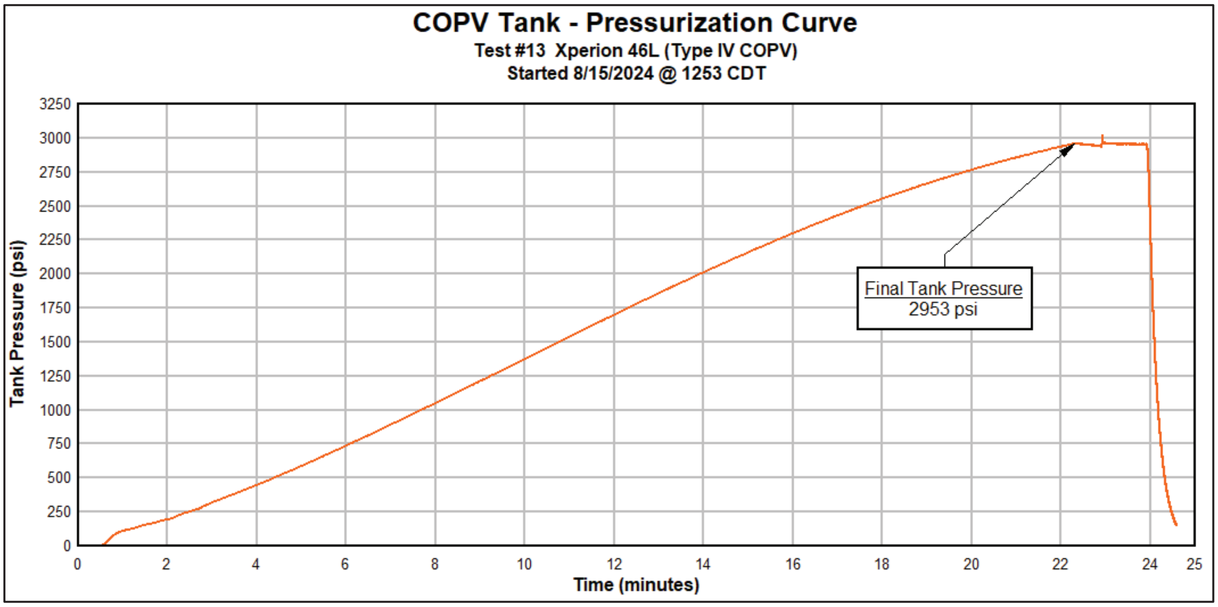

COPV Tank - Pressurization Curve
Test # 8 Xperion 46L (Type IV COPV)
Fill Started 8/14/2024 @ 1349 CST
Tank Pressure (psi)
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
50
55
60
65
Time (minutes)
Final Pressure 2933 psi

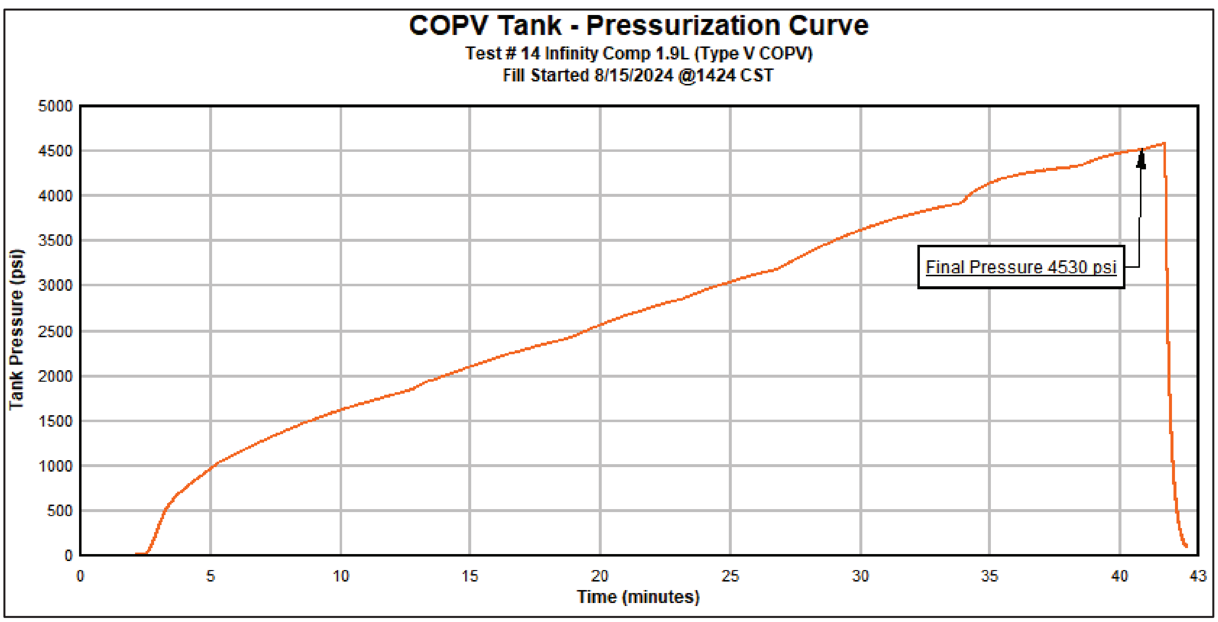

COPV Tank - Pressurization Curve
Test # 9 Experion 46L (Type IV COPV)
Fill Started 8/14/2024 @ 1539 CST
Tank Pressure (psi)
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
Time (minutes)
Final Pressure 2920 psi

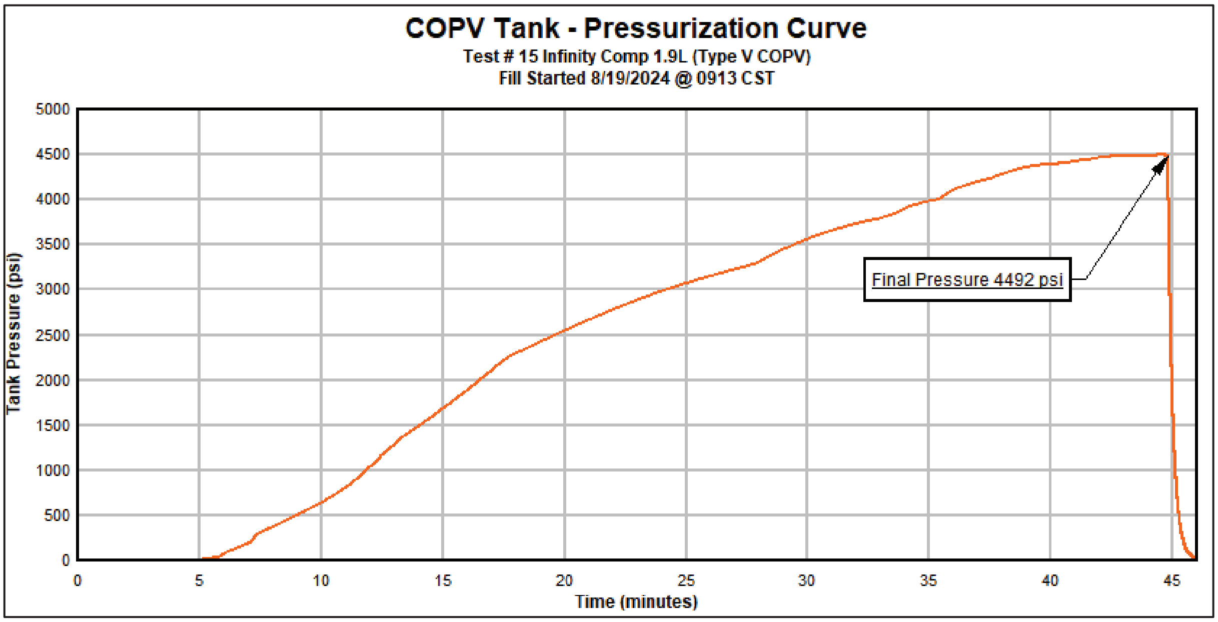

COPV Tank - Pressurization Curve
Test # 10 Xperion 46L (Type IV COPV)
Fill Started 8/15/2024 @ 0900 CST
Tank Pressure (psi)
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
29
Time (minutes)
Final Pressure 2891 psi

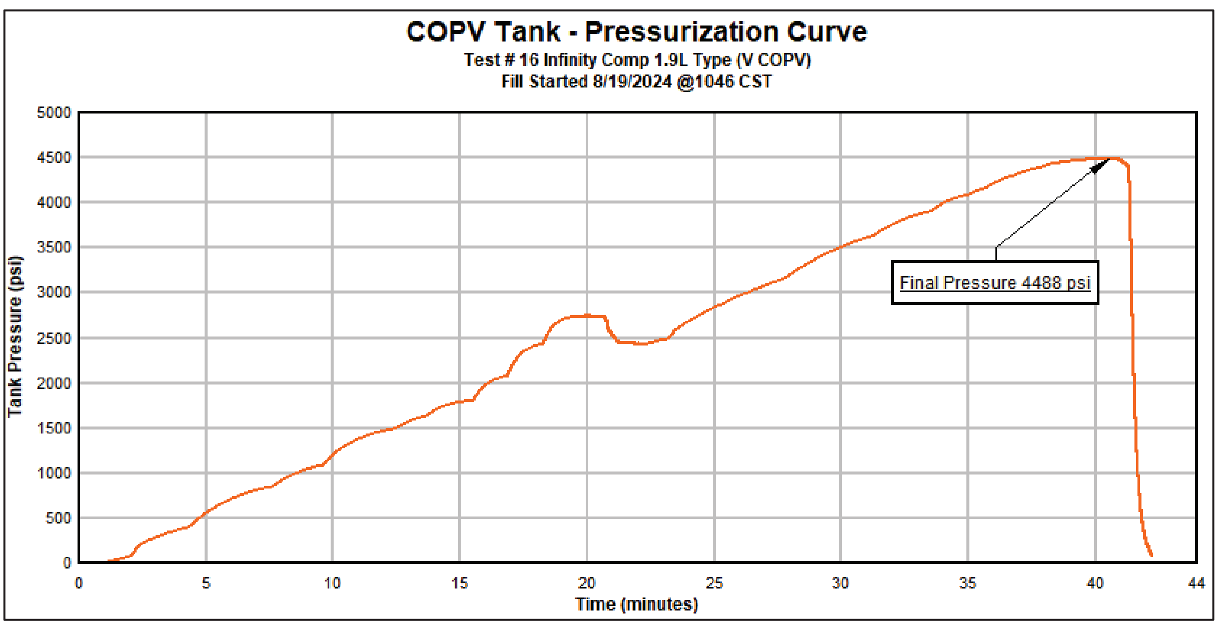

COPV Tank - Pressurization Curve
Test # 11 Xperion 46 L Type IV
Fill Started 8/15/2024 @ 1025 CST
Tank Pressure (psi)
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
Time (minutes)
Final Tank Pressure 2918 psi

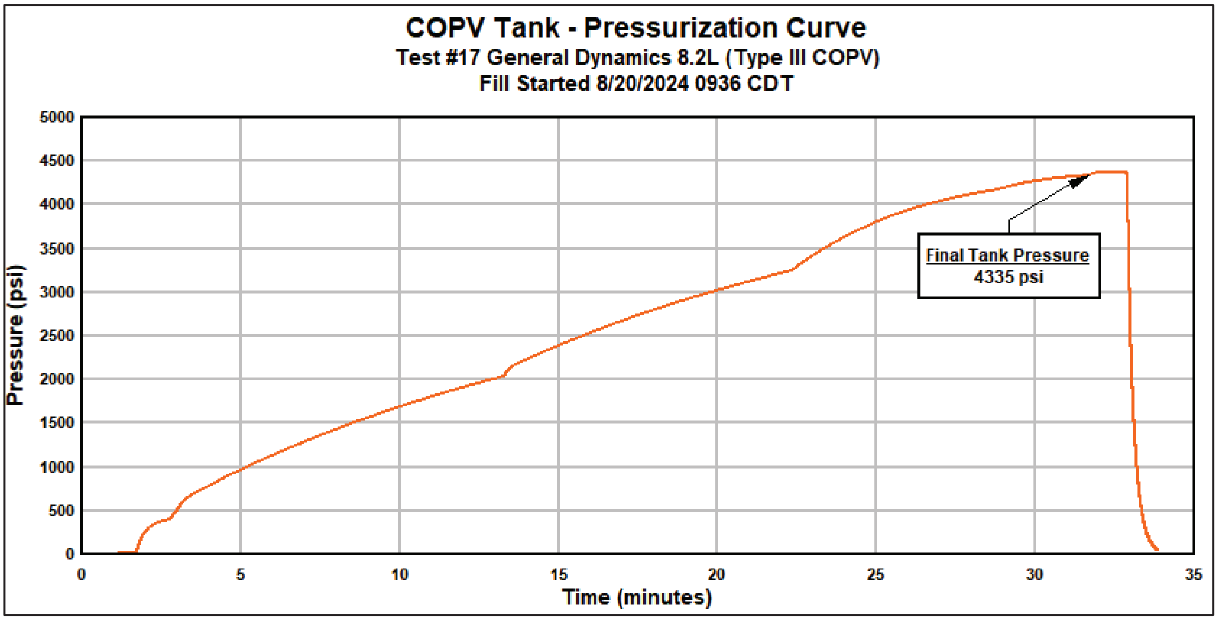

COPV Tank-Pressurization Curve
Test #12 Xperion 46L (Type IV COPV)
Started 8/15/2024 @ 1141
Tank Pressure (psi)
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
Time (minutes)
Final Tank Pressure 2915 PSI

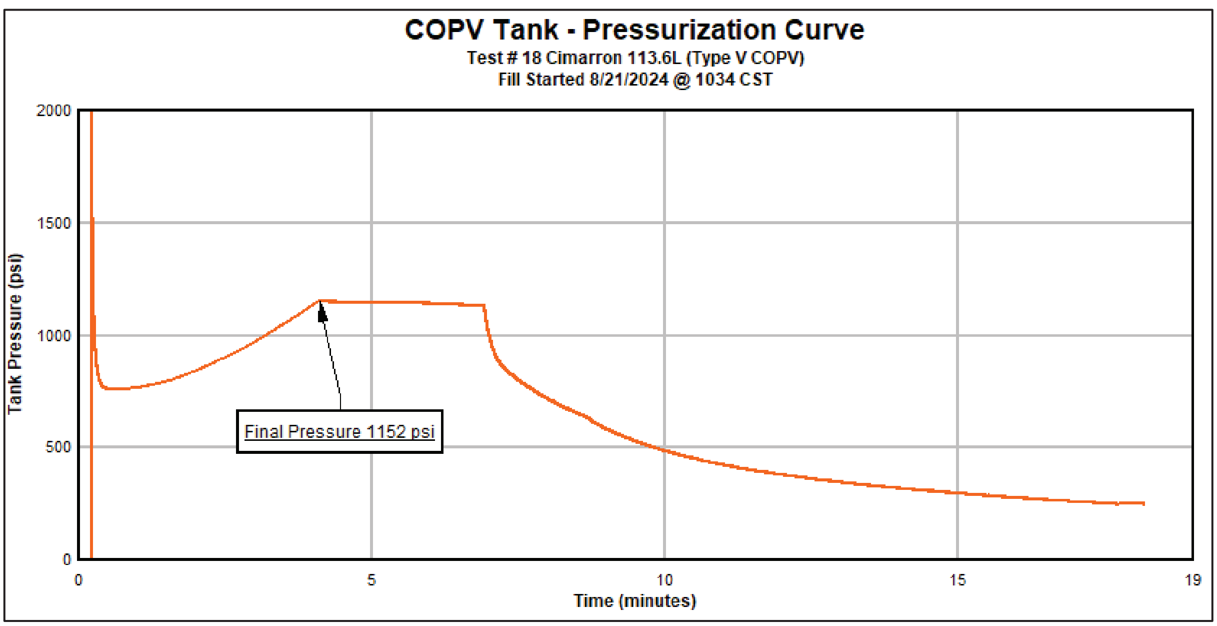

COPV Tank - Pressurization Curve
Test #13 Xperion 46L (Type IV COPV)
Started 8/15/2024 @ 1253 CDT
Tank Pressure (psi)
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0
2
4
6
8
10
12
14
16
18
20
22
24
25
Time (minutes)
Final Tank Pressure
2953 psi

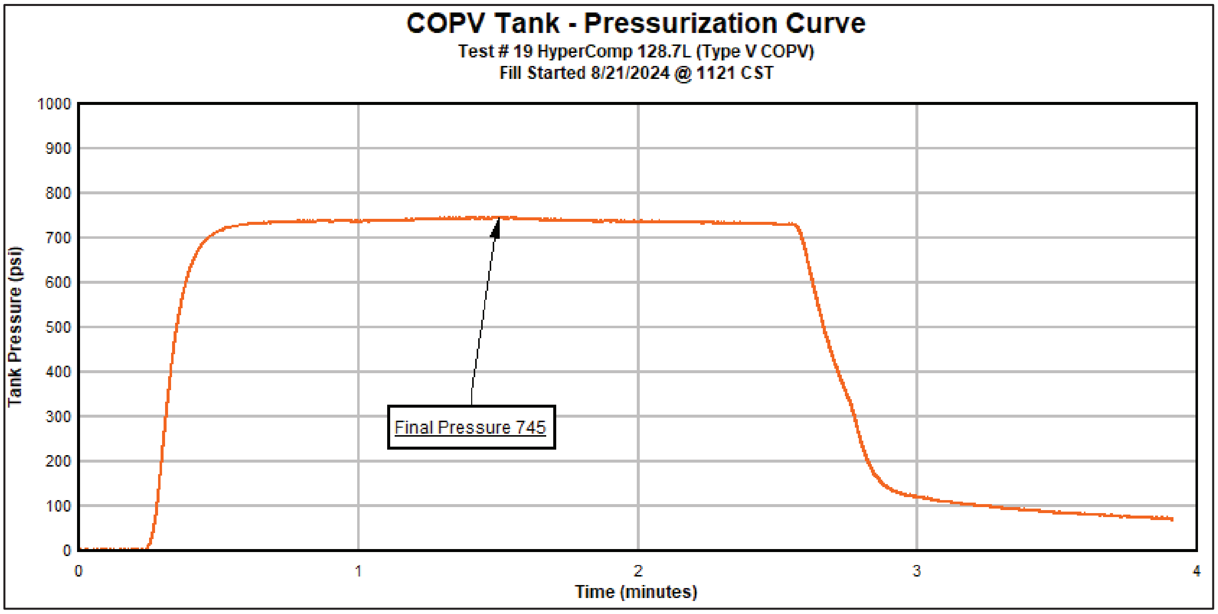

COPV Tank - Pressurization Curve
Test # 14 Infinity Comp 1.9L (Type V COPV)
Fill Started 8/15/2024 @1424 CST
Tank Pressure (psi)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
43
Time (minutes)
Final Pressure 4530 psi

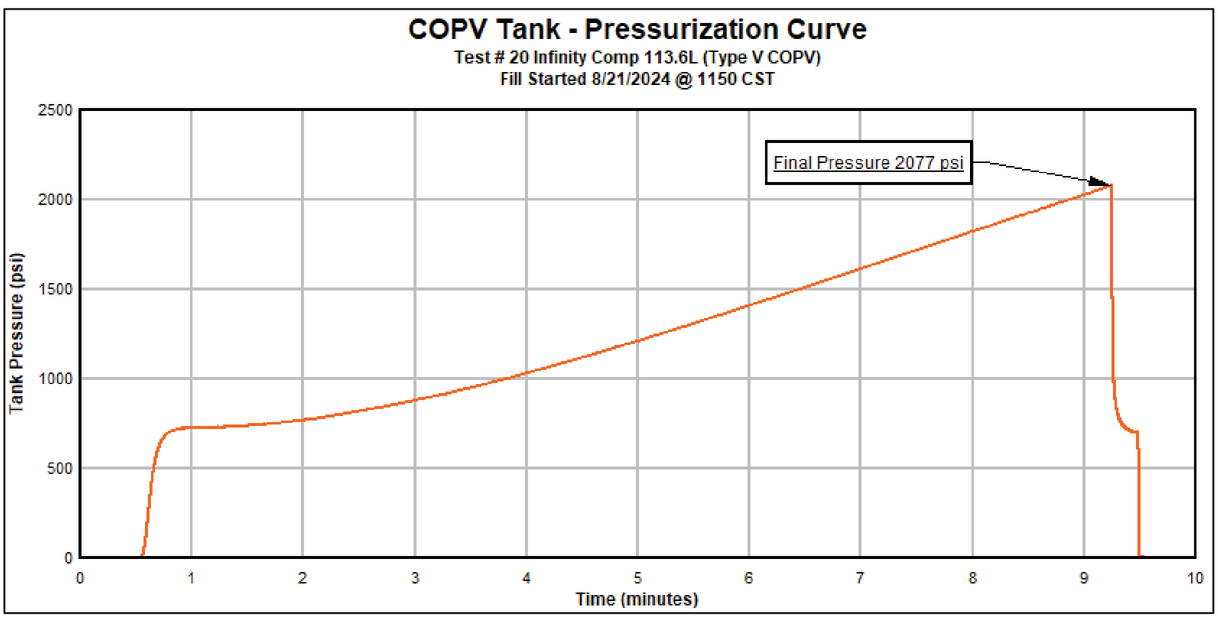

COPV Tank - Pressurization Curve
Test # 15 Infinity Comp 1.9L (Type V COPV)
Fill Started 8/19/2024 @ 0913 CST
Tank Pressure (psi)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
45
Time (minutes)
Final Pressure 4492 psi

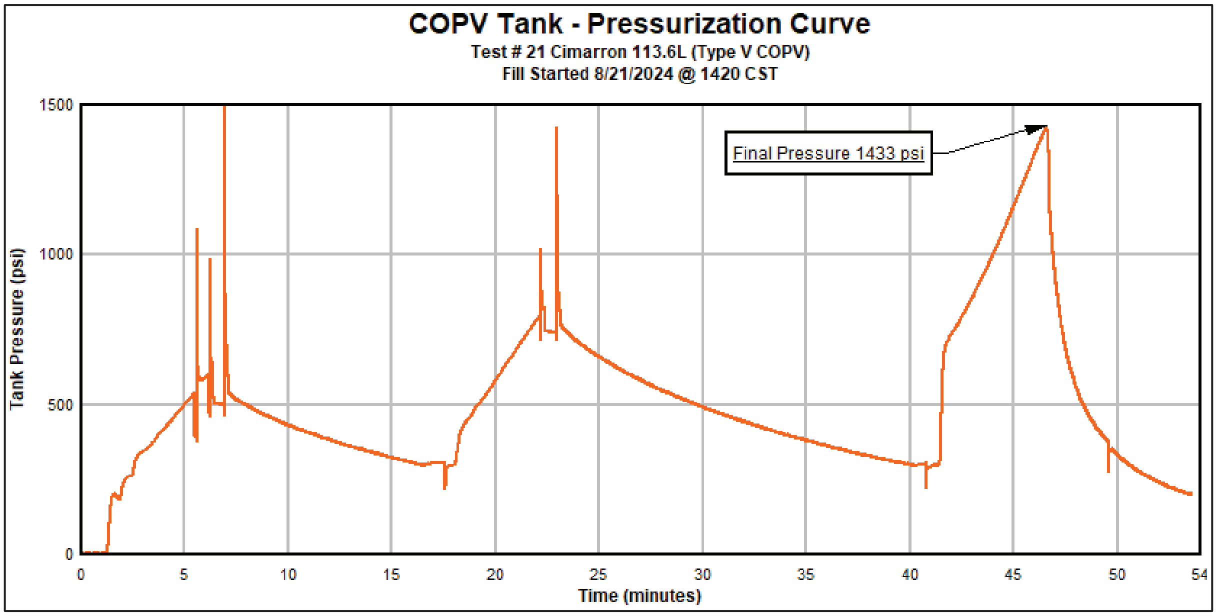

COPV Tank - Pressurization Curve
Test # 16 Infinity Comp 1.9L Type (V COPV)
Fill Started 8/19/2024 @1046 CST
Tank Pressure (psi)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
44
Time (minutes)
Final Pressure 4488 psi

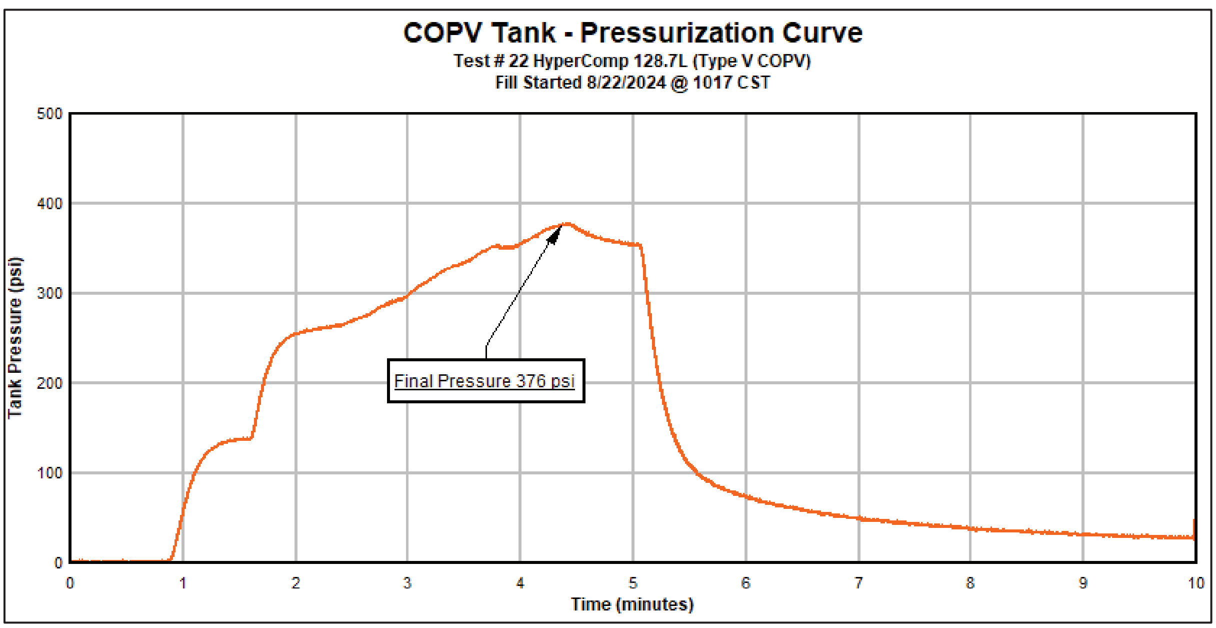

COPV Tank - Pressurization Curve
Test #17 General Dynamics 8.2L (Type III COPV)
Fill Started 8/20/2024 0936 CDT
Pressure (psi)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (minutes)
0
5
10
15
20
25
30
35
Final Tank Pressure
4335 psi

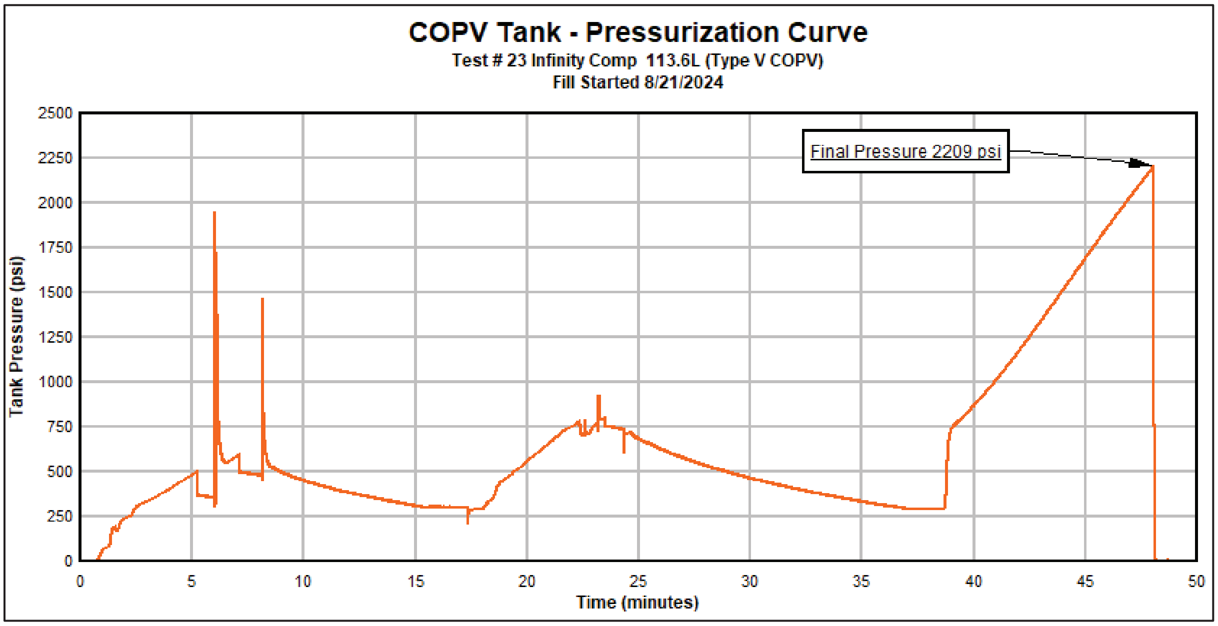

COPV Tank - Pressurization Curve
Test # 18 Cimarron 113.6L (Type V COPV)
Fill Started 8/21/2024 @ 1034 CST
Tank Pressure (psi)
0
500
1000
1500
2000
Time (minutes)
0
5
10
15
19
Final Pressure 1152 psi


COPV Tank - Pressurization Curve
Test # 19 HyperComp 128.7L (Type V COPV)
Fill Started 8/21/2024 @ 1121 CST
Tank Pressure (psi)
Time (minutes)
Final Pressure 745

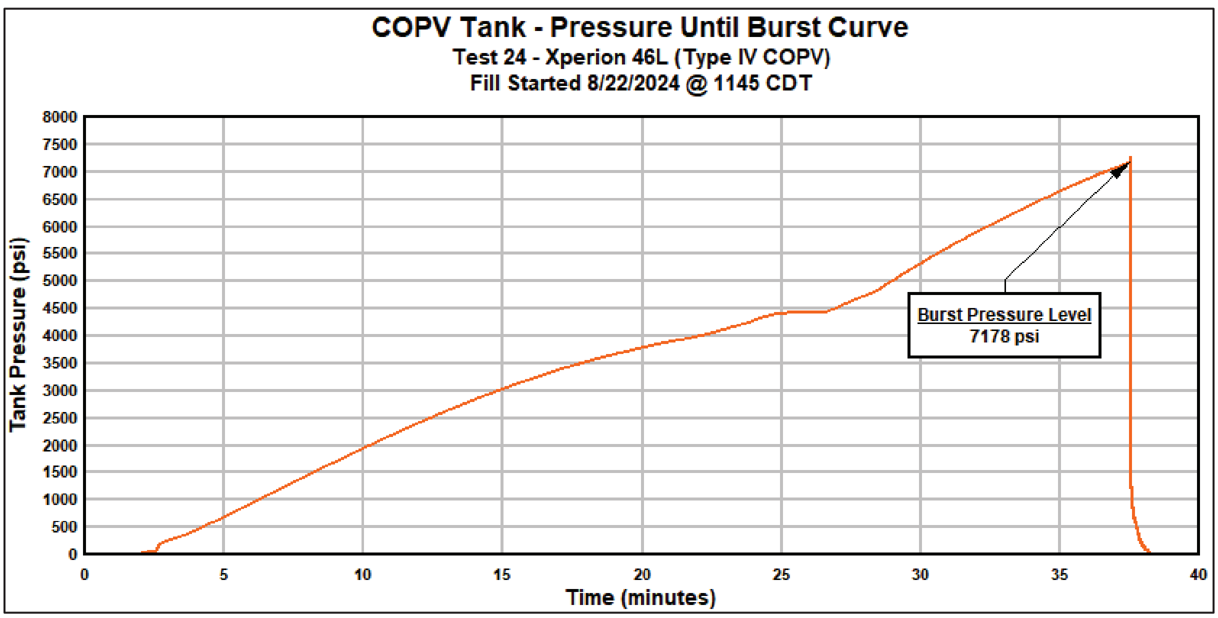

COPV Tank - Pressurization Curve
Test # 20 Infinity Comp 113.6L (Type V COPV)
Fill Started 8/21/2024 @ 1150 CST
Tank Pressure (psi)
Time (minutes)
Final Pressure 2077 psi


COPV Tank - Pressurization Curve
Test # 21 Cimarron 113.6L (Type V COPV)
Fill Started 8/21/2024 @ 1420 CST
Final Pressure 1433 psi
Tank Pressure (psi)
0
500
1000
1500
0
5
10
15
20
25
30
35
40
45
50
54
Time (minutes)

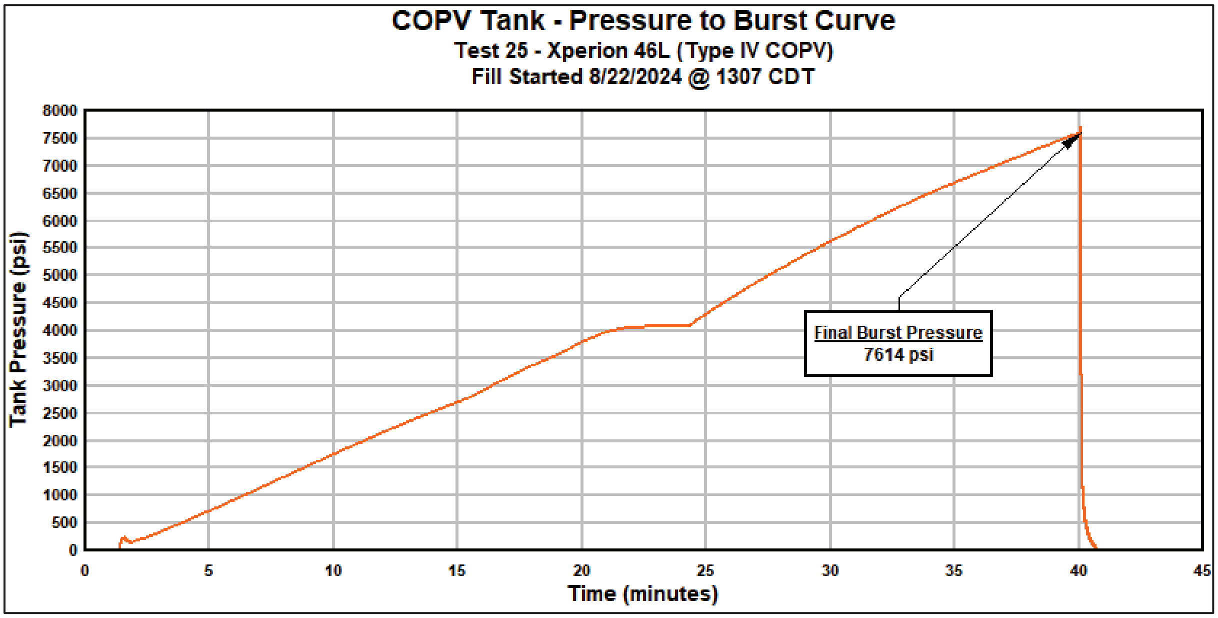

COPV Tank - Pressurization Curve
Test # 22 HyperComp 128.7L (Type V COPV)
Fill Started 8/22/2024 @ 1017 CST
Final Pressure 376 psi
Tank Pressure (psi)
0
100
200
300
400
500
0
1
2
3
4
5
6
7
8
9
10
Time (minutes)

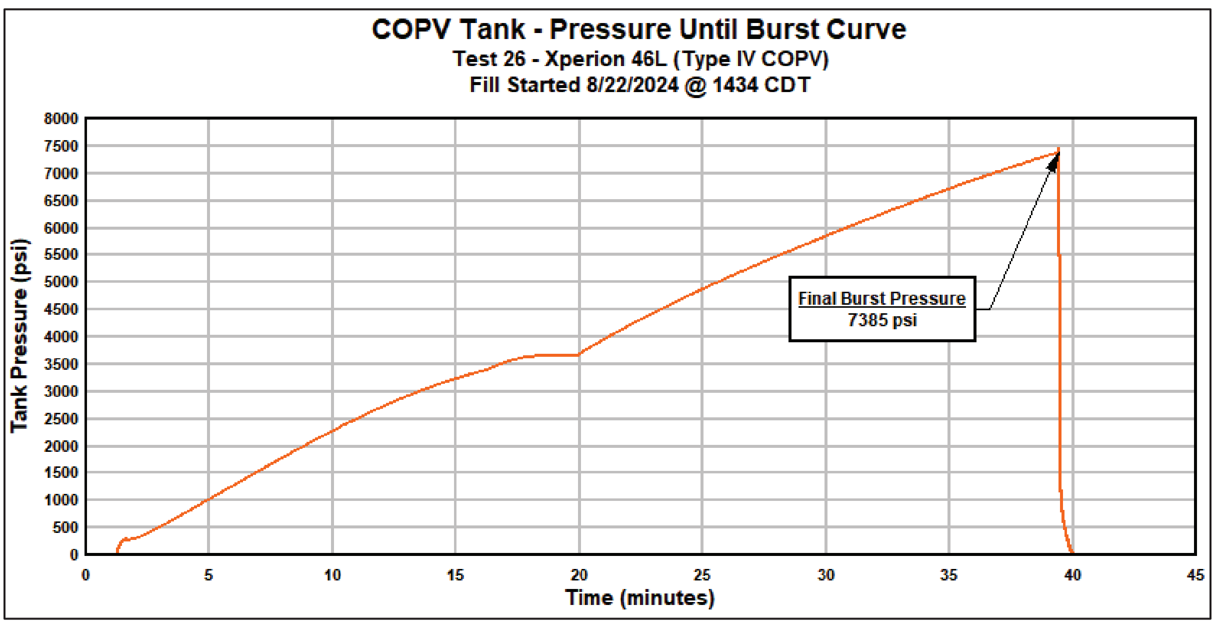


COPV Tank - Pressurization Curve
Test # 23 Infinity Comp 113.6L (Type V COPV)
Fill Started 8/21/2024
Final Pressure 2209 psi
Tank Pressure (psi)
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0
5
10
15
20
25
30
35
40
45
50
Time (minutes)



COPV Tank - Pressure Until Burst Curve
Test 24 - Xperion 46L (Type IV COPV)
Fill Started 8/22/2024 @ 1145 CDT
Burst Pressure Level
7178 psi
Tank Pressure (psi)
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5
10
15
20
25
30
35
40
Time (minutes)


COPV Tank - Pressure to Burst Curve
Test 25 - Xperion 46L (Type IV COPV)
Fill Started 8/22/2024 @ 1307 CDT
Tank Pressure (psi)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
Time (minutes)
0
5
10
15
20
25
30
35
40
45
Final Burst Pressure
7614 psi

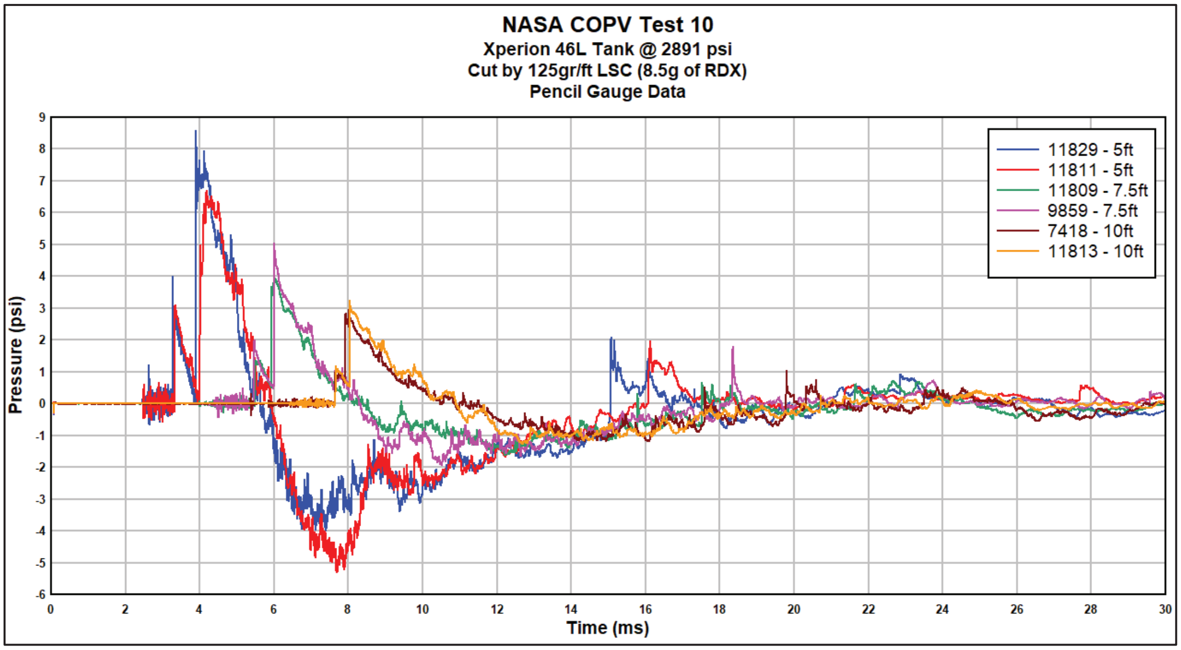

COPV Tank - Pressure Until Burst Curve
Test 26 - Xperion 46L (Type IV COPV)
Fill Started 8/22/2024 @ 1434 CDT
Tank Pressure (psi)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
Time (minutes)
0
5
10
15
20
25
30
35
40
45
Final Burst Pressure
7385 psi

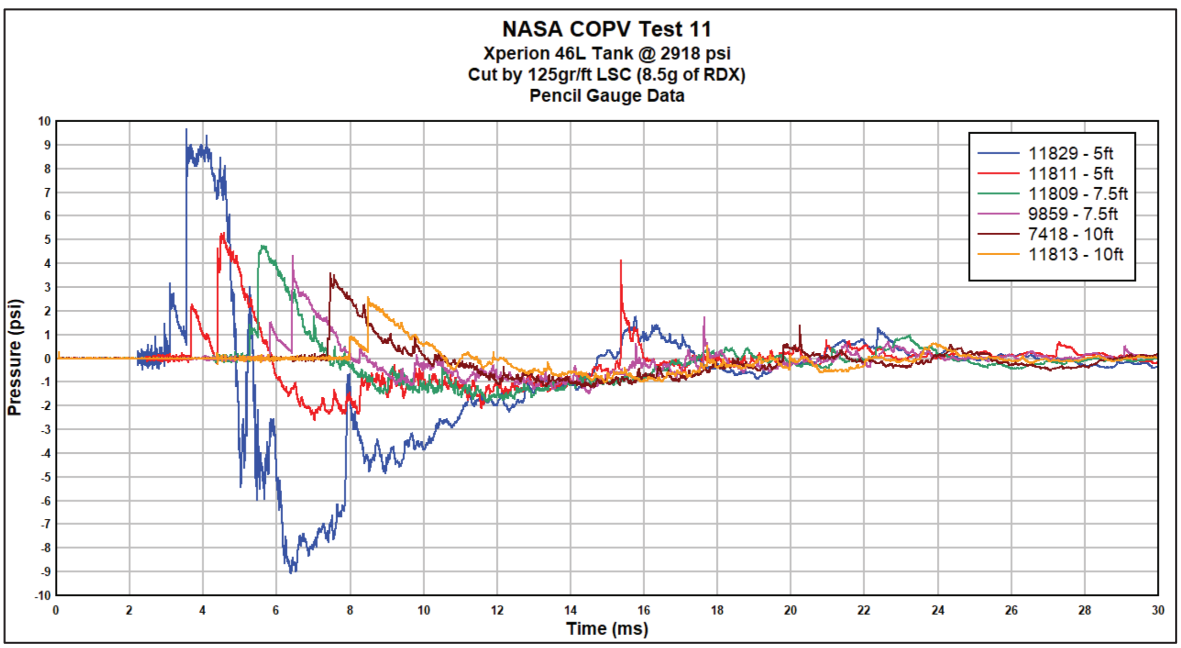
APPENDIX C

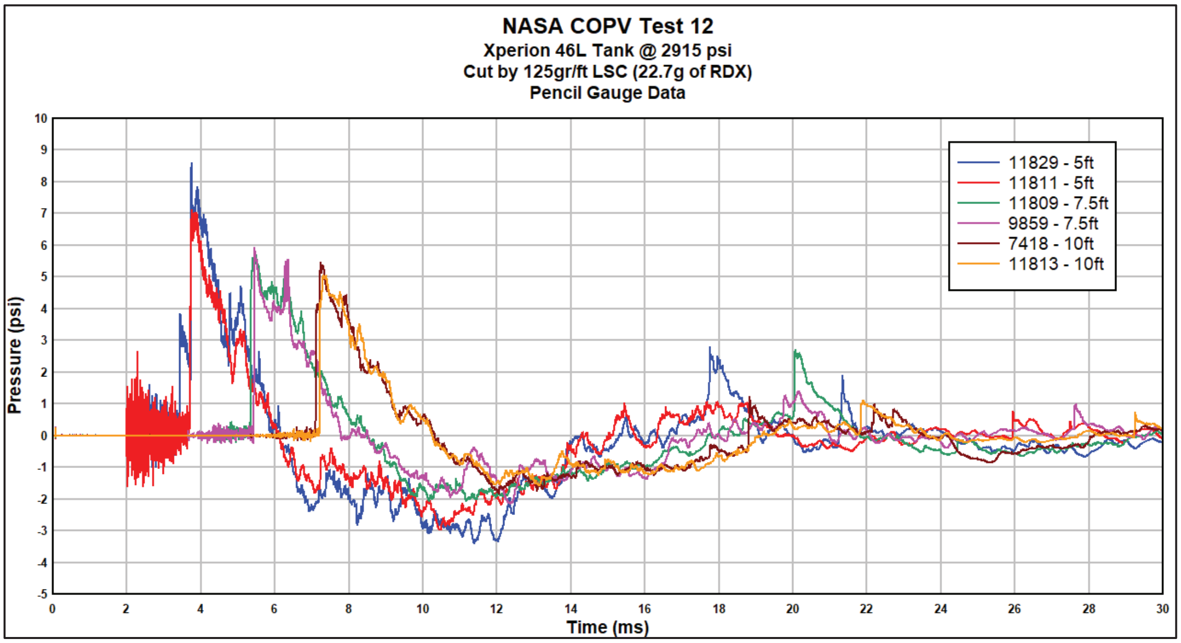
Pencil Gauge Blast Overpressure Curves

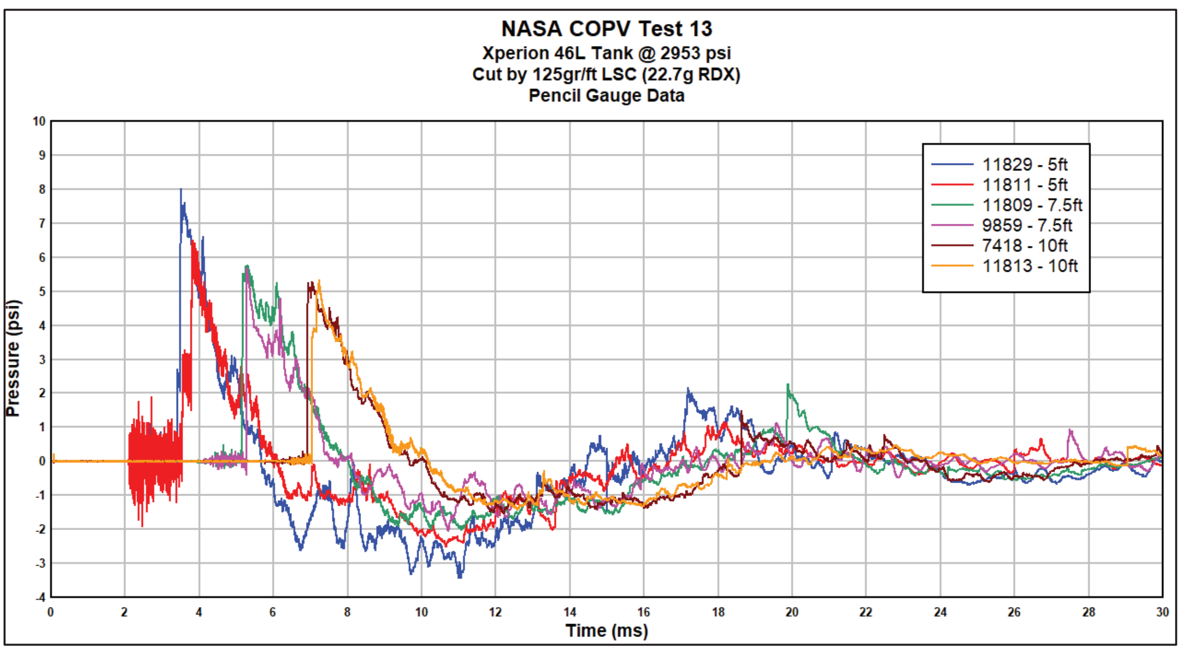
Appendix C – Pencil Gauge Blast Overpressure Curves

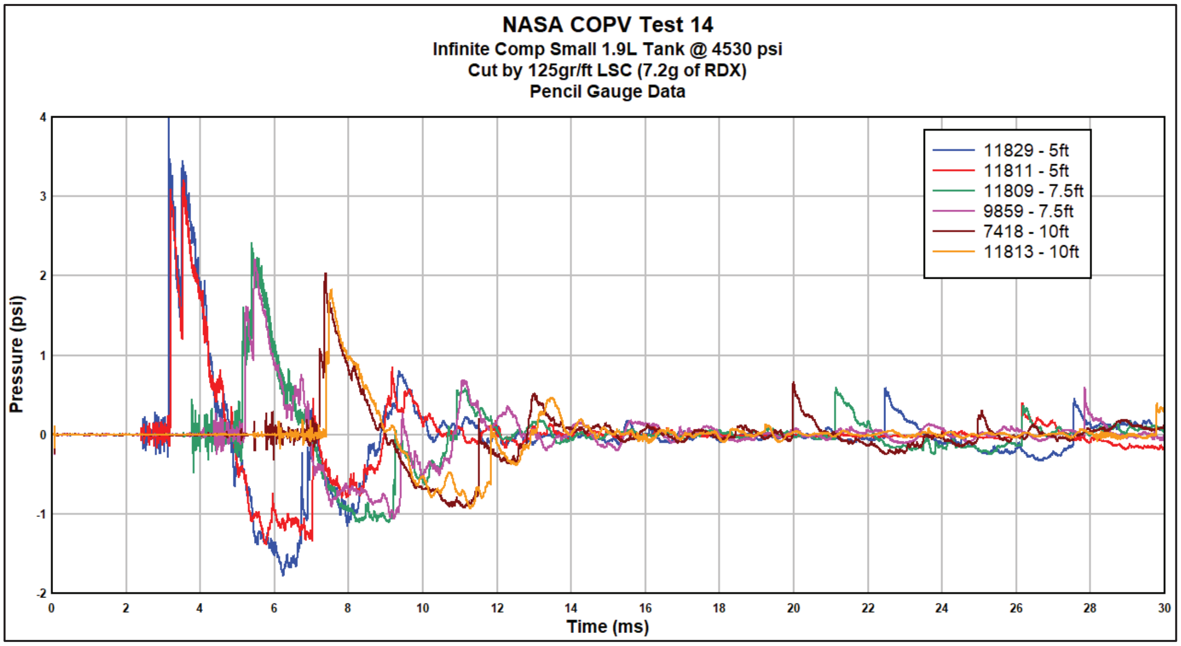
This appendix will include the raw data curves for each of the pencil gauge blast overpressure measurements captured during the test series. Pencil Gauges were only utilized on Tests 10-16. They will be displayed in the order that the tests were conducted.

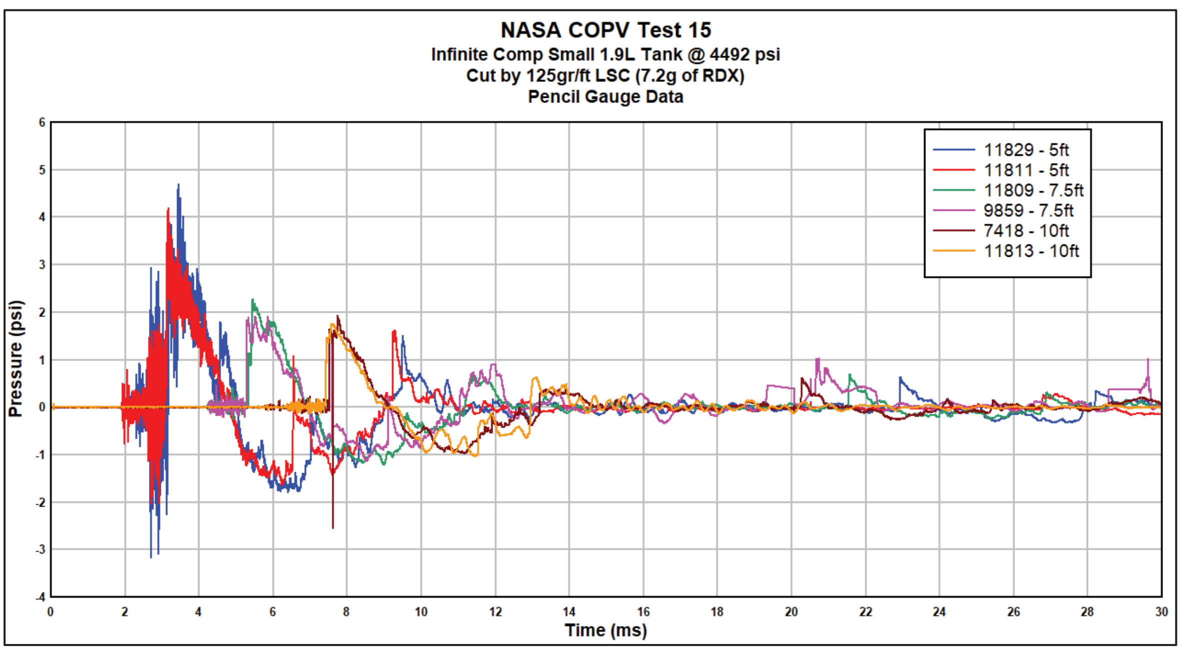


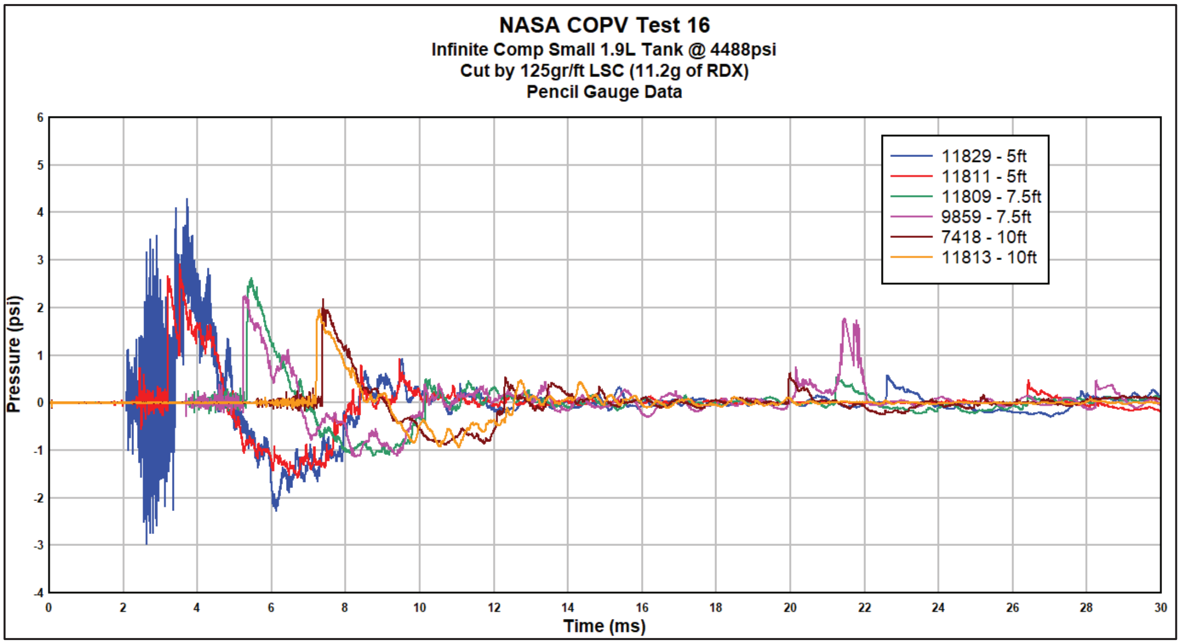



NASA COPV Test 12
Xperion 46L Tank @ 2915 psi
Cut by 125gr/ft LSC (22.7g of RDX)
Pencil Gauge Data
Pressure (psi)
Time (ms)
11829 - 5ft
11811 - 5ft
11809 - 7.5ft
9859 - 7.5ft
7418 - 10ft
11813 - 10ft


NASA COPV Test 13
Xperion 46L Tank @ 2953 psi
Cut by 125gr/ft LSC (22.7g RDX)
Pencil Gauge Data
Pressure (psi)
Time (ms)
11829 - 5ft
11811 - 5ft
11809 - 7.5ft
9859 - 7.5ft
7418 - 10ft
11813 - 10ft


NASA COPV Test 14
Infinite Comp Small 1.9L Tank @ 4530 psi
Cut by 125gr/ft LSC (7.2g of RDX)
Pencil Gauge Data
Pressure (psi)
Time (ms)
11829 - 5ft
11811 - 5ft
11809 - 7.5ft
9859 - 7.5ft
7418 - 10ft
11813 - 10ft


NASA COPV Test 15
Infinite Comp Small 1.9L Tank @ 4492 psi
Cut by 125gr/ft LSC (7.2g of RDX)
Pencil Gauge Data
Pressure (psi)
Time (ms)
11829 - 5ft
11811 - 5ft
11809 - 7.5ft
9859 - 7.5ft
7418 - 10ft
11813 - 10ft


NASA COPV Test 16
Infinite Comp Small 1.9L Tank @ 4488psi
Cut by 125gr/ft LSC (11.2g of RDX)
Pencil Gauge Data
Pressure (psi)
Time (ms)
11829 - 5ft
11811 - 5ft
11809 - 7.5ft
9859 - 7.5ft
7418 - 10ft
11813 - 10ft

Appendix D – List of Acronyms

AGL	Above Ground Level
AvMC	Aviation and Missile Center
BOP	Blast Overpressure Sensor
COPV	Composite Overwrapped Pressure Vessel
DAQ	Data Acquisition System
Det Cord	Detonating Cord
DEVCOM	Combat Capabilities Development Command
DoD	Department of Defense
EBAD	Ensign-Bickford Aerospace & Defense
EBW	Exploding Bridgewire
EOD	Explosive Ordinance Disposal
FLSC	Flexible Linear Shaped Charge (or Flex Linear)
Frag	Shorthand designation for Fragment
HMX	High Melting Explosive
JTCG/ME	Joint Technical Coordinating Group for Munitions Effectiveness
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NVR	Network Video Recorder
PDP	Pressure Distribution Panel
PETN	Pentaerythritol Tetranitrate
PSI	Pounds per Square Inch
PTZ	Pan-Tilt-Zoom
RDX	Royal Demolition Explosive
SCJ	Shaped Charge Jet
TDD	Technical Development Directorate