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V28 Test Report

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ABSTRACT

The V28 containment vessel was procured by the US Army Recovered Chemical Material Directorate (RCMD) as a replacement vessel for use on the P2 Explosive Destruction Systems. It is the fourth EDS vessel to be fabricated under Code Case 2564 of the ASME Boiler and Pressure Vessel Code, which provides rules for the design of impulsively loaded vessels. The explosive rating for the vessel, based on the Code Case, is nine (9) pounds TNT-equivalent for up to 637 detonations. This report documents the results of explosive tests that were done on the vessel at Sandia National Laboratories in Albuquerque New Mexico to qualify the vessel for explosive use. The primary qualification test consisted of six, 1.5 pounds charges of Composition C-4 (equivalent to 11.25 pounds TNT) distributed around the vessel in accordance with the User Design Specification. This test was repeated due to a lack of proper clamp settings. Two additional tests using less explosive were performed, one identical in configuration to a test performed in the V27 qualification series as a baseline for comparison, and one where the separation distance of the charges was increased to extend the V27 analysis of distributed load effects on the P2 vessel. *All vessel acceptance criteria were met.*

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
ASME	American Society of Mechanical Engineers
DIC	Digital Image Correlation
EBW	exploding bridgewire
EDS	Explosive Destruction System
PDV	Photon Doppler Velocimetry
RCMD	Recovered Chemical Materiel Directorate
TNT	trinitrotoluene (explosive)

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1. INTRODUCTION

The Explosive Destruction System (EDS), developed at Sandia National Laboratories, is designed to destroy recovered chemical munitions. The apparatus treats chemical munitions by accessing with explosive shaped charges and chemically neutralizing the contained agents. The process is conducted inside a stainless steel vessel which both contains the detonation and serves as a chemical reactor. As part of the acceptance process, each vessel is subjected to a 1.25X over-test.

The vessel was designed and fabricated per Section VIII Division 3 Revision 4 of Code Case 2564 of the 2019 ASME Boiler and Pressure Vessel Code. This is the fourth EDS vessel to be designed per the code case. The code states that the User's Design Specification shall provide the impulsive loading design basis and the impulse source location within the vessel (i.e., vessel center, off-center, etc.). Because EDS is used to destroy various munitions, it is necessary to define a design basis that blankets all munition configurations. The design basis for the first two vessels fabricated under Code Case 2564 was specified as a single bare charge in the center of the vessel. In the specification for this vessel, we opted to distribute six smaller charges, each with the same total explosive weight. The distributed configuration mimics the destruction of six munitions and provides more realistic strain data relative to actual operations. The distributed configuration has the effect of distributing the strain more evenly through the vessel so the strain at most locations is increased, but the peak localized strain directly adjacent to the charge is less.

The static pressure rating of the vessel is 2800 psi. The explosive rating, based on the code case, is 9 pounds TNT equivalent with distributed charges for up to 637 detonations. Prior to publication of the code case, vessels were designed based on Sandia-defined criteria that limited the pressure rating to 4.8 pounds TNT equivalent.

The vessel consists of a cylindrical cup, a flat cover or door, and clamps to secure the door. The vessel is sealed with a metal compression ring. A fragment suppression system is used to protect the vessel from high-velocity fragments during the detonation, as well as dissipate the blast. Basic vessel dimensions are shown in Table 1. The body is a deep cylindrical cup machined from a 316 stainless steel forging. The door is also machined from a 316 stainless steel forging. Fluid penetrations in the door have either 3/8 or 3/4-inch female coned-and-threaded fittings that adapt to tubing and valves. These fittings have a static pressure rating of 20,000 psi. A flange with four high-voltage electrical feedthroughs is bolted to the door and sealed with a small metal compression ring. These feedthroughs conduct the firing signals for the high-voltage exploding bridgewire (EBW) detonators. Small blast plates on the inside of the door protect fluidic components and electrical feedthroughs. A large blast plate provides additional protection.

The closure clamps are SA 372, grade J, Class 70 (4140 steel). They are secured with four threaded rods with threaded nuts on one end and hydraulic nuts on the other. The rods and nuts are SA 564 Grade 630 (17-4 PH) and SA 372, grade J, Class 70 (4140).

Table 1: EDS vessel dimensions

Overall length	71.89 inches
Inside length	56.58 inches
Outside diameter	36.53 inches
Inside diameter	29.22 inches
Door thickness	9.00 inches
Cylinder wall thickness	3.65 inches
Aft end thickness	6.30 inches

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2. TEST OBJECTIVES

Two tests were performed to qualify this vessel. The objective of the first test was to qualify the vessel for its intended use by subjecting it to a 125 percent over-test. The analysis for Code Case 2564 provides the analytical basis that the vessel design exceeds the in-plane equivalent strains at the 1.25X over-test and the fatigue life at the design impulse limit [6]. The explosive test was conducted to validate the Vessel Impulse Rating, shown below, which is specified in the User Design Specification for the V28 vessel [5]. This qualification test was repeated in the fourth test due to a miscalculation of clamping loads on the vessel door and better indicates the ability of the door seal system to maintain an adequate seal during dynamic loading. As such, certification of this vessel is based primarily on the vessel growth results of the first explosive test and the sealing efficacy from the final explosive test. The following excerpt from the user design specification describes the design impulse and vessel impulse rating [5].

> ***Design Impulse:*** *9 pounds TNT equivalent net explosive weight, consisting of simultaneous detonation of six 1.5 pound cylindrical charges distributed in two clusters of three located forward and aft with the centerline of each charge 4 inches from the vessel centerline and 20.7 inches from the nearest end. Detonation will occur at room temperature. The analysis of the plastic strain accumulation will be based on the 1.25X explosive qualification test consisting of six 1.875 pound TNT equivalent cylindrical charges distributed as described above. Vessel explosive rating for normal operation is 9 pounds of TNT.*
>
> ***Vessel Impulse Rating:*** *In an actual EDS operation, there can be multiple configurations of explosive charges dispersed around the vessel. There are also obstacles such as munition housings and the fragment suppression system that can dissipate or redirect the pressure shocks. Specific munition configurations will be evaluated and approved by the Army and operational procedures will be implemented to ensure that the actual impulse loads will not exceed the design basis load.*

Simply put, the criteria for success are that the measured strains do not exceed the calculated strains from the vessel analysis and are consistent with past acceptable results, there is no significant additional plastic strain on subsequent tests at the rated design load (shakedown), and there is no significant damage to the vessel and attached hardware that affect form, fit, or function.

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3. INSTRUMENTATION

Thin-film strain gauges (Vishay EP-08-250BG-120, 120 ohm resistive bridge) were installed on the EDS vessel in the configuration shown in Table 2. Additional biaxial strain gauges (Vishay CEA-06-250UT-120/P2) were installed on clamping system nuts and rods and one of the clamps and are also listed in the table. Plastic strain, or permanent vessel deformation, was measured after each test at six locations along the length of the vessel by measuring the outer diameter using a stainless steel π-tape around the circumference, as well as by processing the dynamic strain data from the records by comparing before and after static strain offsets. In the table below, 0 degrees is considered top-dead-center of the vessel body, 30-degree and 60-degree radial orientations are offset clockwise while facing the door of the vessel. All longitudinal offsets are measured from the interior aft end of the vessel. An offset of 1/3 is approximately 18.75 inches from the interior aft end, "mid-point" is approximately 28.125 inches from the interior aft end, and 2/3 is approximately 37.50 inches from the interior aft end.

Table 2: Strain gage location. Note that channels beginning with "E" were on the Ectron system and beginning with "S" were on the Synergy system.

Gauge #	Hoop/Axial	Channel	Longitudinal offset (% from interior aft end)	Radial offset (degrees)
1	H	E1	Vessel body 1/3	0
2	H	E2	Vessel body 1/3	30
3	A	E3	Vessel body mid-point	0
3	H	E4	Vessel body mid-point	0
4	A	E5	Vessel body mid-point	30
4	H	E6	Vessel body mid-point	30
5	A	E7	Vessel body mid-point	60
5	H	E8	Vessel body mid-point	60
6	H	S2	Clamp inside	90
6	A	S3	Clamp inside	90
7	H	S4	Clamp outside	90
7	A	S5	Clamp outside	90
8	H	S6	Threaded rod	N/A
8	A	S7	Threaded rod	N/A
9	H	S8	Nut	N/A
9	A	S9	Nut	N/A
10	H	E9	Vessel body 2/3	0
11	H	E10	Vessel body 2/3	30
12	A	S1	Body aft	N/A

In addition to strain gauges, photonic doppler velocimetry probes were located on the door (at the door center, and at four locations around the perimeter approximately two inches in from the outer radius) and the rear face (at two locations around the perimeter) of the vessel to determine movement of the door relative to the vessel during dynamic loading.

A helium leak test was performed on the main seal and the smaller feed-through flange seal before and after each test using approximately 15 psi of helium. On the first three tests, a pressure gauge was connected to the vessel door main leak-check port in order to determine leak annulus pressurization timing. On the fourth test, a balloon was placed over the main seal leak check ports in an effort to detect any transient leaks that occurred. The static pressure in the vessel was measured after each test. The vessel was inspected and photographed after each test. The vessel seal ring was inspected and re-used for all four tests.

4. TEST DESCRIPTIONS

The qualification test series consisted of two 9 lb Composition C-4 (11.25 lb TNT equivalent) qualification tests. The first explosive test was the initial attempt at a qualification test for V28. This test consisted of 6 each 1.5 lb cylindrical charges of Composition C-4 (11.25 lb total TNT equivalent) configured in the orientation shown in Figure 1. The explosive was packed into a 2.5-inch inside diameter, 5.25-inch-long, thin plastic tubes to a density of about 1.6 g/cc. An EBW detonator and 1/2-inch by 1/4-inch Tetryl booster pellet was placed on each charge (Figure 2), oriented towards the ends of the vessel. All detonators were initiated simultaneously (within tens of nanoseconds). The charges were held with 1/4-inch thick sheets of Styrofoam poster board—see Figure 3. The axis of each charge was oriented parallel to the axis of the vessel, centered about the vessel axis on an 8-inch diameter circle. Two sets of 3 charges were positioned flush on an 8-inch circle so that one set was forward, and one set was rearward. The two sets of charges were separated by approximately 10 inches center to center. The forward set of charges was clocked radially so that one charge was bottom-dead-center, with other two at 120 degrees offset locations. The rear set of charges was oriented so that one charge was top-dead-center, with the other two charges at 120-degree offset locations. It was noted after the test that the clamps were not tightened adequately (hydraulic nuts tightened to 1700 psi), and so it was determined that a repeat was necessary and would be conducted at the end of the series.

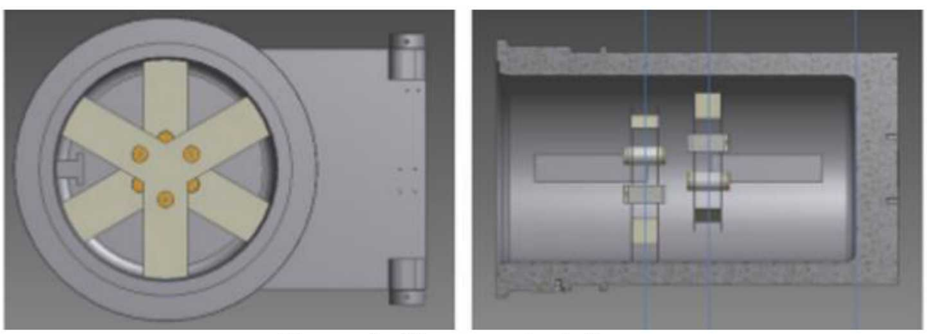

Figure 1: Charge orientations

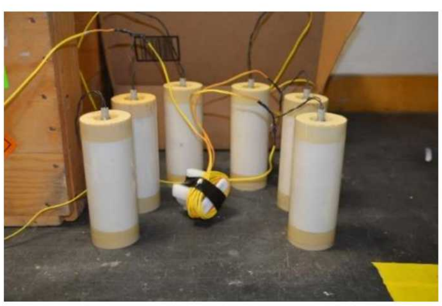

Figure 2: Individual charges packed into plastic bottles—detonator adapter shown at center.

Figure 3: Six 1.5 lb C-4 charges (11.25 lb TNT equivalency) arranged in the V28 vessel.

The final test was an exact repeat of the first test. This test was performed to complete the qualification process in terms of measuring the ability of the vessel to maintain its seal during and after the explosive event. For completeness of analysis, the vessel growth from test one was noted for equivalent plastic strain metrics, and the seal efficacy of the final test was used to highlight the V28 vessel ability to maintain its seal during loading.

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5. RESULTS AND COMPARISONS

The results of the two qualification tests are presented here. For results of two additional non-qualification-related tests, refer to Appendix A.

5.1. Dynamic Testing

For the V28 9 lb C-4 distributed-charge qualification test, the highest vessel body peak strain was recorded for gage #3H, Channel E4 (Table 2: mid-point hoop, top dead-center). Transient strain data from that gage are plotted in Figure 4. The peak strain value was approximately 1500 microstrain. The figure below shows this data plotted with the same location from the V27 testing. The data have been smoothed to eliminate confusing noise. These two datasets were obtained with different strain gage systems, but the results are very similar, giving confidence that these measurements are real and accurate.

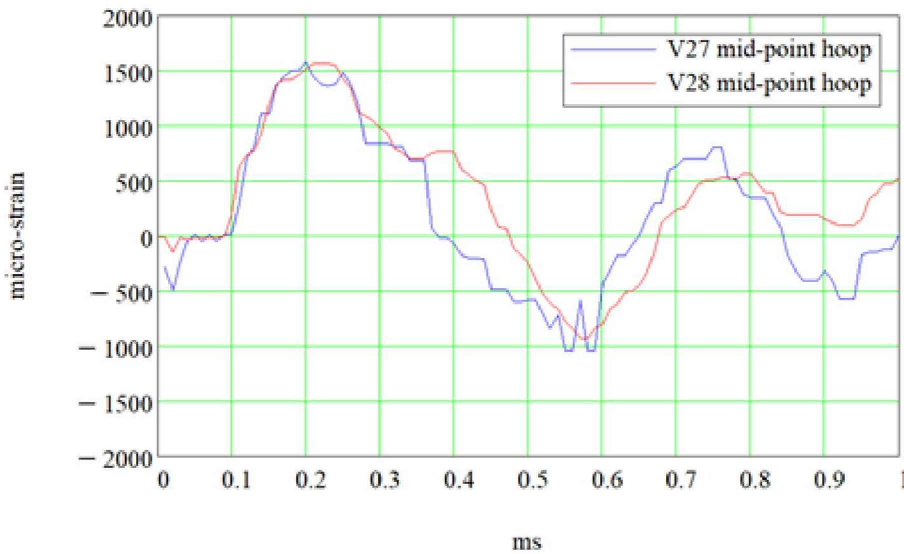

Figure 4: Comparison of dynamic strain at vessel body mid-point for 9 lb C-4 (11.25 lb TNT) distributed charge for V27 and V28 qualification tests.

Plastic strain, or permanent vessel deformation, can be calculated from changes in the outer diameter of the vessel measured with a stainless steel π-tape at six locations along the length of the vessel. For V27 qualification testing, the π-tape measurements made before and after the V27 distributed charge test showed an increase of between 0.015 and 0.020 inches around the mid-point of the vessel body, indicating an average permanent strain of about 508 microstrain, and using the data analysis technique, a value of about 400 microstrain was determined. For V28, the data analysis technique resulted in a permanent strain of about 505 microstrain, consistent with the V27 results. The π-tape measurements on the V28, however, showed a worst-case dimension change of only about 0.003", which translates into a permanent strain of about 85 microstrain.

The data analysis technique correlates better with results from V27. Regarding the differences in π-tape measurements, we suspect that environmental temperature changes from pre-shot π-tape measurements to post-shot measurements may be the culprit. For V28, these pre- and post-test measurements were taken on different days and at different times of day. The pre-shot measurements were not taken just prior to testing, and so thermal expansion could have provided for an error in differential measurements. Because of this misstep, we have used the more conservative data analysis technique (described in detail in the V27 Qualification Test Report, [4]) for the vessel qualification criterion. This technique showed remarkable correlation for V27 results and makes a dimensional comparison just before and just after detonation, eliminating any chance of thermal expansion errors. The worst-case dimensional change was calculated to be 505 microstrain, or 0.0182 inches, or 0.05 percent, which is still well below the ASME threshold for effective plastic strain of 0.2 percent. These values are compared in Table 3.

Table 3. Comparison of strain results between V27 and V28. Note that the measurement is red is expected to be incorrect, as discussed previously.

	π-tape method		Dynamic strain data analysis method	
	Mid-point µstrain	Effective plastic strain	Mid-point µstrain	Effective plastic strain
V27	508	0.05%	400	0.04%
V28	85	0.008%	505	0.05%
Code Case 2564	2000 max	0.2% max	2000 max	0.2% max

5.2. Leak Checking

The helium leak rates at the vessel body seal and at the detonator feed-through seal were measured before and after each test. All measurements were within accepted values (less than 2.0E-3 atm-cc/s, nearly equivalent to mbar-L/s) except for the post-shot door leak rates on Tests 1 and 2, which were 4.9E-3 and 4.2E-3 atm-cc/s, respectively. In each test, either a balloon was placed over the leak check ports or a pressure sensor was adapted to the port. Table 4 lists the results for each test. A helium sniffer was used to determine the presence of helium in the balloon volume.

Table 4: Leak check results

Test	Pre-shot leak check passed? (door/flange)	Post-shot leak check passed? (door/flange)	Balloon inflated? (door/flange)	Contents contained He? (door/flange)
1	yes/yes	no/yes	not applicable/no	yes/no
2	yes/yes	no/yes	not applicable/no	no/no
3	yes/yes	yes/yes	not applicable/unknown*	no/unknown*
4	yes/yes	yes/yes	yes/no	yes/no

* The leak check port separated from the feedthrough flange, so it is unknown whether the balloon would have been inflated or contained He.

6. CONCLUSIONS

The EDS V28 explosive containment vessel has been qualified for use at its design working load rating of 9 lb TNT-equivalent through a 125 percent explosive over-test. The test results meet ASME code criteria—presented in detail in Table 3–and the vessel is fit for use. Acceptable post-detonation helium leak check values were obtained on both the door and feed-through flange on the latter qualification test.

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7. REFERENCES

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[2] Stofleth, J. H. (2012). *Memo to Department of Defense Explosive Safety Board: Determination of the TNT Equivalence of Composition C-4 for Use in the Explosive Destruction System Containment Vessel Ratings.*

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[4] Stofleth, J. H., Tribble, M. K., & Crocker, R. W. (2017). *V27 Test Report (SAND2017-4840).* Albuquerque: Sandia National Laboratories.

[5] US Army. (2017). *Purchase Order W52P1J-17-C-0010 to Grayloc Industries, User Design Specification: Explosive Destruction System (EDS) Vessel.*

[6] Analysis for Code Case 2564-4, Analysis of Grayloc Pressure Vessel Assembly, Grayloc Report 12398, Aug 28, 2018, included in *Grayloc Manufacturer's Data Book CH50795-DB01 , Oct 10, 2018*.

APPENDIX A. OTHER MEASUREMENTS OF INTEREST

The non-qualification-related tests and results are presented in this appendix.

A.1. Test Objectives

In the second and third tests, two orientations were used to hold six charges of a reduced explosive loading (6-0.8 lb C-4, which is 6 lb TNT equivalent, [2][3]) in order to provide insight into the effects of minor variations in placement and orientation of the charges. These tests are also important in providing input for hydrocode calculations for further predictions of various alternative orientations of munitions. The first of these two tests was a repeat of one of the tests performed on the V27 during qualification testing in order to provide a true reference for dynamic loads from that test series. In the second of these two tests, the six charges were separated further than in the first test, thus extending our ability from V27 testing to analyze distributed loads from actual distributed chemical munitions orientations. An additional objective of these tests was to better understand the loads placed on the clamp fasteners (threaded rods and nuts) to attend to intermittent issues with rod galling in operational use of other similar systems.

A.2. Test Descriptions

The two non-qualification-related explosive tests consisted of 6 each 0.8 lb C-4 cylindrical charges (6 lb total TNT equivalent). The explosive was packed into a 2 inch inside diameter, 4.375 inch long cardboard shipping tube to a density of about 1.6 g/cc with an EBW detonator and Tetryl booster placed toward the vessel ends. The charges were held with 1/4-inch Styrofoam board. In each of the two reduced-weight tests, the charge axes were oriented on 8-inch circles in two groups of three charges so that the center line of each group was centered about the central axis of the vessel. In each test, the rotational clocking was set as for Test 1.

In the first of these two tests, the orientation was kept exactly the same as in the V28 qualification test with the longitudinal center-to-center separation at approximately 10 inches. This test was a repeat of the first reduced-weight test conducted in V27 in order to verify repeatable results between V28 testing and V27 testing (note the orientation in Figure 1).

In the second of these two tests, the radial orientation was maintained, but the separation distance was increased to 30 inches center-to-center in order to extend the results from V27 testing, moving the charges closer to the door and aft end than had previously been tested. It was determined that this large separation distance mimics more closely the actual location of munitions destroyed in the 6-pack configurations in EDS.

A.3. Results and Comparisons

A.3.1. Extension of Distributed 4.8 lb C-4 (6 lb TNT) Charge Orientations from V27 to V28

The purpose of V28 Tests 2 and 3 were to extend the results obtained from V27 testing on the effects of orientation of the distributed charges. As the V27 and V28 vessels are the same size and design, obtaining closely-matched results from similar tests in V27 and V28 bolsters confidence in the measurements obtained in both campaigns.

In V27 testing, the six charges were positioned in groups of 3 on two planes along the length of the vessel. In two of the V27 tests, the charge groups were clocked so that one group had charges at top-dead-center (TDC), at 120 degrees from TDC and at 240 degrees from TDC; while the second group had charges at 60 degrees from TDC, at 180 degrees from TDC (or, bottom-dead-center), and at 300 degrees from TDC. Figure 1 shows this orientation. The geometry that was varied in these two tests was the distance that separated the two charge planes. In one test, the charges were separated by 10 inches on center, and in the second test, the separation distance was increased to 18 inches. For V28, Test 2 (10 inches separation) was set up identically to Test 2 in V27 (clocked as described above and separated by 10 inches on center). This test allows for direct comparison of V27 and V28 results for this orientation.

In Figure 5, the matching tests of V27 Test 2 and V28 Test 2, 4.8 lb C-4 (6 lb TNT equivalence) with a separation distance of 10 inches are shown. The strain traces are very similar, providing confidence in the V28 Test 3 (30-inch separation) results.

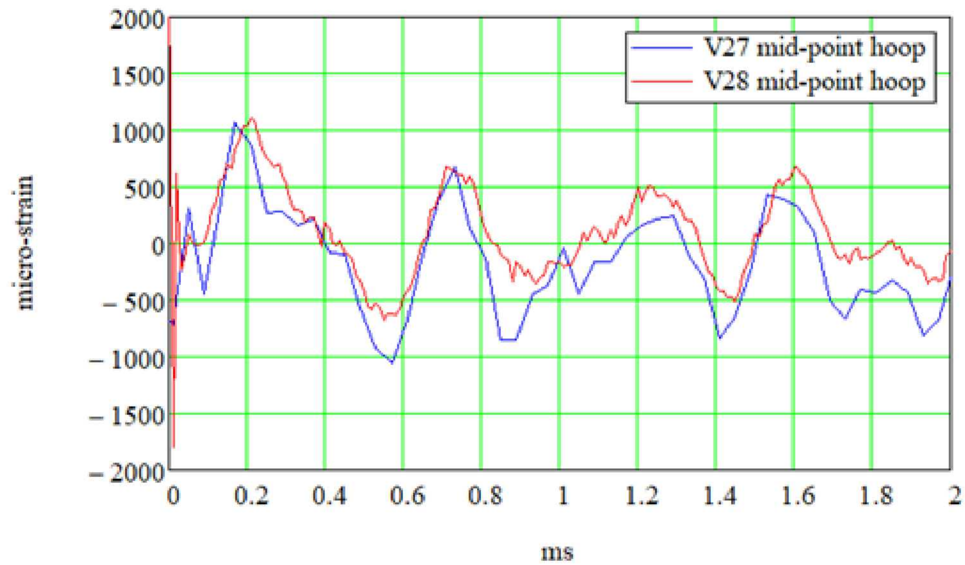

Figure 5: Comparison of dynamic strain at vessel body mid-point, 60 degree gauge for 4.8 lb C-4 (6 lb TNT) distributed charge for V27 and V28 for the planar separation of 10 inches.

The mid-point strains from these three tests is shown in Figure 6 below. In general, the strain magnitudes at on the body of the vessel show very little variation between configurations. The trace for the V27 18-inch test clips the window in a few places, but this is due to a loose connection in this particular sensor (these areas do not indicate real strains).

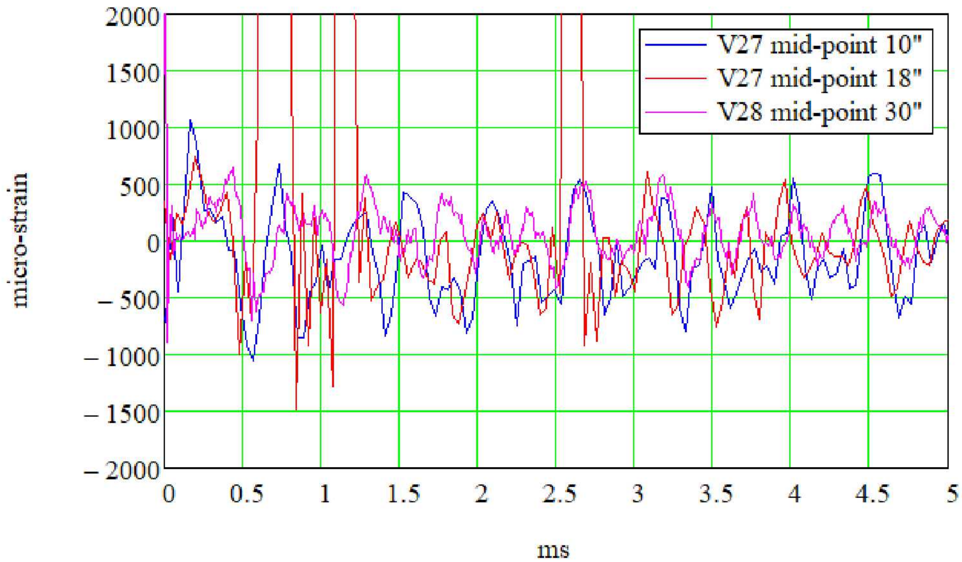

Figure 6: Comparison of dynamic strain at vessel body mid-point, 60 degree gage for 4.8 lb C-4 (6 lb TNT) distributed charge planar separation distances of 10 inches, 18 inches, and 30 inches. Excessive red trace peaks are due to a loose connection—not real strains.

A.3.2. Vessel Door Motion

Measurements were taken on the motion of the V28 vessel door and body—both to compare with the results of a previous similarly-sized vessel (V26) and to study the dynamic response of the vessel. In V26 qualification testing, a Digital Image Correlation (DIC) technique was used. This technique can be expensive, requires long setup time, and requires painting of the vessel door for imaging. DIC provides a measurement of the displacement of the entire surface of the door by mapping a series of stereo images over the duration of motion. Since the motion and deflection of the door is fairly symmetric about the center point, it was deemed unnecessary to map the entire door surface. As well, this technique measures the motion of the door with no reference to the motion of the vessel body, so without the addition of a reference, there is some associated bulk error. For V27 testing, no measurements were made of door motion, other than strain-based deflection.

So, for V28, a simpler method was used, Photonic Doppler Velocimetry (PDV). For PDV, a set of discrete points is measured using a frequency shift of laser light at each point (interferometric method). A series of seven fiber-based gages were positioned to measure five points on the door, shown in Figure 7, and two points on the rear of the vessel. Measurements were made at the center point of the door, and four points around the perimeter, located about 2 inches in from the door edge at top, bottom, left and right points. Two gages were located on the rear of the vessel at accessible locations. In this way the bulk motion of the vessel body could be added to the motion of the door, and a true separation measurement could be made. Reviewing all the PDV data provides insight into several factors of vessel body and door motion during detonation. Table 5 below shows the results from all PDV measurements.

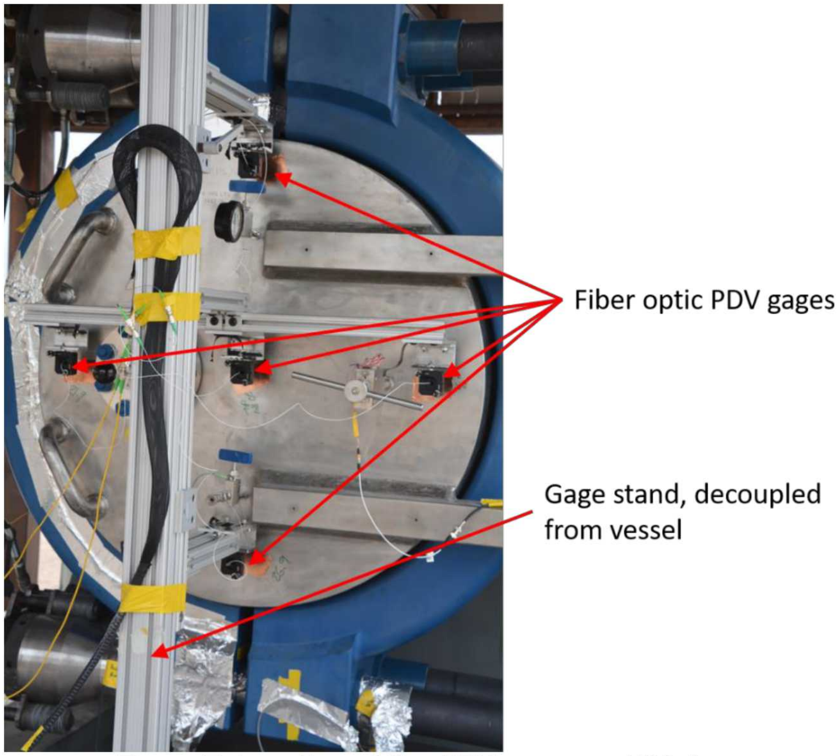

Figure 7: Location of five PDV gages on V28 door

Table 5: PDV results. Displacements measured in millimeters.

Test	Max door center	Average top/ bottom	Average sides	Average all edges	Average rear edges	Door edges plus rear (seal separation)	Door deflection (door bending)
1) 9 lb	1.52	1.36	XX	1.36	0.58	1.94	0.16
2) 6 x 0.8 lb, 10 in. spacing	0.60	0.55	0.33	0.44	0.24	0.68	0.16
3) 6 x 0.8 lb, 30 in. spacing	0.35	0.24	0.20	0.22	0.36	0.58	0.13
4) 9 lb	0.91	0.80	0.62	0.71	1.27	1.98	0.20

Door/vessel separation can be gleaned from adding the average door edge motion plus the average vessel aft motion. This is shown in the next to last column. Note that the total motion for Tests 1 and 4 are consistent at 1.94 and 1.98 millimeters. The reduced-weight distributed charges impose a door/vessel separation of 0.68mm for the closely spaced charges and 0.58mm for the charges placed closer to the ends. This is a bit counterintuitive, but overall, the results indicate that there is no disadvantage in placing the charges closer to the door. The overall motion is related to the overall charge weight for this configuration. Even though the clamps were under-tightened in Test 1, it appears there is no variation in the total separation of the door dynamically.

The last column indicates that the bending (strain) in the door is fairly consistent over all the tests. Tests 1 and 4 should be identical, but there is a slight difference. It is unclear if this is real, or whether it is noise in the data. For the two distributed charge configurations (Tests 2 and 3), there is a slight decrease in bending when the charges are placed closer to the ends. This result is counterintuitive, but again, it is not clear whether this is a real effect or simply noise in the data. The data show that there is not much difference in door strain based on charge location. If the numbers are averaged, the door bending for the 9 lb tests (0.18mm) is somewhat greater than for the reduced-weight, distributed tests (0.145mm).

The data for center-point door deflection from V26 (DIC) and V28 (PDV) are consistent. Both tests (Figure 8 and Figure 9) show a bulk door motion of about 1.5mm at just over 1ms from detonation.

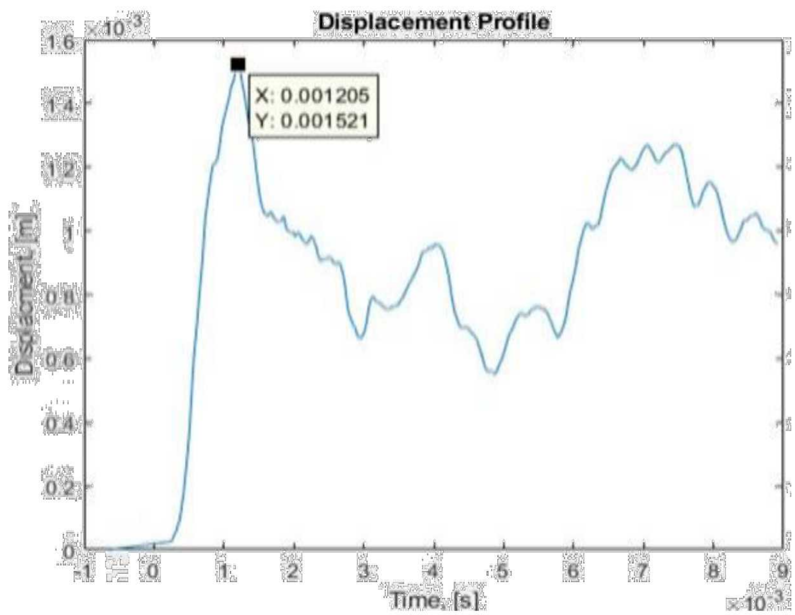

Figure 8: V28 qualification (9 lb C-4) door displacement from PDV

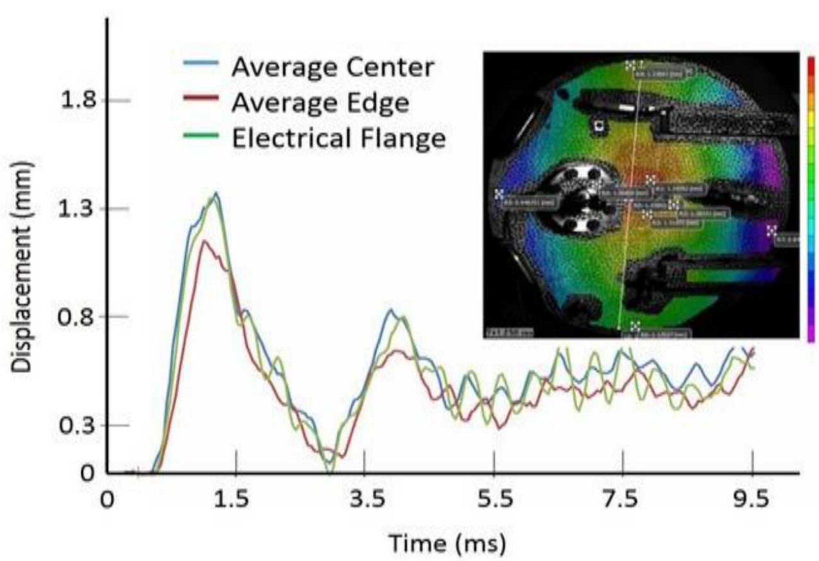

Figure 9: V27 qualification (9 lb C-4) door displacement from DIC

A.3.3. Strain in Threaded Rod and Nut

Figure 10 shows the axial strain seen in the threaded rod and nut during Shot 1. Note the data have been smoothed. As expected, both components see the same major peaks, with the peak observed strain occurring at 1.5 ms (compressive) and just after 4 ms (tensile). Two obvious regions without peaks ("quiet" regions) are visible, one centered at 2.4 ms and the other at 4.8 ms. It is expected that the timing of these regions indicates the breathing cycle of the vessel. The event appears to begin at about 630 μs. The initial peak that is shown in this plot and subsequent plots is noise from the firing lines and is not real.

Unfortunately, the strain data for the threaded rod and nut in Shots 2-4 was collected at too low of a sampling rate (5 kHz) to draw any conclusions. However, since Shot 1 was the larger charge weight with the door clamp insufficiently tightened/constrained, the strains observed are likely the maximum strain that those components will experience.

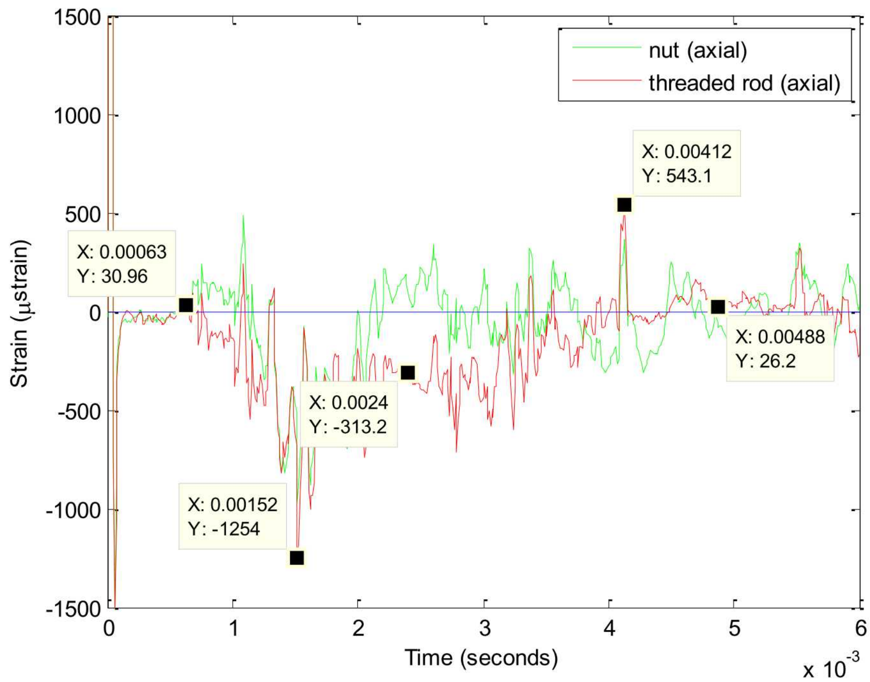

Figure 10: Strain in the threaded rod and nut on Shot 1

A.3.4. Strain in the Door Clamps

Figure 11 shows how the hoop strain on the inside of the door clamp compares to the outside on Shot 1. Note the data have been smoothed. As expected due to its semicircular shape, the outside strain is more extreme than the inside strain. The same "quiet" regions discussed in the previous section are again centered at 2.4 and 4.8 ms. The maximum strain is in compression on the outer face of the clamp—this makes sense, as the gage element was located nearly at the center where it is expected that the clamp would tend to "open up", thereby putting the gage in compression. The first indications of the event occur at about 620 μs after the fireset fired.

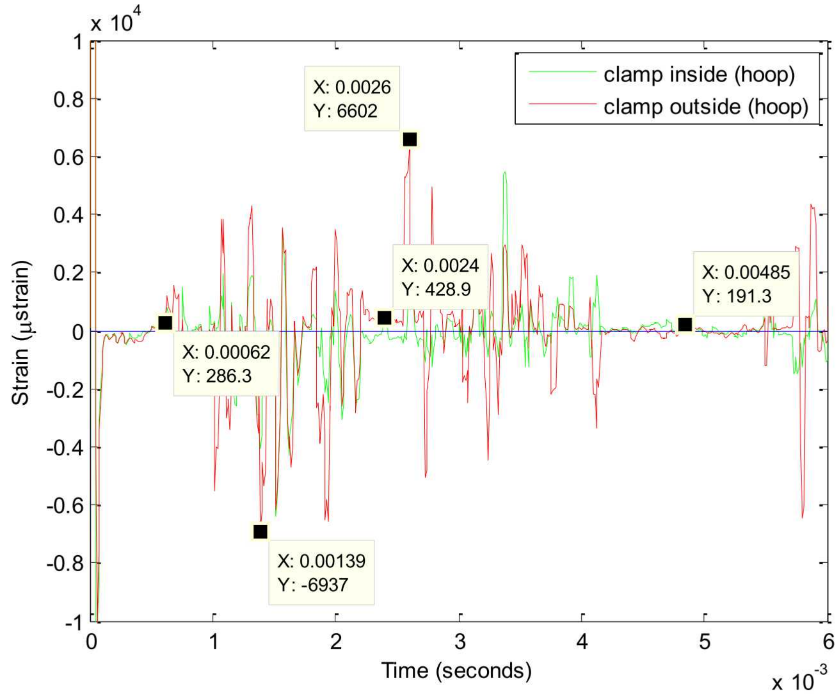

Figure 11: Strain in the door clamp on Shot 1 (comparing inside to outside)

Figure 12 shows the hoop and axial strain on the outside surface of the door clamp. Note the data have been smoothed. As expected, since the hoop direction is weaker than the axial direction on the clamp, the hoop strain is much higher than the axial strain. The same "quiet" regions exist, and the event appears to begin at the same time mentioned previously.

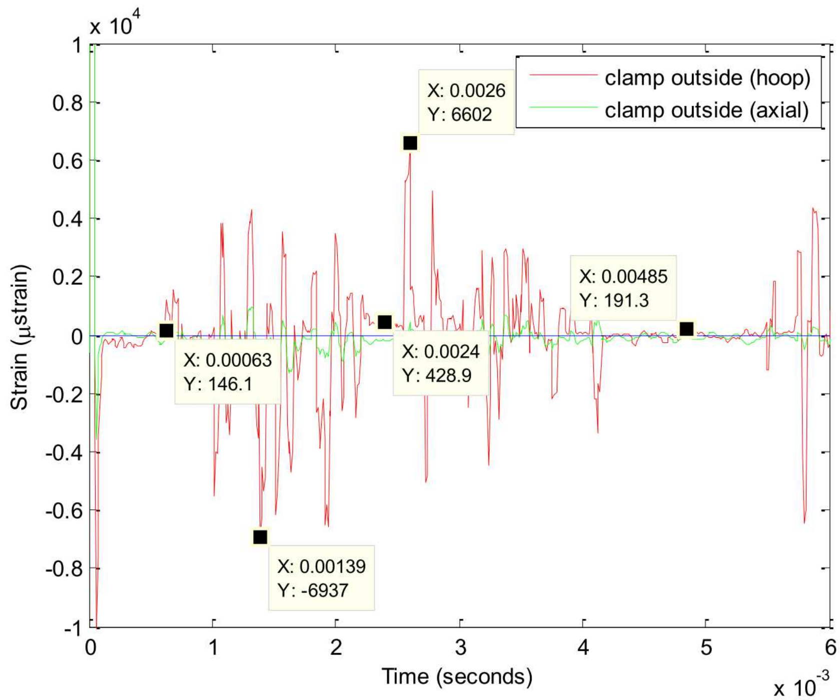

Figure 12: Strain in the door clamp on Shot 1 (comparing hoop to axial)

A.3.5. Static Pressure

Static pressure inside the vessel was measured for each of the four tests. As expected, the static pressure from the qualification test (and its repeat test) was greater than from the two smaller tests. The static pressure from the two orientation tests was reasonably consistent as shown in the table below. Note that the static pressure on Test 1 exceeded the gauge measurement range, hence it is only recorded that the pressure was higher than 160 psi.

Table 6: Static residual pressure

Test	Details	Static Pressure (psi)
1	9 lb C4, orientation 1/1	>160
2	4.8 lb C4, orientation 1/1	95
3	4.8 lb C4, orientation 1/2	90
4	9 lb C4, orientation 1/1	190

A.3.6. Pressure Inside Leak Check Annulus

A PCB dynamic pressure sensor (PCB 1501B02EZ100PSIG, 50 mV/psi) was installed into the door leak check port on Shots 1-3. It is not unusual to find inflated balloons on the leak check ports after a shot—generally on the door port. Figure 13 shows the pressure inside the door leak check annulus—note the data have been smoothed. The peak values measured on Shots 1, 2, and 3 were 60, 39, and 60 psi, respectively. It is hypothesized that the signal for Shot 2 is lower than the other tests because the explosive charge weight was lower than Shot 1 (the same distance away from the door) and the charges were farther away from the door than on Shot 3 (the same charge weight).

The peak pressures occurred between 60 and 670 μs after the detonation signal was sent. In terms of what material could be leaking into the annulus—whether from the vessel interior or exterior—the process of opening the munition and spreading chemical agent around in the vessel would likely be on the order of 1-2 milliseconds. This info, coupled with the fact that helium is occasionally detected in these burps, indicates that while the burp can contain interior vessel gases, it cannot contain chemical agent from the target munitions. This is because, as stated earlier, the munition opening and agent spreading occurs later than the peak pressures that were measured in the leak check annulus.

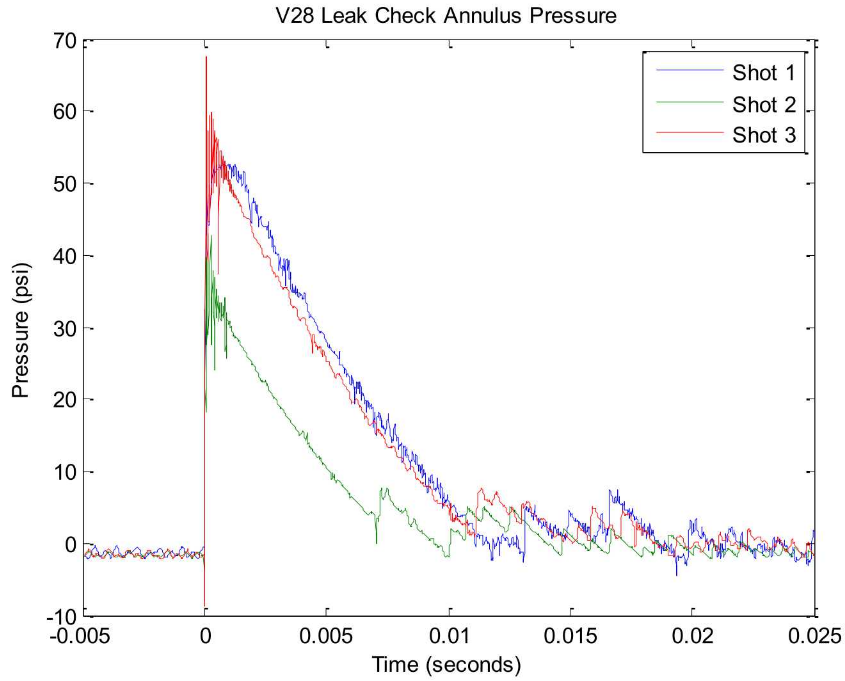

Figure 13: Door leak check annulus pressure-time history

A.3.7. Door Sagging

There were a few instances during these tests in which the door had to be realigned and secured with the door hinge set screws. The first time door misalignment was observed was prior to the first test. The set bolts were loose and not properly tightened. Another instance was prior to Test 4. It appeared that the tests had loosened the set bolts once again.

A.3.8. Resistance Measurement Difficulties

During the course of these four tests, there were two times at which resistance checks ("loop checks") could not be performed on the firing lines of the system or produced inconsistent results. On one occasion, the threaded banana connection on the end of one of the feedthrough assemblies was not tight enough. It appeared tight visually, but had to be tightened with a wrench before good electrical contact was made. Prior to tightening, the resistance measurements were inconsistent. On the second occasion, the interior ground conductor in the "spider assembly" was not threaded tightly enough into the door to enable a resistance check of the circuit. After tightening with a wrench, resistance measurements could be made.

A.3.9. Hardware Response

A.3.9.1. Large door valve

A large ¾" three-way sample valve (Parker/Autoclave Engineers 20SM12074) was fitted for Tests 1 and 4. This valve was installed in one of the two large drain ports on the door, as shown in Figure 14. The sample port of the valve was connected to the door and the common flow ports were plugged. The smaller 3/8"-size is used for drawing liquid and gas samples in the existing EDS systems. The goal was to determine if this larger valve could survive the explosive event while remaining functional and sealed to qualify it for future system designs.

After Test 1, it was determined that the valve had failed. It was loose after the shot and the high-speed video showed gas release during the event. Hence, the valve was left off for Tests 2 and 3. However, upon inspection while setting up for Test 4, it became obvious that the valve was still fully functional and that the leak was most likely due to improper installation (improperly torqued fitting). The valve was re-installed and successfully survived Test 4.

Figure 14: Large three-way sample valve installed on the drain port.

A.3.9.2. Sample port filters

Two styles and sizes of sample port filters were tested in this campaign. One design was smaller and used a thin wire mesh supported by a perforated 'thimble', while the other design was a straight version of the existing liquid sample dip tube screen with a larger tube and more substantial mesh. The port filters were covered by a more restrictive small blast cover, a model of which is shown in Figure 15. The smaller design was used on Tests 1, 2, and 3, while the larger design was used on Test 4. The small filter was repeatedly damaged, while the large filter did not exhibit any damage. As shown in Figure 16, Figure 18, and Figure 19, the small filter had multiple holes after only one test. Post-mortem analysis showed that the mesh was damaged at several of the 0.090" thimble openings.

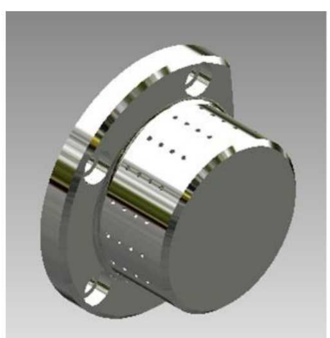

Figure 15: Model of port filter blast cover

Figure 16: Small filter

Figure 17: Large filter

Figure 18: Holes in small filter mesh

Figure 19: Holes in small filter mesh

A.3.9.3. Leak check fitting

On Test 3, the feedthrough flange was installed with its leak check fitting closest to the center of the door. Normally, the flange is installed with the fitting at the bottom or on the side opposite the center of the door. The fitting, a Kwik-flange-to-pipe adapter (MDC 731024), failed during this test. The failure is attributed to two causes. First, the fitting was closer to the center of the door than normal, an area which clearly experiences the most movement. Second, the charges were located closer to the ends of the vessel in this test, thereby increasing the coupled energy to the door. The fitting failed at the neck of the leak check flange and was later welded back together for future testing use (not in operations). Later leak checks with the fixed fitting indicate that the weld does not allow any leaks.

Figure 20: Failed fitting as found on feedthrough flange post-shot

Figure 21: Fixed fitting

Figure 22: Close-up picture of door, showing the positioning of the fitting on Test 3.

A.4. Conclusions

Additional non-qualification-related tests were completed using a distributed, reduced-load charge configuration where the longitudinal orientations of the six charges were varied. These tests were used for informational purposes to ensure that the design basis for actual munitions is robust against reasonably small variations in placement of the distributed charges.

Vessel and door displacement measurements were made during the tests using Photonic Doppler Velocimetry. The results show door separation gaps of roughly 2 and 0.5 mm for the 11.25 and 6.0 lb. TNT equivalent shots. The effect of separating the charges towards the vessel ends was minor.

New door hardware was evaluated for future designs. Larger three-way Autoclave Engineer sample valves were qualified. Interior sample port filters were also tested with a more restrictive blast cover. Straight versions of the existing liquid sample port dip-tube filters and thimble-supported large area screen filters were installed behind a more restrictive small blast cover.

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